43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
8 - 11 July 2007, Cincinnati, OH

AIAA 2007-5537

Hydrogen Peroxide – Optimal for Turbomachinery and Power Applications

Mark Ventura, PE*
General Kinetics Inc., Huntington Beach, CA, 92649

Dr. Eric Wernimont, PhD†
General Kinetics Inc., Huntington Beach, CA, 92649

Jim Dillard‡
Barber-Nichols., Arvada, CO

Decomposed hydrogen peroxide has been and is being used in a wide range of power applications due to several unique features of the monopropellant such as temperature control, safety, ease of use, non-toxicity, cool combustion temperatures, and attractive working fluid properties. Numerous power applications, especially those for turbo-machinery, both past and present are described and discussed providing technical information and analytic tools to help designers determine if hydrogen peroxide is the optimal choice for power applications. Modern usage of hydrogen peroxide with turbo-machinery is discussed to illustrate the inherent advantages of this working fluid.

Nomenclature

A-50	=	Aerozine 50
APU	=	Auxiliary Power Unit
BTU	=	British Thermal Unit
CH4	=	Methane
C	=	carbon
CO	=	Carbon monoxide
CO2	=	Carbon Dioxide
C_p	=	Specific heat
CPIA	=	Chemical Propulsion Institute Agency
deg	=	degrees
ft	=	feet
GG	=	Gas Generator
GK	=	General Kinetics
GPM	=	Gallons per minute
H2	=	Hydrogen
H2O	=	Water
H2O2	=	Hydrogen Peroxide
hp	=	horespower
IRFNA	=	Inhibited Red Fuming Nitric Acid
Isp	=	Specific impulse
lbf	=	pounds force

* 5362 Bolsa Ave. Ste G, Huntington Beach, CA www.gkllc.com.

† 5362 Bolsa Ave. Ste G, Huntington Beach, CA www.gkllc.com.

‡ 6325 W. 55th Avenue, Arvada, CO www.barber-nichols.com.

lbm	=	pounds mass
LITVC	=	Liquid Injection Thrust Vector Control
LOX	=	Liquid Oxygen
MON	=	Mixed Oxides of Nitrogen
MMH	=	Monomethylhydrazine
NPSH	=	Net Positive Suction Head
N2H4	=	Hydrazine
N2O4	=	Nitrogen tetroxide
O/F	=	Oxidizer to Fuel Ratio
psia	=	pounds per square inch absolute
R	=	Rankine
R_t	=	Turbine pressure ratio
RCS	=	Reaction Control System
RP-1	=	Rocket Propellant 1
rpm	=	revolution per minute
sec	=	seconds
SPGG	=	Solid Propellant Gas Generator
T_o	=	Turbine inlet temperature
thp	=	Turbine shaft power
TVC	=	Thrust Vector Control
UDMH	=	Unsymmetric dimethylhydrazine
Vdc	=	Volts direct current
$\dot{w}_t$	=	Turbine hot gas flow rate
η_t	=	Turbine efficiency
γ	=	Specific heat ratio

I. Introduction

THE launch vehicle and rocket propulsion industry has numerous applications and requirements for power applications such as turbo-machinery drive power, torpedos[1,2], reciprocating machines, vacuum aspiration, acoustic energy devices, blowing systems, thermal sources, pressurization, and others. Many of these applications are being operated by using propellant grade hydrogen peroxide because of the chemicals unique features which lend themselves to power applications. These unique features include:

- Power density
- Non-toxic
- Low temperature combustion gases
- Homogenous and uniform hot gas temperatures
- Safety
- Monopropellant operation
- Non-afterburning hot gases
- Non-condensing hot gas species

Turbo-machinery is a mainstay of the liquid rocket propulsion community, and drive power for turbo-machinery is a key design parameter in the coupled design and convergence of these devices. The use of hydrogen peroxide as the drive fluid offers a design space that can help make some turbo-machinery systems more optimal. Details regarding prior usage of hydrogen peroxide for turbine drive and other power applications are shown to illustrate what has been done and modern applications are discussed to show what is being done.

Turbines are commonly driven by cold gas system (spin bottles), solid propellant gas generators (SPGG's) and liquid propellant hot gas generators[3]. Gas generators have had and will continue to have a wide and variant use. The general requirements for gas generators is that the very high temperatures and combustion efficiencies typically needed for rocket propulsion are less important than other functional requirements such as size, storability, on-demand usage, operating pressure (sometimes very high or very low), gas temperature, gas species, size, complexity and other requirements; and as a result one often uses a gas generator that has specific features that fit the specific need. Hydrogen peroxide has been used as a liquid propellant in gas generator applications in a similar fashion to hydrazine and was used more extensively as a gas generator propellant in the early history of liquid rocket propulsion. It was very attractive due to its relatively low temperature gases and simplicity of a monopropellant liquid system. Examples of heritage and historical liquid hydrogen peroxide gas generators are shown in Figure 1.

Description	Device Type
Type 18-X submarine, Germany WWII	300 ton class H2O2-kersosene turbine drive
V-2 turbo-pump gas	Liquid injection of catalyst
V-1 catapult	Liquid injection of catalyst
X-1 turbo-pump gas	Mono-propellant gas generator
Redstone turbo-pump gas	Pellet bed mono-propellant gas
Jupiter turbo-pump gas	Pellet bed mono-propellant gas
Centaur boost pump gas	Mono-propellant gas generator
Viking turbo-pump gas gen.	Mono-propellant gas generator
X-15 turbo-pump gas gen.	Mono-propellant gas generator
Mk 16 torpedo	70% H2O2
X-1 mini submarine	Mono-propellant gas generator
GE hybrid	H2O2-PE hybrid
GE plug nozzle	Mono-propellant thrusters
Hyprox system	Mono-propellant gas generator for

Figure 1 - Turbo-pump Gas Generator Applications

II. Historical Usage

The application of hydrogen peroxide for turbo power systems essentially begins when the German government developed relatively safe concentrations of 80 to 82% H2O2 during the period from 1933 to approximately 1936. Based upon the availability of the new propellant, Walter began his own business of hydrogen peroxide combustion devices in 1935 (Walterwerke), and by 1936 had a 2200 lbf ATO engine and a 400 hp submarine turbine driven by hydrogen peroxide (T-Stoff) and liquid injection of permanganate catalyst (Z-Stoff). One of the most important historical applications of hydrogen peroxide by Germany was the V-2 turbo-pump gas generator[4]. This application brought hydrogen peroxide into the common use in rocket propulsion systems after WWII. The V-2 preeminence as the state of the art in high performance rockets was an important starting point for the majority of rocket propulsion activities that followed afterwards. The V-2 used liquid injection of catalyst (potassium permanganate solution) with 80% H2O2. Figure 2 shows the schematic of the V-2 powerplant and system.

Historically, the first proposed turbo propulsion and power application of hydrogen peroxide as a propellant was for submarines (Type 18-X 300-ton class submarines), which burned H2O2 with kerosene. The English evolved Walter rocket engines into the Gamma series of rocket engines used by Saunders Roe in the Black Knight launch vehicle, circa 1957[5,6,7,8,9 10,11,12,13,14]. The Gamma rocket engine was a pump fed regeneratively cooled gas generator cycle engine. All of the hydrogen peroxide was pre-decomposed in a silver screen catalyst bed and the hot gases were then after-burned with kerosene at a mixture ration of 8:1. The United States produced several hydrogen peroxide turbo-combustion devices and some deployed systems that were based on hydrogen peroxide.

Gas Generators - Turbo-Pumps

Hydrogen peroxide has been used in many launch vehicles and rocket engines as a working fluid to drive turbines. This application is traceable to the first significant application as the V-2 turbo-pump drive gas. Table 1 shows some of the historical turbine applications of hydrogen peroxide.

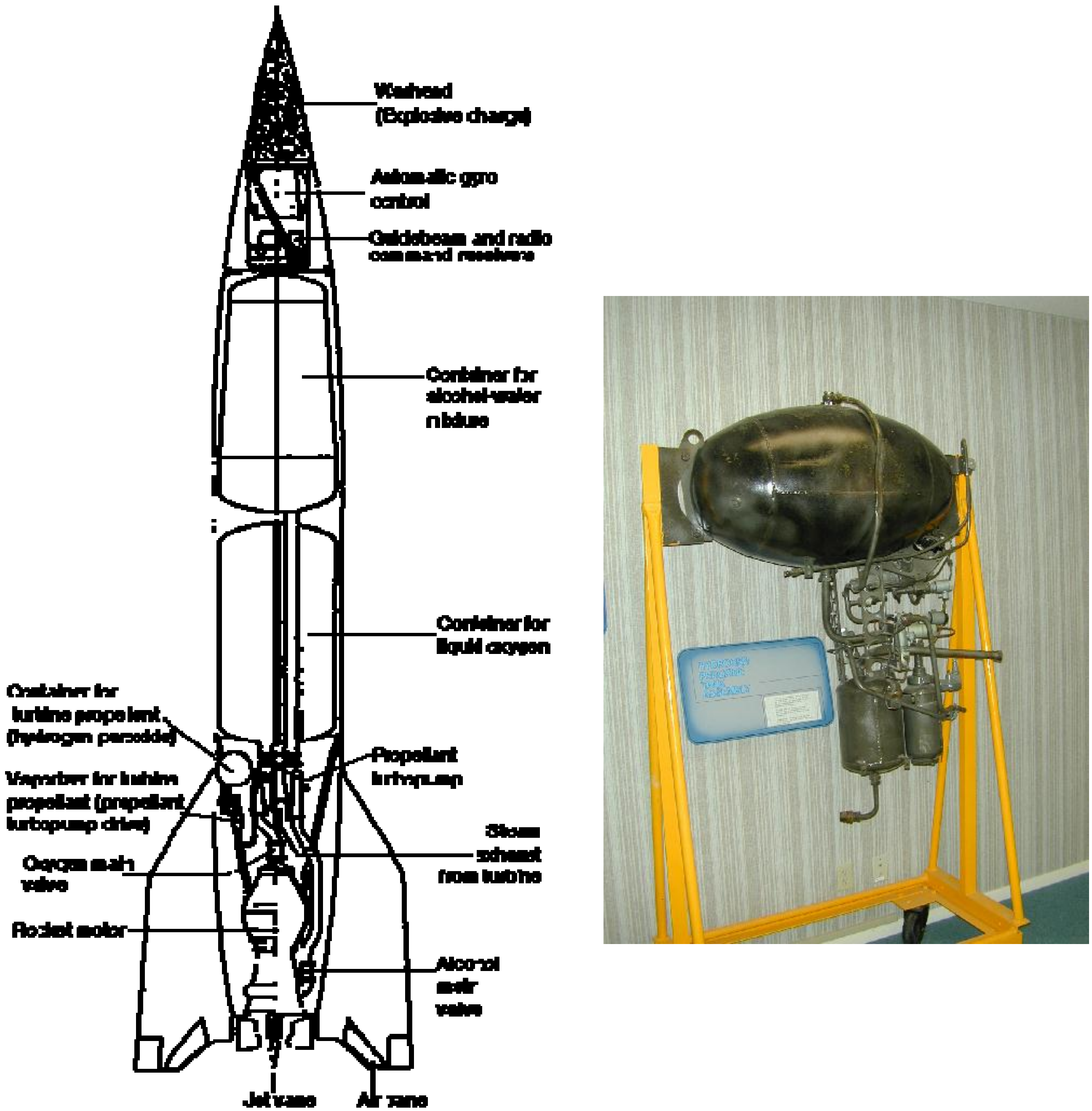

Figure 2 - V-2 Rocket Cross Sectional Schematic Layout[15] and Hydrogen Peroxide System[16]

V-2	Turbo-pump gas generator
Redstone	Turbo-pump gas generator
Jupiter	Turbo-pump gas generator
X-15[17]	Auxiliary Power Unit
NF-104A	AR2-3 Turbo-pump gas generator
LR-40	Staged combustion turbine drive (Topping cycle)
Gamma(s)	Turbo-pump gas generator
Beta(s)	Turbo-pump gas generator
Spectre	Turbo-pump gas generator
Viking	Turbo-pump gas generator

Table 1 – Historical Turbine Applications of Hydrogen Peroxide

Hydrogen peroxide is an attractive turbo-pump drive gas because the decomposition gas temperature is relatively close to the physical limits for uncooled turbines blades and the hot gas temperature can be controlled by varying the amount of water in the hydrogen peroxide solution. This allows the turbine hot gas temperature to be adjusted to fit the design requirements. Hydrogen peroxide was the most common source for hot gas to drive turbo-pumps and was used on the Redstone, Jupiter, and Viking launch platforms. Unlike the V-2, the Redstone turbo-pump gas generator used silicon carbide pellets with impregnated calcium permanganate and 76% hydrogen peroxide. These pellets or "stones" produce many of the problems that are endemic with ceramic catalyst by fracturing and producing small particle fines.

The Gamma engines represent a good example of the maturity of gas generator cycle turbo-pump fed rocket engines. Recent work by Northrop has developed a more modern gas generator cycle system using state of the art high performance high flux catalyst technology. An interesting turbo-pump fed engine cycle was developed by Reaction Motors in the late 1950's designated the LR-40 or Super-performance rocket engine. This engine was unique when it was developed and one of the chief engineers believes that it was pioneering in the U.S. efforts to develop staged combustion engine cycles[18]. Notably the engine cycle is closed and used a style of semi-staged combustion. All of the hydrogen peroxide is fully decomposed in a catalyst bed and the full flow hot gases pass through a turbine and the turbine exhaust is injected into the main combustion chamber and after-burned with fuel.

This engine was originally developed for aircraft rocket engine thrust assist applications and had like requirements to the Rocketdyne AR2-3 which was used in the NF-104. In some sense this engine is more like an aircraft engine than a rocket engine. The engine profile is long and thin to minimize frontal cross sectional area and the engine is closely packed around the major engine components for efficient packaging inside an airframe. It also had unique design requirements to operate at any attitude including the plume pointing directly upwards and to be capable of throttling continuously across a broad range, much like any aircraft gas turbine might have to do as well.

A simple engine cycle schematic (Figure 3) depicts the basic flow of propellants through the engine components. This figure is not the actual physical configuration of the engine, which is quite complicated, but shows the basic operation of the engine cycle. It as appropriately called a topping turbine cycle, because some of the enthalpy from the main decomposed hydrogen peroxide hot gases was converted into shaft power much like a topping turbine in a steam power plant removes some of the steam enthalpy. One of the benefits of this type of cycle is that the turbine has a large enthalpy flow because of the inherent energy released in the hydrogen peroxide decomposition hot gases. Hydrogen peroxide kerosene engines optimize with an O/F ratio between 6 to 8 which yields a very high oxidizer flow rate. This allows the turbine to operate as a topping style turbine and not be constrained to try and convert a significant portion of the enthalpy into shaft power. This reduces the thermodynamic demands on the turbine and permit less optimal turbine speeds and blade designs and configurations. Figure 4 and Table 2 shows the LR-40 engine and some pertinent specifications.

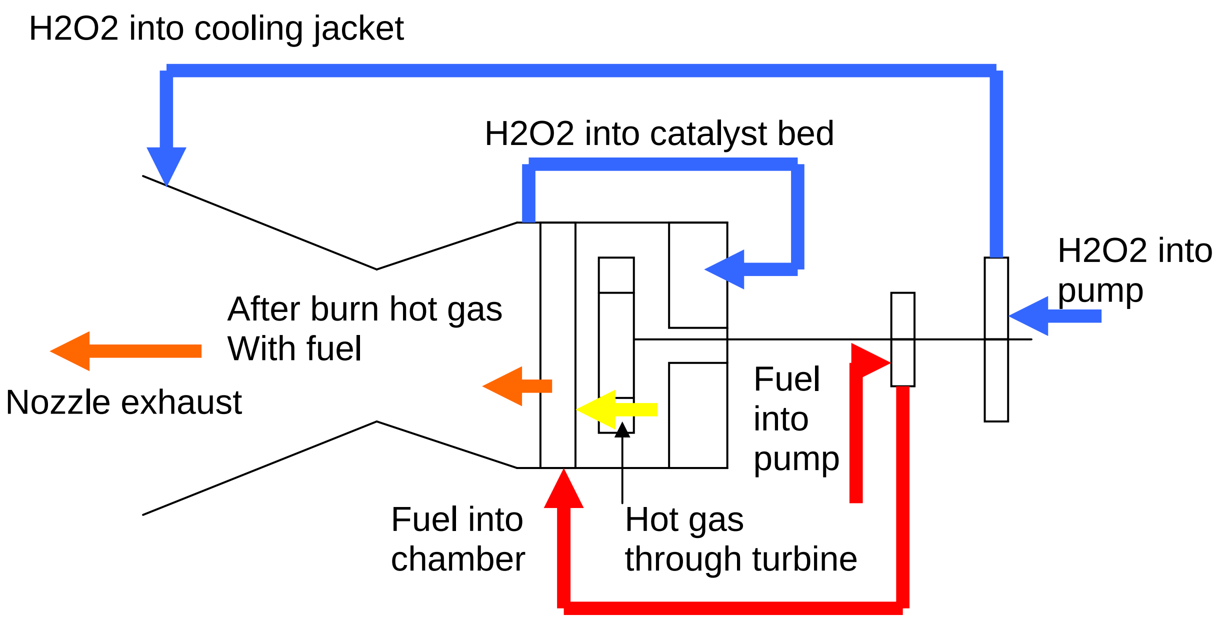

Figure 3 – LR-40 Topping Cycle Schematic Representation

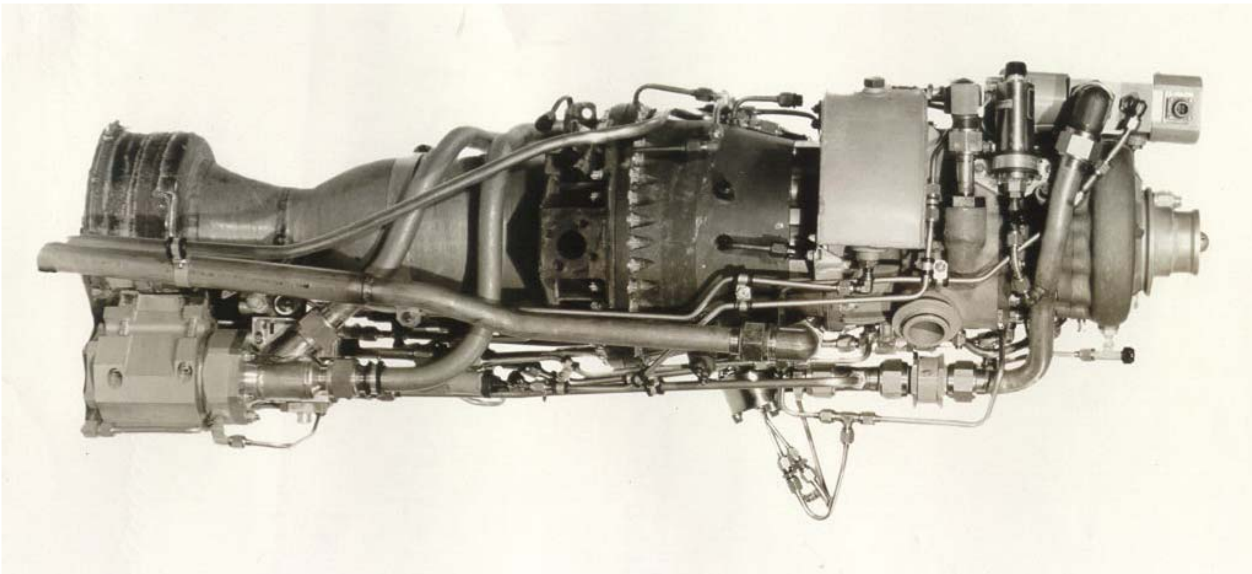

Figure 4 - LR-40 Rocket Engine

Parameter	Units	CPIA LR40	Thiokol LR40	GK LR40	AR2-3
Thrust	(lbf)	3500-8000 (2)	3500-10,200 (3)	3500-10,200 (4)	3300-6600
Specific Impulse	(lbf-sec./lbm)	220	257	257 (7)	241
O/F ratio		7.1	7	7	8
Chamber pressure	(psia)	530	530	530	280 (6)
Mass, dry	(lbm)	213	215	215	256
Length	(inches)	42	46.6	42	32.1
Diameter	(inches)	15.3	14	15.3	19.8
Oxidizer		MIL-H-6005C	90% H2O2	90% H2O2	90% H2O2
Fuel		MIL-F-5624C (JP5)	JP5	Kerosene	Kerosene
Expansion ratio		8.5:1	8.5:1	5.6:1	12:01
Thrust coefficient		1.645	1.645		
Turbo-pump					
Oxidizer flow rate	(lbm/sec.)	151 (1)	34.75		
Fuel flow rate	(lbm/sec.)	37 (1)	4.95		
Oxidizer inlet pressure					
Min. NPSH, start	(ft.)	21.1			47 (5)
Min. NPSH, run	(ft.)	15.7			
Fuel inlet pressure					
Min. NPSH, start	(ft.)	18.2			44 (5)
Min. NPSH, run	(ft.)	14.7			
Speed	(rpm)	18,800	18,800	18,800	26,500
Environmental temp. limits	(deg. F)		-35 to 160		
Power	(Vdc)	17 to 29			

Notes:

1) Units are GPM.
2) Thrust and Isp are values at 50,000 ft. CPIA notes that engine is continously throttleable from 3500 to 10,000 lbf, and can throttle to 1000 lbf in mono-propellant mode.
3) Thrust and Isp are vacuum.
4) Thrust and Isp are vacuum. Throttle to 1000 lbf in mono-propellant mode.
5) Assumed to be start NPSH and psia
6) Pressure assumed to be at low thrust level. High thrust level pressure estimated at ~ 560 psia.
7) Expansion ratio = 8.5

Table 2 - LR-40 Rocket Engine Specifications[19]

III. Esoteric Propulsion and Power Applications

Hydrogen peroxide has also been used for less common applications such as: vacuum aspiration, wind tunnel hot gas, acoustic energy sources, oil well recovery enhancement, catapults, “jump belts” (which were man carried rocket engines mounted on hips to make humans jump farther), rocket belts, astronaut maneuvering unit, robotic power for manned exoskeletons, rocket on rotor augmented power systems, and auxiliary power units[20,21]. Recent work with miniature reciprocating rocket engine pumps may soon provide a new design space for expanding pump fed systems to smaller scales traditionally the domain of pressure fed systems. Much of this recent work has used hydrogen peroxide as the working fluid to drive the pumps[22,23].

Gas Generator - Vacuum Aspiration: A less well known but very useful application of hydrogen peroxide is to generate large volumes of steam in a very short period of time to aspirate large vacuums. In the past, hydrogen peroxide was used to create vacuums with the Thiokol Hyprox system, which was installed in many test facilities and were used with great success.

Robotic Man-Exoskeleton Power Systems: Recent work in augmented manned exoskeleton power systems has preferred H2O2 as a high energy material with good power density and non-toxic effluents[24].

 

Figure 5 - Exo-skeleton Power Applications

Rocket On Rotor Tip – Reaction Motors developed a concept to provide augmented thrust for Marine helicopters by installing small hydrogen peroxide rocket engines at the tips of the helicopter blades. This provided short term added horsepower to provide rapid lift for combat applications. This concept has been further developed with the Rotary Rocket test vehicle.

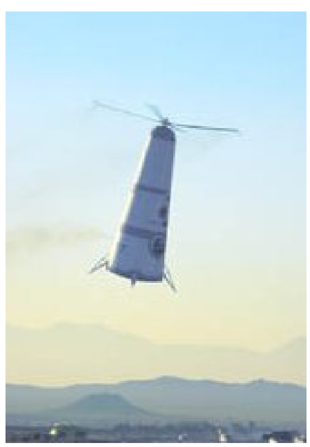

Figure 6 – Rotary Rocket Rocket on Rotor Power System[25]

IV. Turbo-machinery Requirements

Turbo-machinery works by the passage of a high velocity high enthalpy flow of hot gas across a working surface. The passage of the flow of the gas creates pressure loads on the turbine blades that are reacted through the blades and transferred to a rotating shaft. The rotating shaft power is the desired output and this shaft power is then used for various applications such as driving propellant pumps. The first key physical process is the production of a high enthalpy gas stream and the direction of that gas stream through turbine blades to extract the maximum possible energy and convert this energy into mechanical shaft power at the highest possible efficiency. The specific design of a turbine power system is quite complex and involves trade offs between numerous factors to arrive at an optimal configuration. In general, for rocket propulsion system applications, the preferred values for turbine design parameters is shown in Table 3. The shaft power extracted from a turbine is a function of the hot gas temperature, the thermodynamic properties of the hot gas, the shape of the turbine blades, stators, and/or nozzles, the velocity of the turbine blades, the angle of attack of the blade with respect to the hot gas, and other parameters. In general high power density power turbines prefer the following design criteria:

1) Higher gas temperatures
2) Faster turbine blades speeds
3) Higher speed of sound
4) Blisk speed matched to system power

Parameter	**Values**
Practical Design Limit Temperature (deg. F)	1600
Number of Stages	1 (as few as possible)
Turbine Speed	Slower than optimal to match with pump speeds
Hot gas species	Non-condensing (non-sooting, etc…)
Materials	Non-exotic, machinable (typically metals)
Reliability	Simple
Blade cooling	Un-cooled

Table 3 - Preferred Rocket Propulsion Turbine Design Parameters

An optimal turbine design would then have a hot gas temperature less than 1600 degrees F, have one stage, have the turbine speed match closely with the pump optimal speeds, have non-condensing hot gas species, be very reliable, use un-cooled blades, and make the entire product out of non-exotic easy to machine materials. Hydrogen peroxide provides the ability to design turbines to meet all of these requirements. Table 4 shows historical turbine hot gas temperatures as a point of comparison.

Engine or Vehicle	Propellants	Chamber Pressure (psi)	Temperature (deg. F)
F-1	LO2/RP-1	1000	1500
M-1	LO2/LH2	1100	1000
J-2	LO2/LH2	697	1200
H-1	LO2/RP-1	495	1200
Atlas sustainer	LO2/RP-1	770	1100
Atlas MA-3 booster	LO2/RP-1	475	1200
Atlas MA-2 booster	LO2/RP-1	570	1200
Thor	LO2/RP-1	450	1250
Agena	IRFNA/UDMH	475	1450
Titan II 1 stage	N2O4/A-50	540	1640
Titan II 2nd stage	N2O4/A-50	480	1660
Jupiter	LO2/RP-1	490	1200
Jupiter, storable	N2H4	500	1600
Redstone	H2O2		
Navaho	LO2/RJF-1	570	1200
Vanguard	H2O2	540	1300

Table 4 - Historical Turbine Hot Gas Temperature

Turbine Temperature – The maximum potential temperature that can be obtained from hydrogen peroxide ranges from roughly saturated water (212 deg. F) to 1735 deg. F for 98% H2O2. Other temperatures are easily created by blending water with hydrogen peroxide to thus produce tailored hot gas temperatures with a simple monopropellant. In addition hydrogen peroxide creates a uniform hot gas source without localized hot spots or streaks of hot gas that can impinge onto turbine components. The nature of a low O/F ratio bi-propellant combustors can produce hot gas streams that have localized zones of very hot gas and variations in chemical composition. This can produce localized heating of turbine components which may be much higher than the bulk overall gas temperature. These localized temperatures can have a significant influence on the turbine materials and life. Another feature of bi-propellant gas generators is that they may produce varying temperatures and chemicals species during either the start or shutdown transients. For example if a bi-propellant gas generator shuts down oxidizer rich due a leaking oxidizer valve, this will inject oxidizer rich hot gas into a hot turbine which can damage turbine components. These kinds of failures and risk are eliminated with monopropellant turbine operation.

Hydrogen Peroxide Concentration (%)	Adiabatic Decomposition Temperature (deg. F)
98	1735
90	1363
70	460
65	212

Table 5 - Theoretical Adiabatic Hot Gas Temperature for Various Concentrations of Hydrogen Peroxide

One sees that the preferred upper temperature limit of 1600 degrees is easily met with hydrogen peroxide between 90 and 98%, while 90% offers a reasonable and highly tolerable temperature of approximately 1400 degrees F.

Number of Stages and Condensing Species – In general the preferred design for rocket engines will prefer to use a single stage as additional stages add complexity, cost, and size. In order to achieve the maximum power extraction from a single stage turbine, one will wants to use the highest possible pressure ratio across the turbine. With most bi-propellant gas generators that operate at fuel rich conditions, this requires the hot gases to combust and rapidly change temperature which offers the opportunity to form soot. Figure 7 and Table 6 show the expected the O/F ratio ranges and the expected gas generator hot gas species under these conditions. Huzel suggests that LOX/RP-1 gas generators operate at O/F ratios of 0.308 to 0.516[26]. One sees that the theoretical exhaust chemical species under these conditions is very rich in carbon. Hydrogen peroxide on the other hand will produce a highly pure stream of steam and oxygen eliminating any issues with sooting or deposition of materials onto the turbine components. Turbines that operate with hydrogen peroxide essentially show no degradation due to the hot gas species. The hot gas from hydrogen peroxide can be dropped across a very high pressure ratio (as is commonly done in monopropellant rocket nozzles) without any concern for condensing species. An example of the turbine exhaust from the H-1 rocket engine showing the high fuel content of gas stream (Figure 8).

Turbine Speed – Optimal turbine speeds are often much faster than a preferred optimal pump speed. Matching the turbine to the pump may require a gear box, a less preferred design, or by running both pump and turbine under less than optimal conditions, which is more typical.

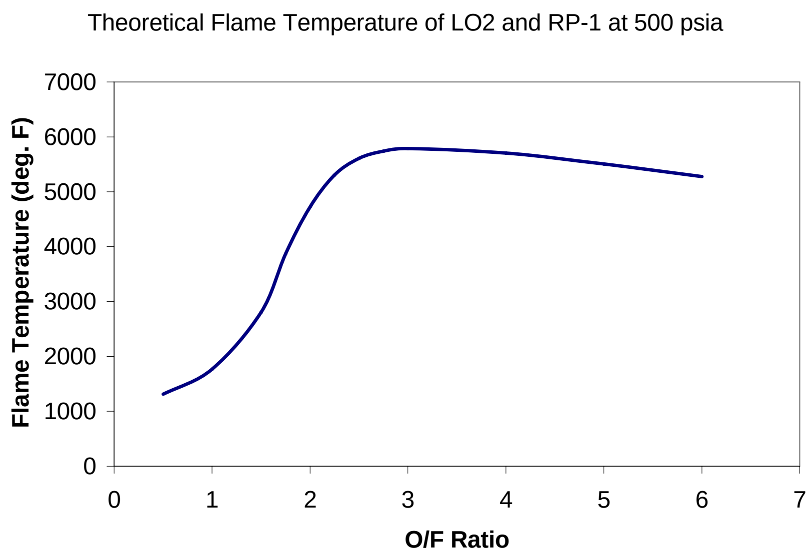

Figure 7 - Theoretical LOX and RP-1 Flame Temperature at 500 psia[27]

Species	O/F = 0.5	O/F = 1.0
CH4	0.18	0.06
CO	0.03	0.32
CO2	0.05	0.05
H2	0.16	0.36
H2O	0.16	0.08
C	0.42	0.13

Table 6 - Theoretical Plume Species for LOX RP-1 Gas Generator Combustion[27]

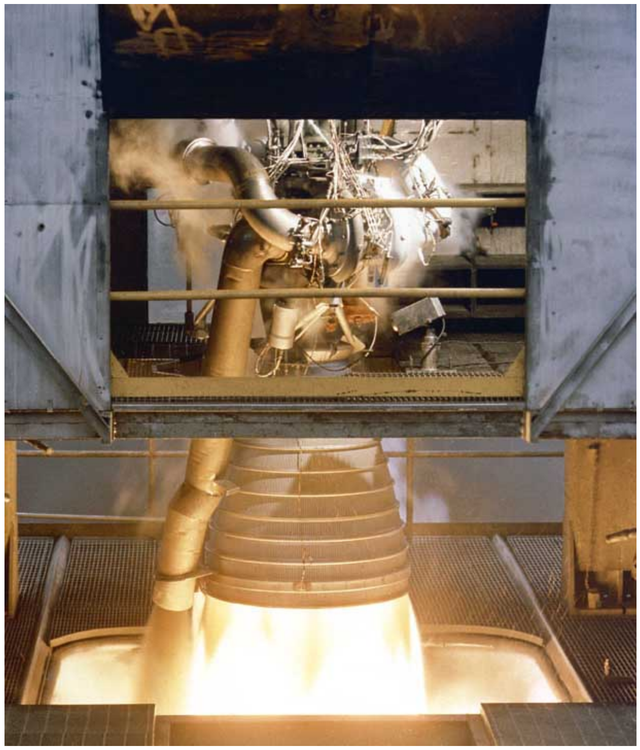

Figure 8 – Test Firing of H-1 Rocket Engine[28]

Materials and Blade Cooling– Monopropellant hydrogen peroxide produces a uniform and well moderated temperature from the exit of the gas generator to the inlet of the turbine nozzles. The temperatures of 90% and 98% hydrogen peroxide permit the use of common easy to fabricate materials like stainless steel and Inconel. Unlike bi-proprellant combustors, there is no possibility of localized high temperatures and temperature gradients inside the gas generator or at the turbine inlet. Hydrogen peroxide offers the ability to build un-cooled turbo-machinery components, including the blades, with simple, easy to machine materials.

V. Hydrogen Peroxide is Mass Optimal in Comparison to LOX and Kerosene Driven Turbines

A particular case will be made that hydrogen peroxide is superior as a working fluid in comparison to other chemistries in terms of overall system mass performance. It is possible that for some solutions that hydrogen peroxide will actually yield a lower system mass if it used in lieu of available propellants, such as LOX-kerosene. This is due to the fact that at the temperature of interest of 1000 – 1600 degrees F, hydrogen peroxide provides a very low molecular weight gas with the resulting thermodynamic properties that permit a light mass system. An example of this is shown by comparing the masses of two systems; one using hydrogen peroxide as a hot gas and the other using fuel rich combusted LOX/RP-1 as the working fluid.

Huzel provides a detailed example of a LOX/RP-1 gas generator cycle engine. This example is most likely a version of the H-1 rocket engine[29]. An example of the H-1 engine showing its gas generator is in Figure 9. The pertinent performance factors for this example engine from reference 26 are in Table 7.

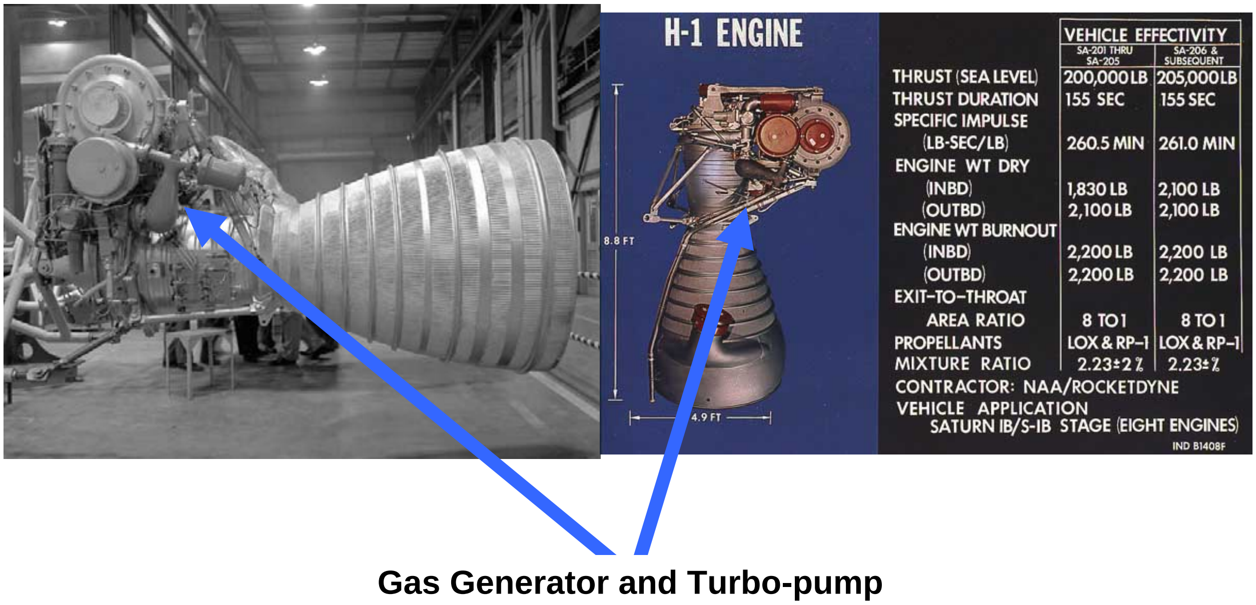

Figure 9 – Example of a Rocket Engine Gas Generator and Turbo-pump

Main Engine Propellant Flow Rate (lbm/sec.)	743.7 lbm/sec.
Turbine Efficiency	66.2 %
Turbine Brake Horsepower	3793 hp
Turbine Hot Gas Flow Rate	17.34 lbm/sec.
Turbine Inlet Gas Temperature	1200 deg. F
Turbine Pressure Ratio	18.21
Turbine Gas Chemistry	LOX/RP-1 (assumed)

Table 7 - Example LOX/RP-1 Turbo-pump Performance Parameters (ref. 26, pg. 163)

A first order comparison between hydrogen peroxide and LOX/RP-1 shows that hydrogen peroxide can offer a lower mass system.

Using the simple ideal gas equation for a power turbine from Huzel shows:

Equation 1

$$\eta_t = 0.707 \frac{thp}{\dot{w}_t C_p T_o \left[1 - \left(\frac{1}{R_t} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

A table of gas generator hot gas properties for a LOX/RP-1are shown in Table 8,

Temperature (deg. F)	Cp (BTU/lbm-R)	Specific Heat Ratio	Mixture Ratio
1100	0.635	1.097	0.308
1200	0.643	1.106	0.337
1300	0.648	1.115	0.372
1400	0.653	1.124	0.408
1500	0.657	1.132	0.443
1600	0.660	1.140	0.478

Table 8 - Example of LOX/RP-1 Gas Generator Hot Gas Properties

and the comparable hot gas properties for hydrogen peroxide are shown in Table 9.

Temperature (deg. F)	Cp (BTU/lbm-R)	Specific Heat Ratio	H2O2 Concentration
1824	0.440	1.248	100%
1593	0.435	1.256	95%
1363	0.428	1.266	90%
460	0.391	1.318	70%

Table 9 - Hydrogen Peroxide Decomposition Hot Gas Properties[30]

One can calculate the mass of propellants needed to provide the required shaft power. A simple factor of 11% will be applied to the ideal-gas analytic value for both propellants to account for gearing losses, real gas effects, and other losses as a first order analysis. Assuming a 200 second burn duration with a 1200 degrees F hot gas temperature, yields the following masses:

Propellant	Total Gas Generator Flow Mass (lbm)	Gas Generator Flow Rate (lbm/sec.)
LOX/RP-1	3468	17.34
H2O2	2832	14.16
Difference (LOX/RP-1 less H2O2)	636	3.18

Table 10 - Comparison of LOX/RP-1 and Hydrogen Peroxide Gas Generator Flow Rates and Masses

This shows that a hydrogen peroxide gas generator can lower the mass of the propellant required to drive the turbine, all other factors considered equal.

In order for hydrogen peroxide to be a reasonable choice for optimal system mass, the system would need to be able to contain 2323 lbm of hydrogen peroxide and to deliver that propellant to the turbine with less than 636 lbm of system inert mass. That equates to a sub-system mass fraction for the hydrogen peroxide of 82% which is not unrealistic with current system mass fractions. It is not inexplicable that the usage of H2O2 may actually reduce the system mass and increase system performance. In the case of a LOX/RP-1 system, that would require the addition of a new fluid and fluid system which is highly unattractive for cost and system complexity. On the other hand it eliminates the complexity and improves the system reliability by exchanging a bi-propellant gas generator with a monopropellant gas generator with the associated reduction in valving, controls, and ignition systems. Hydrogen peroxide offers a cleaner and possible more reusable turbine, and other system development enhancements. In the event that hydrogen peroxide is considered for other vehicle operations such as roll control, thrust vector control (liquid injection thrust vector control - LITVC) or for Auxiliary Power Unit to provide hydraulic power for a TVC system, or other applications, it may become more attractive when considered at a higher level of an integrated system design and optimization.

VI. Current and Future Propulsion and Power Applications

One of the most mature and modern hydrogen peroxide turbo systems is the Northrop TR108 hydrogen peroxide-kerosene rocket engine[31]. This engine uses a gas generator cycle with a monopropellant gas generator that decomposes approximately 91% hydrogen peroxide to provide hot gas to drive a single shaft turbo-pump as seen in Figure 10.

Figure 10 – Northrop TR-108 Rocket Engine Turbo-pump Made by Barber-Nichols

Miniature power systems may also benefit from hydrogen peroxide. For very small scale power applications lasting in durations of minutes, monopropellants have been analytically shown to be an optimal solution and hydrogen peroxide is an excellent candidate[32]. Recent work has also been pursued for hydrogen peroxide based turbo-pump fed systems[33].

Auxiliary Power Systems for Re-Usable Reentry System: Hydrogen peroxide is an excellent power system working fluid for manned reusable reentry systems and manned high speed rocket plane applications. It is notable that all early manned high speed high altitude and exo-atmospheric planes and spaceraft used hydrogen peroxide for reentry control including the: NF-104, X-15, X-1, D558, and the Mercury capsule. (Note that the X-15 did suffer from reliability problems with the hydrogen peroxide APU which were due to the specific catalyst bed design and possibility due to the quality of the propellant.) These systems prefer non-toxic chemistry, generally need high peak power requirements for actuating aero-surfaces, are active when available atmospheric oxygen is absent, ingest ambient gases inside vehicle structure, and need high reliability, The Space Shuttle Orbiter is one of the best examples of a manned reusable reentry system and while the current storable chemistry systems have demonstrated the functional requirements for reentry attitude control and power, the specific chemistry of hydrazine, monomethyl hydrazine and nitrogen tetroxide have also demonstrated some attributes that are less desirable and could be changed by using hydrogen peroxide.

The Space Shuttle Reaction Control System (RCS) and the Auxiliary Power System use conventional storable chemicals. These systems are active during entry and in particular the yaw thrusters and the APU system are active to very low altitudes. The APU system is active during entry to provide power to the main aerosurfaces and this system produces an exhaust stream of nitrogen, ammonia, and hydrogen. The exhaust vapors from the APU vent near the aft end of the Orbiter and are pulled into the wake and aft areas of the vehicle as it flies. During entry, the vehicle external surface is subjected to increasing pressure as the vehicle descends into the atmosphere. This causes gases from the atmosphere and surrounding the vehicle to be ingested and re-pressurize the interior spaces of the vehicle. Specific provisions for gas ingestion are located in various areas to ensure that the structure does not implode under the increasing pressure of reentry. In addition, the blunt shape of the vehicle causes a local recirculation zone behind the Orbiter that can trap gases venting from the APU. This creates the risk that APU exhaust gases can be ingested inside the vehicle structure during entry creating trapped cavities of hydrogen gas. Since hydrogen has such a wide range of flammability and detonation, this creates the very real concern that ingested APU exhaust gases could create hydrogen explosion hazards. The Orbiter system attempts to mitigate this risk through a helium purge of the some of the cavities during entry in an attempt to apply a positive pressure and inhibit the ingestion of APU wake gases. This will be a recurrent problem for any and all reentry system that require high horsepower at periods of the time inside an atmosphere that can support combustion. Improvements in other technologies such as batteries and fuel cells may offer other design solutions as well. Hydrogen peroxide offers an alternate and viable design option for reentry vehicle turbine drive requirements.

VII. Conclusion

Hydrogen peroxide offers a unique combination of features that permit turbines to be designed to more preferred conditions. Under some conditions and designs, hydrogen peroxide may offer the highest performing system configuration for turbo-pump systems. This feature was well utilized in the past and is finding applicability in modern applications. Hydrogen peroxide offers additional unique features which are well suited for specific applications especially those that require reusability and interaction with human operators that require non-toxic operations.

VIII. References

[1] Brady, John, "Torpedo Propulsion, 1964", *1st[h] AIAA Annual Meeting*, AIAA-64-518, Washington, DC, 1964.

[2] Wolf, S., McNally, W. A., "Hydrogen Peroxide as a Torpedo Propellant," US Naval Underwater Ordnance Station, NUOS Consecutive No. 360, Newport, Rhode Island, March 1963.

[3] "Liquid Propellant Gas Generators," NASA SP-8081, March 1972.

[4] Healy, Roy, "V-2's Power Plant Provides Key to Future Rocketry," Aviation, May 1946, p.p. 63-67.

[5] Harlow, J., "Alpha, Beta and RTV-1, The Development of Early British Liquid Propellant Rocket Engines," *44th Congress of the International Astronautical Federation*, IAA93-676, Graz, Austria, October 16-22, 1993.

[6] Millward, Douglas, *The Black Arrow Rocket – A history of a satellite launch vehicle and its engines*, 1st ed, NMSI Trading Ltd, Science Museum, Exhibition Road, London SW7 2DD, 2001.

[7] Harlow, John, "Hydrogen Peroxide Engines – Early Work on Thermal Ignition at Westcott," *2nd International Hydrogen Peroxide Propulsion Conference*, Purdue University, Nov 7-10, 1999, pp. 211-219.

[8] Becklake, J., "The British Black Knight Rocket," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 283-290, London, July 1990

[9] Robinson, H. G. R., "Overview of the Black Knight Project. Black Knight, It's Genesis," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 291-296, London, July 1990

[10] Scragg, J., "A Contractor's View of the Black Knight Programme," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 297-300, London, July 1990.

[11] Andrews, D., Sunley, H., "The Gamma Rocket Engines for Black Knight," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 301-310, London, July 1990.

[12] Harlow, J., "Black Knight Upper Stages," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 311-316, London, July 1990.

[13] Robinson, H. G. R., "Suggested Developments of Black Knight," Journal of the British Interplanetary Society, Vol. 43, No. 7, p.p. 317-318, London, July 1990.

[14] Harlow, John, "Hydrogen Peroxide - A U.K. Perspective," Lecture at University of Surrey Symposium on Hydrogen Peroxide, July 20-24, 1998.

[15] James, Donald, "A Brief History of Rockets,", NASA Quest, http://quest.nasa.gov/space/teachers/rockets/history.html, [cited June 2, 2007]

[16] "V2 Hydrogen Peroxide Tank," White Sands Missile Range Museum, http://www.wsmr-history.org/InsidePhotos1.htm, [cited June 2, 2007]

[17] Wiswell, R., "X-15 Propulsion System," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 97-2682, Seattle WA, July 6-9, 1997.

[18] Gay, Cadwell, private communication, circa 1998.

[19] Ventura, Mark C. and Wernimont, Eric J., "History of the Reaction Motors Super Performance 90 Percent H2O2/Kerosene LR-40 Rocket Engine," *37th AIAA Joint Propulsion Conference and Exhibit*, AIAA-2001-3838, Salt Lake, UT, 2001.

[20] Ventura, M., Mullens, P., "The Use of Hydrogen Peroxide for Propulsion and Power," AIAA-99-2880, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 20-24, 1999, Los Angeles, CA.

[21] Ventura, M., Garboden, G., "A Brief History of Concentrated Hydrogen Peroxide Uses," AIAA-99-2739, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 20-24, 1999, Los Angeles, CA.

[22] Ledebuhr, A.G., et al, "Recent Development on Hydrogen Peroxide Pumped Propulsion," UCRL-CONF-203137, 2nd Missile Defense Conference and Exhibit, Washington D.C., March 22-26, 2004.

[23] Whitehead, John C., "Hydrogen Peroxide Gas Generator Cycle with a Reciprocating Pump," AIAA-2002-3702, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, July, 2002.

[24] "Monopropellant-Powered Actuation for a Powered Exoskeleton," Center for Intelligent Mechatronics, Vanderbilt University, http://research.vuse.vanderbilt.edu/cim/projects/exoskeleton.htm, [cited June 2, 2007]

[25] "Interview with Gary Hudson ," Hobbyspace, http://www.hobbyspace.com/AAdmin/archive/Interviews/Systems/GaryHudson.html, [cited June 2, 2007], June 9, 2003

[26] Huzel, Dieter K. and Huang, David H., *Modern Engineering For Design of Liquid-Propellant Rocket Engines*, 2nd ed, Vol 147 Progress in Astronautics and Aeronautics, AIAA, Washington DC, 1992.

[27] Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflective Shocks; and Chapman-Jouguet Detonations," NASA SP-273, NASA Lewis Research Center, 1971.

[28] Akens, David, S., "Saturn Illustrated Chronology, Saturn's First Eleven Years: April 1957 through April 1968," MHR-5, NASA-Marshall Space Flight Center, http://history.nasa.gov/MHR-5/figures.htm, [cited 6/2/2007].

[29] Puglisi, A. G., "Saturn IB/S-IVB Stage Separation Controllability Report," Douglas Report SM-46758, November 1964.

[30] "Field Handling of Concentrated Hydrogen Peroxide," Director of the Chief of the Bureau of Aeronautics, NAVAER 06-25-501.

[31] Kim, P. Y., Majamaki, A., Papesh, C., Schneider, D., Thomson, M., Wenstock, V., "Design and Development Testing of the TR108 – a 30 Klbf Thrust Class Hydrogen Peroxide/Hydrocarbon Pump-Fed Engine," AIAA-2005-3566, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 10-13, 2005 Tuscon, Arizona.

[32] Wernimont, E., "Monopropellant Hydrogen Peroxide Rocket Systems: optimum for Small Scale" 42nd AIAA Joint Propulsion Conference and Exhibit, AIAA-2006-5235, Sacramento, CA, 2006.

[33] Scharlemann, C., et al, "Test of a Turbo-Pump Fed Miniature Rocket Engine" 42nd AIAA Joint Propulsion Conference and Exhibit, AIAA-2006-4551, Sacramento, CA, 2006.