42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit AIAA-2006-4547
Sacramento, CA, July 9-12, 2006

Novel Concepts for an Advanced Non-Toxic Gas Generator

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Gas generators are widely used for numerous applications in the aerospace and defense power and propulsion industries and most application's functional requirements drive the selection of the gas generator configuration and chemistry. Many of the industry standard gas generator concepts use toxic chemicals and/or produce toxic hot gas combustion species. Existing chemicals and configurations limit some applications and non-toxic needs exist for current and future gas generator applications. Novel solid-like concepts using hydrogen peroxide can provide non-toxic chemicals which produce hot gas sources with low temperatures and less toxic gas species and combustion products which will enable new types of non-toxic gas generators.

Nomenclature

AP = Ammonium Perchlorate
APU = Auxiliary Power Unit
DoT = Department of Transportation
DTIC = Defense Technical Information Center
EPU = Emergency Power Unit
FAA = Federal Aviation Administration
GG = Gas Generator
H2 = Hydrogen
H2O = Water
H2O2 = Hydrogen Peroxide
HTP = High Test Peroxide (propellant grade)
LH2 = Liquid Hydrogen
LN2 = Liquid Nitrogen
LO2 = Liquid Oxygen
N2 = Nitrogen
N2H4 = Hydrazine
O/F = Oxidizer to Fuel Ratio
RP-1 = Rocket Propellant 1

I. Introduction

THE launch vehicle and rocket propulsion industry has numerous applications and requirements for gas generators[1]. Gas generators have a multitude of uses such as driving turbomachinery, operating other machines, pressurizing and inflating structures and numerous others. The functional requirements of gas generators typically drive specific design requirements which have historically been created from using existing state of the art knowledge of propellant chemistry or by using chemistry or technology which is convenient or accessible on a specific system. Generally, design considerations such as toxicity are of lesser interest and as such little to no work

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has been done on specifically trying to create non-toxic gas generator products, with the exception of some commercial work for car air bag inflation devices. As the launch and propulsion community continues to develop more non-toxic systems in the future, new concepts for gas generators will be needed to support the overall non-toxic architectures. To support the future need for specifically non-toxic gas generators, innovative and novel concepts for using hydrogen peroxide as a gel, hydrogen peroxide trapped in a solid storage matrix, and hydrogen peroxide as a propellant with a solid fuel matrix are discussed. Initial testing is shown to investigate the feasibility of new forms of using hydrogen peroxide in gas generator applications. These concepts may also be of value for other chemistry in addition to those explored with hydrogen peroxide.

II. Gas Generator Applications

Gas generators have had and will continue to have a wide and variant use. Some examples of the many applications of gas generators are: Rocket engine turbo-pump drive power[2], auxiliary or emergency power systems, vacuum aspiration, drive gas for reciprocating machinery[3], inflating air bags[4], pressurizing cavities[5], thermal heat, ejecting torpedoes, spin-starting turbo-pump rocket engines, turbine drive power for many different devices, rocket engine fuel source, rocket engine oxidizer source[6], hydraulic system pressurization, light sources (flares), smoke generators, and many others.

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. It is unlikely that there will ever be a perfect one size fits all gas generator and that each functional application will have a preferred choice of chemicals and configuration. That does not preclude that all current and future applications are being best met with existing designs and concepts.

Examples of existing gas generators are shown in Figures 1 and 2. An assorted, but not comprehensive list of gas generators illustrating the diversity of gas generator application and chemistry is shown in Figure 3.

III. State of the Art for Gas Generators

Gas generators typically fall into either being liquid propellant systems or solid propellant devices. Liquid propellant systems are either off nominal bipropellant combustors or liquid monopropellants. Other concepts are also possible such a gaseous monopropellants, such as Tridyne or gaseous bipropellants. Liquid bipropellant combustors are commonly used on rocket propulsion systems which already have the two propellants for some other purpose, such as main propulsion, and then use these chemicals to create hot gasses for other applications, such as driving turbo machinery.

Often an optimal solution for bipropellant gas generators is to operate in a fuel rich mixture ratio to reduce the flame temperature based on the design and optimization of the turbine materials. These bipropellant rocket systems sometimes also use a solid propellant gas generator to spin start the turbine (H-1 rocket engine) and afterwards the main propellants are used to drive the turbine for the duration of the rocket engine operation. Liquid monopropellants can also be used at the expense of sometimes adding a separate fluid system. The two most common monopropellants, hydrogen peroxide and hydrazine, are sometimes more attractive because the flame temperature of the hot gas can be somewhat controlled to lower temperatures than most bipropellant combustion reactions and the exhaust effluent is sometimes more preferred in comparison to fuel rich carbon filled gases from a bipropellant flame.

Solid propellants perform many gas generator applications and these devices are typically some solid propellant formulation, which again burns fuel rich, or has some diluents or cooling additive which permits the tailoring of the hot gas temperature and chemical species[4]. The state of the art in solid propellant combustion limits the ability to control the chemical species of the exhaust effluent to within the family of currently known solid propellants.

Hydrazine has been used as a liquid propellant for gas generator systems in such notable applications as the Space Shuttle APU system and the F-16 EPU system. The decomposition temperature of hydrazine is a function of the dissociation of ammonia in the initial decomposition reaction of N2H4 into ammonia and nitrogen. The ammonia dissociation reaction absorbs energy. The ammonia dissociation can be controlled and this permits the gas temperature to be tailored to some desired value. Figure 4 shows the decomposition temperature of hydrazine as a function of the ammonia dissociation[8]. Gas generators typically operate with an ammonia dissociation of 60% to 80% which yields a range in hot gas temperatures of 1270 to 1660 deg. F. The chemical species likewise vary as the disassociation occurs and Figure 5 shows the approximate hot gas chemical species[8]. In the range of 60% to 80% ammonia dissociation one sees that the exhaust gas is composed of approximately 33% nitrogen (N2), 54% hydrogen (H2), and 14% ammonia. This exhaust has the potential to after burn in air and in general the exhaust plumes from hydrazine gas generators need to be treated as a flame or a flammable gas.

Solid propellant gas generators burn a variety of chemicals such as sodium azide in automobile air bag inflators, and various composite blends using ammonia nitrate and other chemicals. The chemical composition is created to produce a relatively low temperature hot gas which typically requires solid propellant gas generators, like most bi-propellant liquid gas generators, to run at a fuel rich mixture ratio. This fuel rich mixture ratio produces a hot gas stream which contains partially combusted fuel and carbon exhaust products and can be a smoky plume. This plume may or may not after burn in air.

Liquid bipropellant gas generators operate much the same as rocket engines, except that often the mixture ratio is tuned to control the hot gas temperature and is commonly fuel rich. This produces a gas stream which contains partially combusted fuel and may or may not after burn in air. Figures 6 and 7 show the theoretical temperature and chemical species for a LO2-kerosene flame. Note that to meet typical gas generator temperature requirements, the O/F ratio needs to be less than 1.0 which yields a very fuel rich hot gas. Sometimes gas generators direct exhaust plumes into the cone or nozzle skirt of a rocket engine to increase performance and provide nozzle cooling. It should also be noted that many Russian rocket engines use oxidizer rich gas generators[2] which is a significant difference in the approach of liquid bipropellant gas generator design from US designed rocket engines. Figure 8 shows a tabulation of various liquid gas generator operating conditions.

Hydrogen peroxide has been used as a liquid propellant in gas generator applications[6,9-15] 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 liquid hydrogen peroxide gas generators are shown in Figure 1.

Based upon a review of the state or the art for gas generators it seems that flames temperatures on the order of 1550 degrees F are desirable and variations in flame temperature can be as low as 1000 degrees F and higher than 1640 degrees F depending on the application. Very low temperatures are needed for some applications like air bags with hot gas temperatures on the order of 600 degrees F[4]. More advanced turbo-machinery may be able to tolerate higher turbine inlet temperatures. The plume species are often dictated by the available chemistry and these vary from highly flammable to fuel rich or oxygen rich hot gases. The propellant chemistry and hot gas exhaust toxicity is clearly a secondary consideration to functionality in many of these applications.

IV. Benefits of Hydrogen Peroxide for Gas Generator Applications

As previously noted, gas generator applications are quite variable and no single chemical or configuration will provide the best figures of merit for all applications. The novel gas generator concepts of this paper are based on the chemistry of hydrogen peroxide and hydrogen peroxide and its combustion has certain features which are of interest for some, but probably not all gas generator applications.

The state of the art in gas generator technology is essentially bounded by liquid hydrogen peroxide, liquid hydrazine or hydrazine blends, main propulsion propellants burning at an off nominal O/F ratio, and solid propellants of various chemistries. The criteria for a gas generator typically includes specifications such as gas temperature, gas chemical species, and burn duration, throttling, start and re-start, munitions application environments, storability, transportability, on-demand usage and others. Hydrogen peroxide tends to offer advantages for applications that need non-toxic chemicals[16], very low gas temperatures, a non-toxic plume, a plume that does not after burn, a clear plume, temperature control of the hot gases; or the various benefits of a liquid system, such as throttling, start and re-start, and others.

Liquid hydrogen peroxide, like liquid hydrazine, will always have limitations for those applications that are only effectively provided by solids where a liquid propellant is highly undesirable or not reasonable, such as many militarized applications. The ability to treat hydrogen peroxide like a solid propellant may offer some new applications for non-toxic gas generators. Monopropellant hydrogen peroxide is an excellent propellant for providing gases at temperatures less than 1500 degrees F and as low at 500 degrees F and probably lower. Selection of the water content can be used as a design tool to tailor the exhaust temperature. Figure 9 shows the amount of potential horse power that could be generated from monopropellant hydrogen peroxide[9]. As a result, hydrogen peroxide has been widely used in numerous gas generator applications as see in Figure 10[10,11].

V. Gelling Hydrogen Peroxide

One means to render hydrogen peroxide into a form which is solid-like is to gel the propellant. There has not been significant work done with gelling hydrogen peroxide and most gel propellant research has been with the more common storable propellants. One reason for this is a gelling agent by definition is a high surface area material and in the case of hydrogen peroxide, the addition of a high surface area material could increase the rate of decomposition of the hydrogen peroxide. Also the gelling agent would need to be compatible with the propellant such that the gelling agent and the propellant would not interact and form a new potentially dangerous substance. For example, a simple gelling agent is corn starch. Corn starch is an organic compound which will most likely react with hydrogen peroxide. Corn starch could also interact with hydrogen peroxide after exposure and perhaps form another compound which could also be unstable or potentially explosive. Corn starch would be an example of what would probably be a poor choice as a gelling agent. Therefore a gelling agent should be effective at forming a solid-like gel substance with the propellant, introduce as little mass as possible and be non-reactive with the propellant.

A proprietary gelling agent is currently being tested to determine if it meets these criteria. The gelling agent has been mixed with the propellant and is undergoing the initial compatibility test which is exposure of the gelling material to the propellant and a qualitative assessment of whether the propellant interacts with the gel agent. At the time of publication, a 3% hydrogen peroxide gel has been observed for 17 days with no evidence of adverse hydrogen peroxide decomposition. Very slow low rate decomposition may be occurring but is not evident from this test. Prior discussion of this subject shows that the sensitivity of hydrogen peroxide to interactions with materials is dependent on the concentration and that lower concentrations of hydrogen peroxide are more prone to decompose hydrogen peroxide when exposed to materials[17]. Figure 11 shows the effect of rate of decomposition of hydrogen peroxide for various concentrations. This data shows that a compatibility test can be more sensitive with lower concentrations of hydrogen peroxide and this effect was used for this initial gelling assessment test. Figure 12 shows an example of a hydrogen peroxide gel.

Gelling hydrogen peroxide seems feasible. Further work is progressing in creating gels of hydrogen peroxide at higher concentrations with the goal to culminate in some long term exposure tests of hydrogen peroxide gels. Further work will be necessary to quantitatively ascertain the compatibility and stability of the gelling agent. These tests would include standard decomposition and stability tests[18], as well as elevated temperature tests and impact sensitivity.

VI. Solid Matrix Storage with Liquid Hydrogen Peroxide

Prior work with absorptive media has shown that a chemical, liquid nitrogen, which is not easily air transportable, can be trapped in a solid matrix material and rendered safe for commercial air transportation. This technology is used in a product called dry vapor shippers which are liquid nitrogen cryogenic shipping containers that are used in air freight. This technology permits the shipment of items at cryogenic temperatures by aircraft which is a valuable technology for artificial insemination, vaccines, genetic material handling, and other specialty cryogenic shipping applications. Figure 13 shows a current dry vapor LN2 shipper. The same concept may be possible for hydrogen peroxide or other hazardous liquid propellants which currently have air transportation limitations. This concept is not without significant work since this will create a new class of materials which will probably need assessment and review by the DoT and FAA, however it could be an enabling concept to make substances like hydrogen peroxide, hydrazine, and nitrogen tetroxide more amenable for some air transportation applications. In particular, it could enable hydrogen peroxide to be used in commercial aircraft for applications like oxygen generators, raft/slide inflation, military gas generator applications which require aircraft transportability, and other applications which hydrogen peroxide cannot currently service.

Dry vapor shippers have a solid matrix material which can achieve a very high liquid loading efficiency, perhaps on the order of greater than 90% of the liquid matrix mass is the absorbed liquid. These absorbents are quite tenacious and the liquid is unable to leave the matrix except by evaporation as a vapor, hence the name dry vapor.

If hydrogen peroxide, or other liquid propellants, especially hydrazine or hydrazine hydrate, could be trapped inside a solid matrix and rendered “non-liquid” and then expelled in some controlled manner from the matrix, then these propellant may have new applications. One concept would be to use a solid matrix material, such as is used in dry vapor LN2 shippers, trap the liquid inside the matrix and then expel the propellant by pressure, thermal energy, mechanical, or some other means.

A candidate proprietary solid matrix was fully loaded with 90% propellant grade hydrogen peroxide. The mass ratio of the hydrogen peroxide to the matrix material was greater than 25 to 1, or greater than 96% of the solid-liquid matrix mass was liquid hydrogen peroxide. Figure 14 shows the matrix material fully loaded with the hydrogen peroxide. This matrix material has remained wetted with 90% HTP for > 7 hours with no evidence of adverse reaction with hydrogen peroxide. This solid matrix material is unable to burn in a sustained manner even when it was impinged by a torch igniter. The igniter was left on the material until all of the hydrogen peroxide was thermally decomposed. While this material is not completely ideal, it is a good example of what can be done and shows that it is not unreasonable that a solid matrix storage material for propellant grade hydrogen peroxide can be made. In a like argument to the hydrogen peroxide gelling agent, significant work would be needed to understand and validate the safety of this material.

VII. Solid Fuel Matrix with Liquid Hydrogen Peroxide

A variation on storing the hydrogen peroxide inside a matrix and then expelling the material from the matrix is to have the matrix become part of the reaction. In the case of hydrogen peroxide, since this is an oxidizer, one could choose a solid absorptive matrix which was a fuel. Once the liquid oxidizer is absorbed into the solid fuel matrix one would create a substance that is somewhat like a solid propellant. Note that in a similar manner to solids, this configuration works best with the oxidizer trapped inside a fuel matrix. The inverse is to trap a fuel inside of an oxidizer matrix. Current chemical and materials technologies make this configuration difficult to make. Though it is conceivable that a similar concept using an solid oxidizer matrix could be developed for a fuel such as kerosene or hydrazine.

The preferred configuration of a solid fuel matrix and a liquid oxidizer could also be used with different oxidizers, such as liquid oxygen (LO2), nitric acid, and nitrogen tetroxide (NTO). LO2 may have problems with this approach because LO2 will absorb at the molecular level into many solid fuels and create a high explosive and some prior work by the author's company demonstrated that phenomenon. Similar events have occurred with LO2 hybrid rocket engines. NTO has a relatively high vapor pressure, so one may also have a problem with NTO out gassing; however this may be readily handled by closing off the matrix material to prevent evaporation, which will probably be necessary for any liquid oxidizer. Nitric acid has a reasonably low vapor pressure and its very high density make it a nice choice for many applications. Nitric acid may also have problems with the formation of explosives as the absorption of nitric acid into other fuel matrix materials is a common method for producing explosives (e.g. nitro cellulose).

Hydrogen peroxide may also interact and absorb into the matrix producing new compounds and again like gels, will require significant work to validate the concepts. However it should be noted that commercial grades of hydrogen peroxide from 50% to as high as 70% are stored in polyethylene drums, and polyethylene is an excellent fuel with hydrogen peroxide. There may be a unique instance with lower concentration hydrogen peroxide and polyethylene for a safe and reliable solid fuel, liquid oxidizer combination.

The theoretical decomposition temperature of 90% HTP with a solid fuel like polyethylene is shown in Figure 15 and the exhaust species are shown in Figure 16. Note that the theoretical adiabatic decomposition temperature of 90% HTP is approximately 1364 deg. F and the theoretical adiabatic decomposition temperature of 98% HTP is 1735 deg. F. Very high O/F ratios of ~ 100:1 provide flame temperatures similar to 98% H_2O_2. Lower concentration of hydrogen peroxide such as 70% could be used to tailor lower temperature hot gases. A family of combustion temperatures for various concentrations of hydrogen peroxide are shown in Figure 17. Note that 50% hydrogen peroxide and polyethylene produce very attractive temperatures for gas generator applications and 50% hydrogen peroxide is highly compatible with polyethylene suggesting that this may be a viable form of this propellant.

A proprietary fuel matrix material was tested with 90% propellant grade hydrogen peroxide. This material was loaded with hydrogen peroxide and ignited. The material burns vigorously at atmospheric pressure. This testing demonstrates that the combination of a liquid oxidizer in a solid fuel matrix can produce a material which can burn in a like manner to a conventional solid propellant gas generator. This work will need to be vastly expanded to ascertain if this matrix material is a viable choice. Much more tests and similar tests that are classically applied to solid propellants should also be considered, such as pressure sensitivity, shock sensitivity, and pressure effects on burn rate. Figure 18 shows a solid fuel combusting with 90% HTP which demonstrates the feasibility of combusting solid fuel matrices with liquid HTP.

VIII. The Solid Fuel Matrix with Liquid Hydrogen Peroxide Gas Generator or Rocket

One application of this concept would be the creation of a solid propellant like device, such as a rocket motor or a gas generator whereby the oxidizer is left out of the device or system until just prior to use. In a sense, this will be a solid propellant device where the oxidizer is not loaded into the device until prior to use, like a liquid system. This concept tries to take the best of solid propellant forms, the inherent simplicity of the propellant and low part count, and combine it with the inherent safety of a liquid system by only creating a propellant hazard just prior to use. This concept would reduce or eliminate the concern one has with very large masses of solid propellant. One would then make the device using only 100% inert materials. The device would be transported, again, as a non-propellant to the point of use. At the point of use, the oxidizer could be loaded into the system and at that point the device would then have the handling features and hazards of a large amount of propellant mass. This may be very attractive for a low cost launch system. Figure 19 shows the fundamental propulsion system concept.

For some gas generator applications this will of course be impractical, such as gas generators which are installed for on-demand use that prohibit propellant handling, such as some ordnance. However, even some of these devices, such as large ordnance in big guns, may find this attractive because it permits the segregation of chemicals and reduces the hazards of handling charges of propellant and magazine storage, such as aboard naval vessels. This propellant could be viewed as an alternative to liquid gun propellants.

IX. The Solid Propellant Hybrid with a Solid Matrix Liquid Hydrogen Peroxide Gas Generator

Hydrogen peroxide has a very low vapor pressure, which makes it an easy energetic material to handle, but makes it very difficult to initiate combustion. The most common means to initiating the decomposition reaction of hydrogen peroxide is to use a catalyst. Thermal decomposition of hydrogen peroxide does occur, but in general, it is difficult to achieve in power densities that are of use for the aerospace and defense industries. An attractive concept which takes advantage of this behavior of hydrogen peroxide is to trap the hydrogen peroxide in an inert matrix material or a gel and then initiate the decomposition of the hydrogen peroxide by using a much smaller solid propellant combustion device, which provides thermal energy and/or a steady source of catalyst. The solid propellant device would combust and deliver a stream of hot gas loaded with a small amount of catalyst, such as a manganese dioxide. Figure 20 shows a version of this concept. The hot gas and catalyst would impinge the gel or matrix hydrogen peroxide and react on the surface, somewhat like a hybrid rocket combustor. The exhaust effluent from this device would then be essentially that of hydrogen peroxide with a small amount of catalyst and a small amount of the solid propellant charge. This could radically alter the chemical species and flame temperatures which would be delivered from a gas generator. The careful selection of the hydrogen peroxide would then permit the exhaust temperature to be tailored to a wide range of temperatures and the exhaust effluent would be much friendlier for use with humans in close contact. The solid propellant charges could also be used in groups such that the device could be re-started for multiple firings. The existing work discussed in this paper and the existing state of the art for solid propellants makes this concept quite viable.

X. Further and Future Work

Much work will be needed to develop the technology of forming hydrogen peroxide or other non-toxic chemicals into states such as solid-like materials which render them more suitable for specific gas generator applications. This work is essentially the development and characterization of new propellants and the total amount of work expected is non-trivial. The near term future work will concentrate on the investigation into material compatibility of gelling agents with higher concentrations of hydrogen peroxide. Other work which is also important includes characterization of the burn rate of the solid fuel matrix and liquid oxidizer combination, compatibility of solid fuel and inert matrix materials, pressure dependence on burn rate, hydrogen peroxide stability and rate of decomposition, long term storability, shock sensitivity, and temperature effects.

XI. Conclusions

Hydrogen peroxide is a viable non-toxic propellant which has had a significant history as a propellant for numerous gas generator applications. The unique chemistry of hydrogen peroxide lends itself to creating systems with non-toxic propellants and non-toxic exhaust species. The temperature of hydrogen peroxide hot gases can be controlled across a wide range which is commonly used in the gas generator applications area. Several novel concepts for modifying the state of hydrogen peroxide have been explored and initial testing suggests that these concepts may be possible and that further research and investigation could provide new functionality of hydrogen peroxide in non-liquid states. Gelling hydrogen peroxide, storing hydrogen peroxide in a non-reactive solid matrix and combustion hydrogen peroxide in a solid fuel matrix have all been considered and initial investigations show that one or more of these concepts may have potential. Hydrogen peroxide can provide non-toxic gas generator capabilities in new applications beyond what has been demonstrated in current and historical hydrogen peroxide systems.

References

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

[2]Demyanenko, Y., Dmitrenko, A., Ivanov A., Pershin V., "Turbopumps for Gas Generator and Staged Combustion Cycle Rocket Engines," AIAA-2005-3946, 41^{2t} AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, AZ, July, 2005.

[3]Whitehead, John C., "Hydrogen Peroxide Propulsion for Small Satellites," 12th AIAA/USU Conference on Small Satellites, SSC98-VIII-1.

[4]McGrath, David K., Kirschner, Thomas, J., Mionske, Gary L., Goldstein, Steven J., "Mars Pathfinder Airbag Gas Generator Development," AIAA-1999-3845, AIAA Joint Propulsion Conference, July 1999.

[5]Maybee, Jeffrey C., Krismer, David J., "A Novel Design warm Gas Pressurization System," AIAA-1998-4014, Joint Propulsion Conference, July 1998.

[6]Markopoulos, P., Abel, T., "Development and Testing of a Hydrogen Peroxide Hybrid Upper Stage Propulsion System," AIAA-2001-3243, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Salt lake City, UT, July, 2001.

[7]Schmidt, Eckart W., "Hydrazine and Its Derivatives, Preparation, Properties, and Applications," 2nd Edition, Volume 1, John Wiley & Sons, New York, 2001.

[8]Rocket Research Company, "Hydrazine Handbook," Rocket Research Company, Redmond, WA, circa 1997

[9]J. McCormick, "Hydrogen Peroxide Rocket Manual", FMC Propulsion Department, 1965.

[10]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.

[11]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.

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

[13]Runckel, Jack F., Willis, Conrad M., Salters, Leland B. Jr., "Investigation of Catalyst Beds for 98-percent Concentration Hydrogen Peroxide," NASA Technical Note TN D-1808, Langley Research center, Langley Station, Hampton Virginia, June 1963.

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

[15]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.

[16]Ventura, M. C., Wernimont E., "Review of Hydrogen Peroxide Material Safety Data Sheets," AIAA-2002-3850. 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, July, 2002.

[17]Ventura, Mark C., "Long Term Storability of Hydrogen Peroxide," AIAA-2005-4551, 41^{2t} AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, AZ, July, 2005.

[18]"Materials of Construction for Equipment in Use with Hydrogen Peroxide," Technical Data, Bulletin #104, 1966 Revision, FMC, 1735 market St., Philadelphia, PA, circa 2002.

[19]"Solid Rocket Motor Igniters," NASA SP-8051, March 1971

Figure 1 - Typical Hydrogen Peroxide Gas Generator

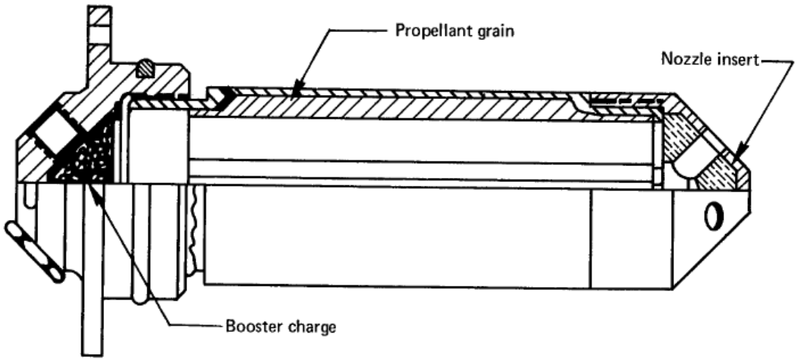

Figure 2 – Typical Solid Propellant Gas Generator[19]

Application	Chemistry	Description
Space Shuttle	N2H4	Auxiliary Power Unit
Space Shuttle Main Engine	Fuel rich LH2/LO2	Staged Combustion
F-16	N2H4/H2O	Emergency Power Unit
Air Born Laser	H2O2	Vacuum Aspiration
Car Airbag	Sodium Azide	Airbag Inflation
Flares/Smoke	Solid	Signally Devices
Wind Tunnels	LO2/Ethanol	Vacuum Aspiration
RS-27 (Delta II)	LO2/Kerosene	Turbo-Pump Drive Gas

Figure 3 – Examples of Different Gas Generator Applications and Preferred Chemistry

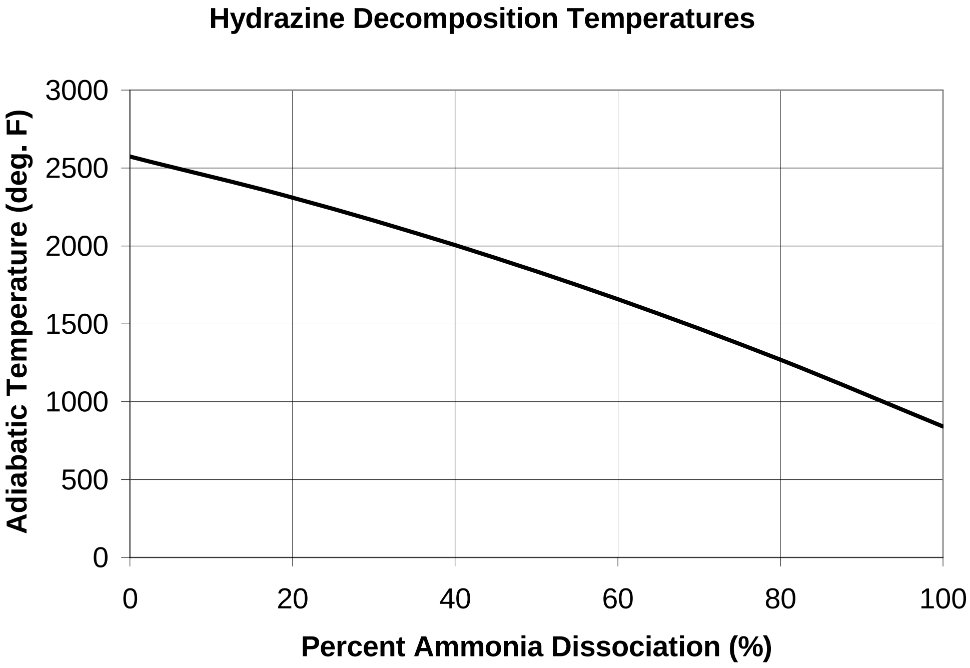

Figure 4 – Hydrazine Decomposition Temperatures versus Ammonia Dissociation

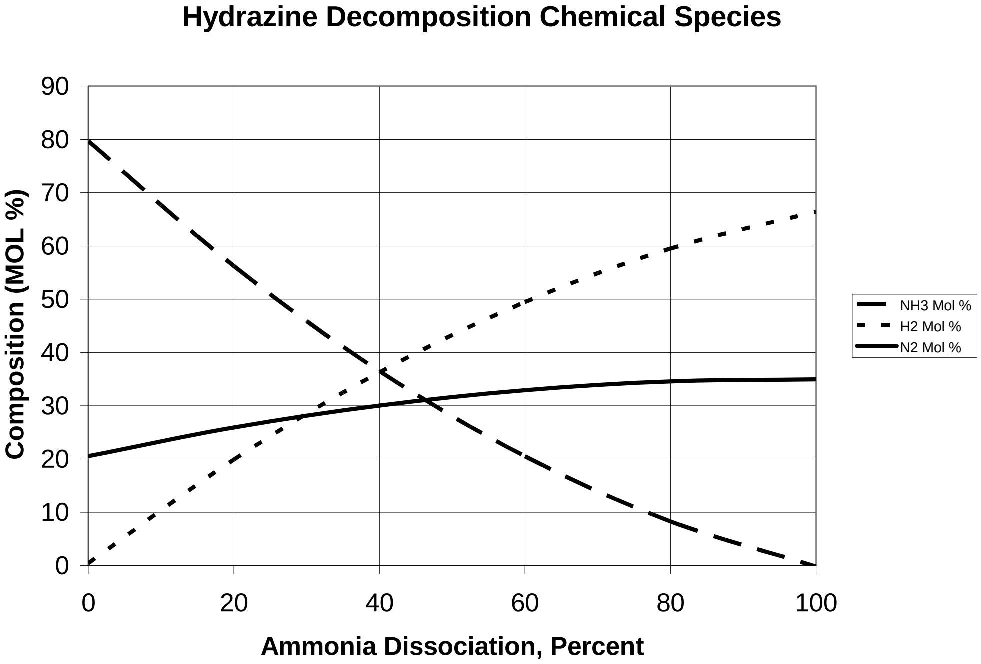

Figure 5 – Hydrazine Decomposition Chemical Species

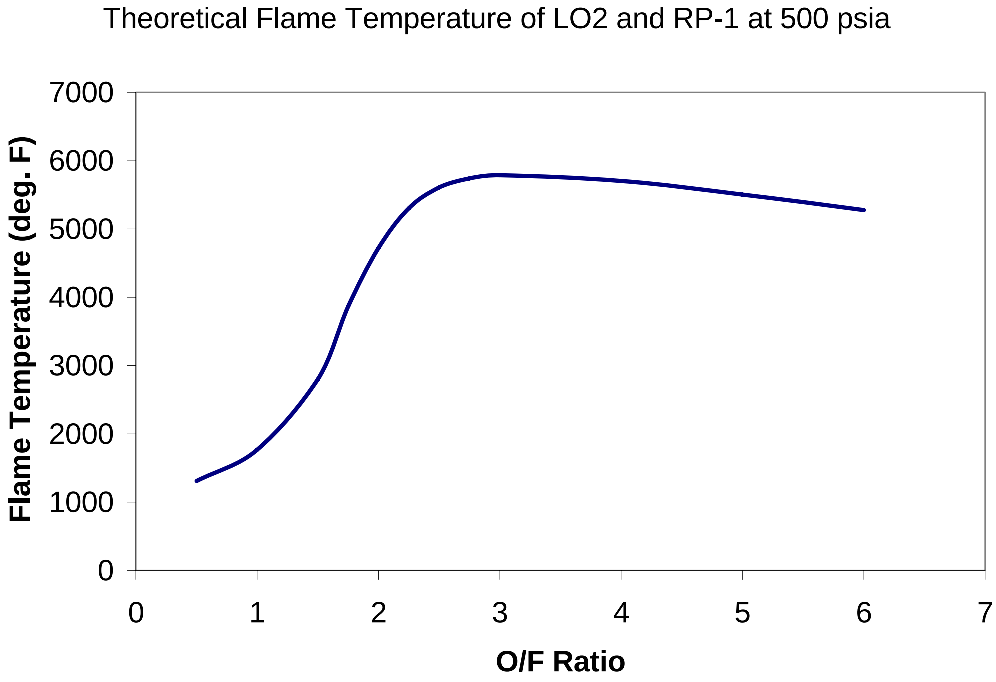

Figure 6 – Theoretical LO2 and RP-1 Flame Temperature at 500 psia

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

Figure 7 – Theoretical Plume Species for LO2 RP-1 Gas Generator Combustion

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

Figure 8 – Historical Liquid Gas Generators for Rocket Engine Turbine Drive

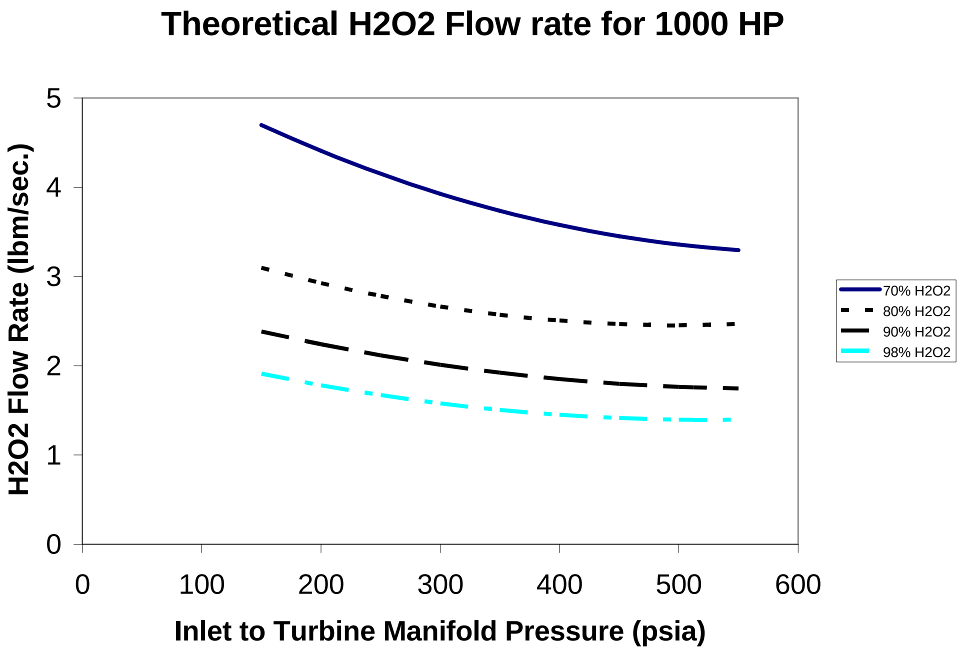

Figure 9 – Hydrogen Peroxide for Turbine Power

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 10 – Liquid Hydrogen Peroxide Gas Generator Applications

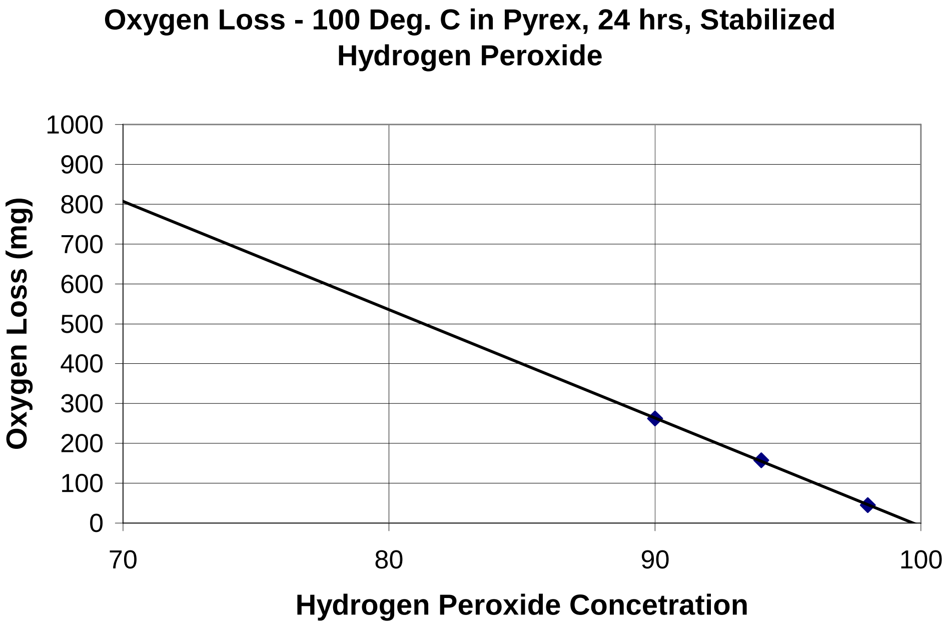

Figure 11 – Effect of Water on the Stability of Hydrogen Peroxide

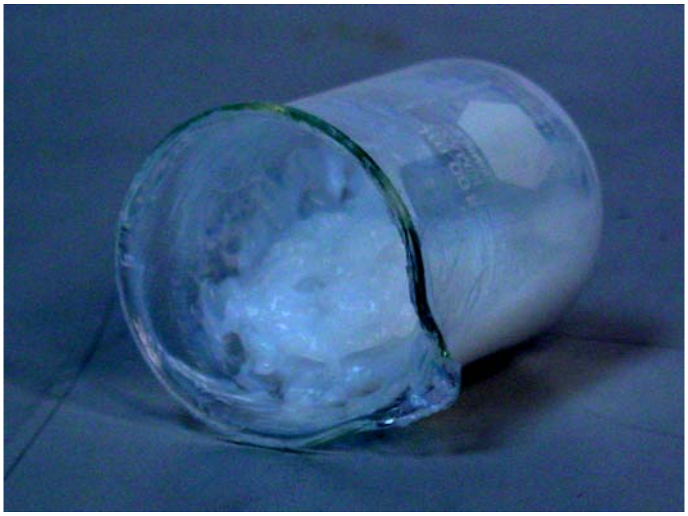

Figure 12 – Gelled 3% Hydrogen Peroxide

Figure 13 – LN2 Dry Vapor Shipper

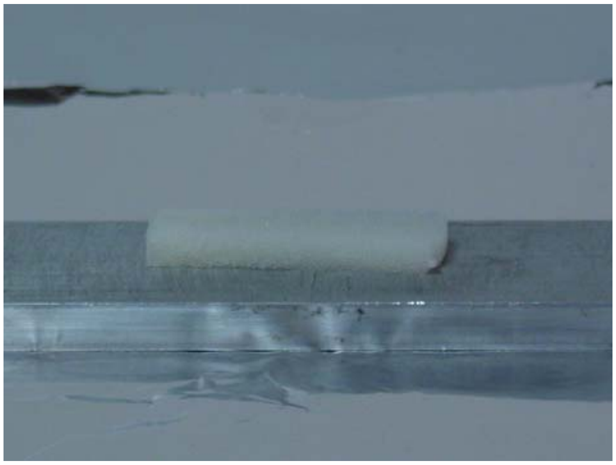

Figure 14 – Absorption of 90% Hydrogen Peroxide in a Solid Matrix

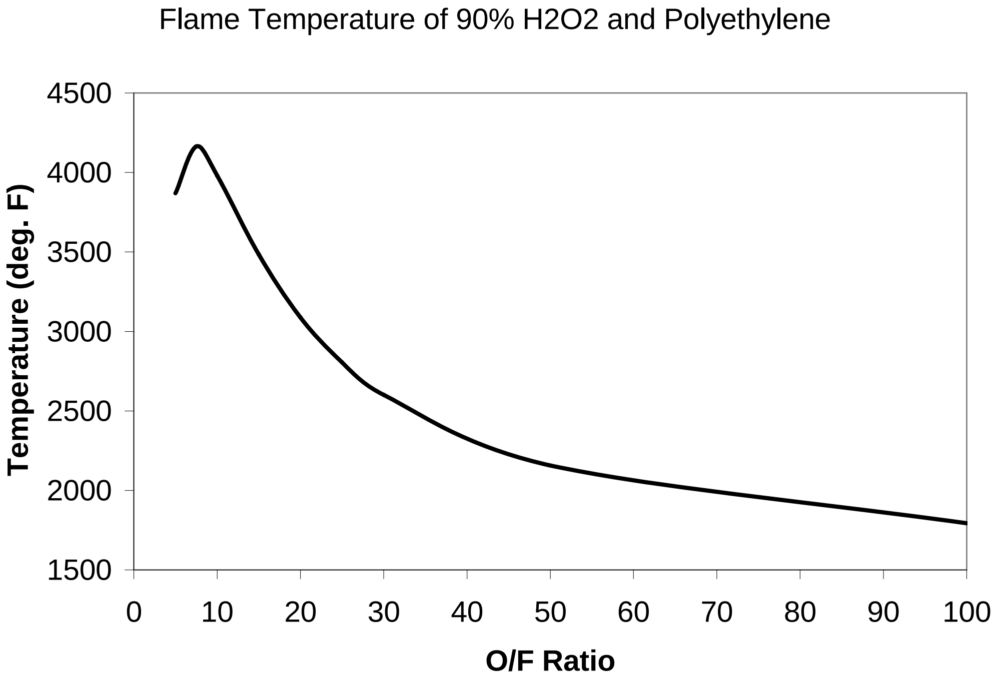

Figure 15 – Hydrogen Peroxide and Solid Fuel Combustion Temperatures at ~ 1 atm

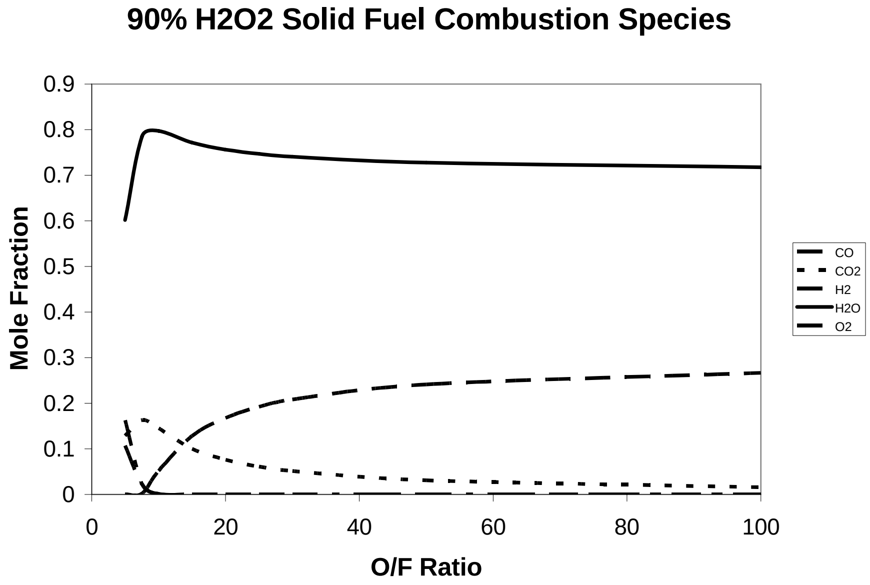

Figure 16 – Hydrogen Peroxide Solid Fuel Combustion Species

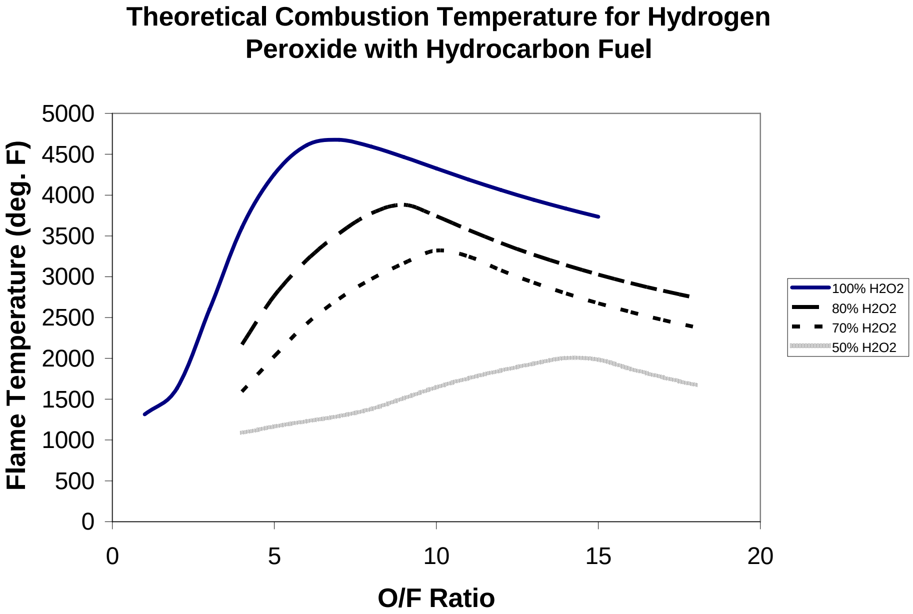

Figure 17 – Comparison of Flame Temperature for Various Concentrations of Hydrogen Peroxide with a Typical Hydrocarbon (kerosene)

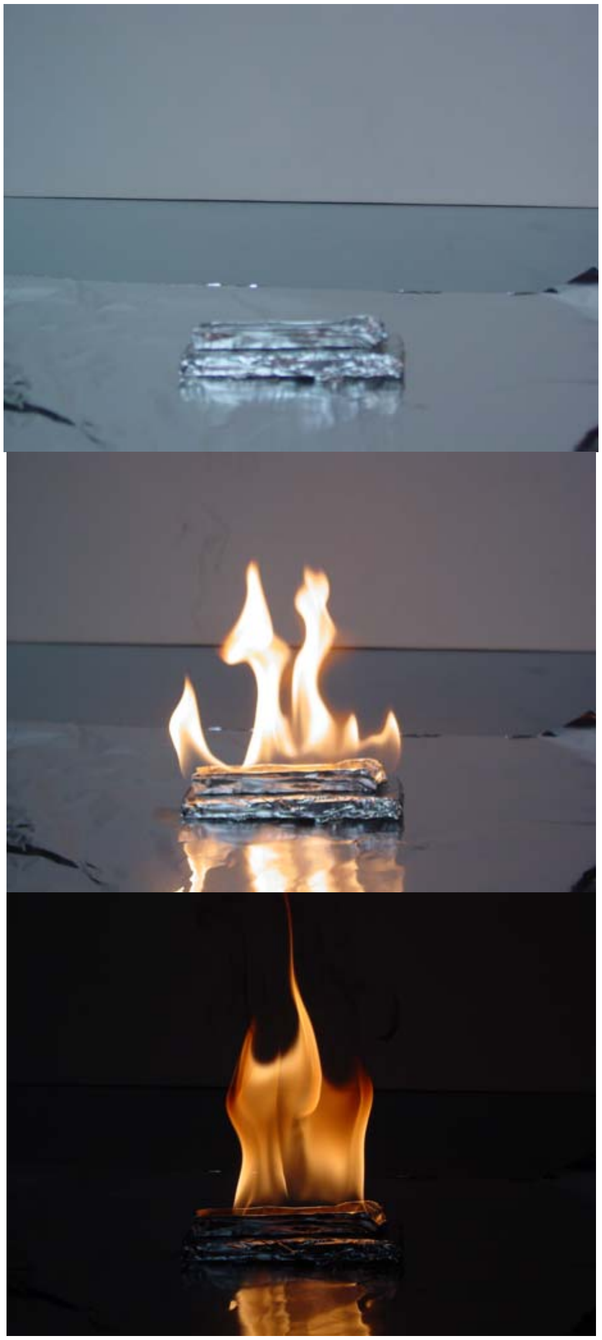

Figure 18 – Combustion of 90% Hydrogen Peroxide in a Solid Fuel Matrix

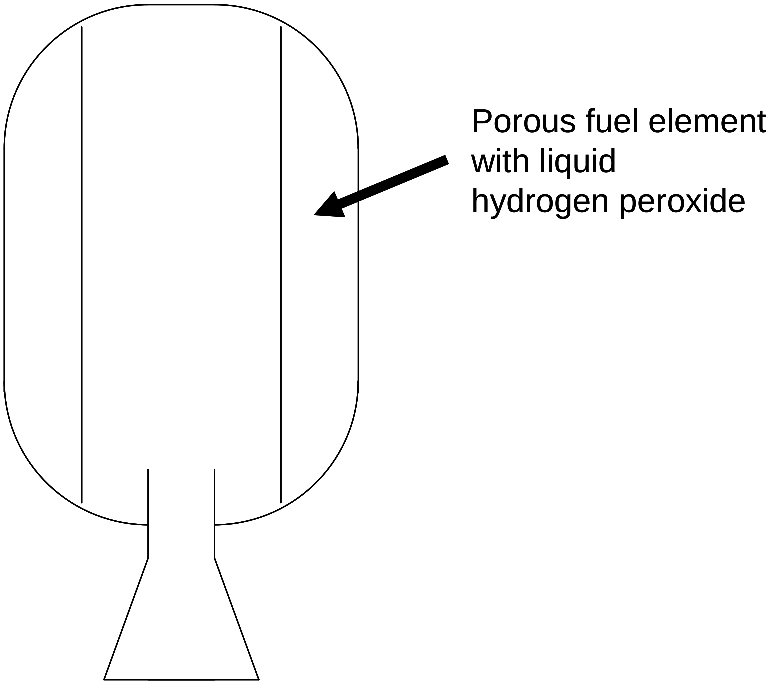

Figure 19 – Solid Liquid Rocket Concept

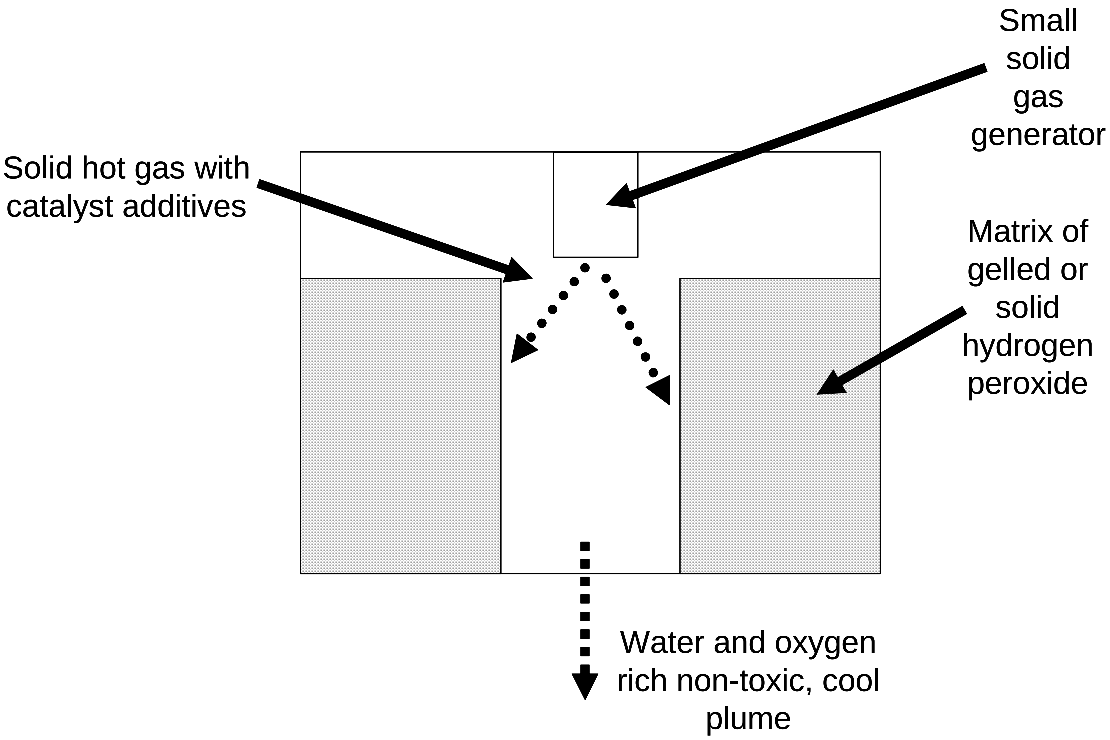

Figure 20 – Solid Propellant and Solid/Liquid Gas Generator Concept