

Low Temperature Operation of Hydrogen Peroxide Gas Generators: Verification Testing & Possible Applications**

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Monopropellant gas generators find use in applications that demand high power density for time periods which are generally in excess of one minute. Additionally, the system level requirements are such that a complex bi-propellant system is not warranted or other factors such as toxicity might favor hydrogen peroxide systems over hydrazine. This paper seeks to review recent testing involving a monopropellant gas generator using 82% H₂O₂ under low temperature conditions involving both the fluid temperature and the initial hardware temperature. It is demonstrated that the gas generator design was able to achieve nominal start transient rates and C* efficiencies greater than 98%. Start and steady state operation was achieved with fluid and initial hardware temperatures of around zero (0°) Fahrenheit. This temperature is just above that of the freezing point of 82% H₂O₂ suggesting that the operational limit is the freezing point of the H₂O₂ solution. The experimental test data opens operating conditions previously thought inaccessible to liquid monopropellant gas generators. This paper also provides some examples of applications where a low toxicity, low freezing point hydrogen peroxide monopropellant system might find application.

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Nomenclature

APU	=	Auxiliary Power Unit
BAT	=	Brilliant Anti-Tank Weapon
C^*	=	Characteristic Exhaust Velocity (ft/s)
FINDER	=	Flight Inserted Detector Expandable for Reconnaissance
GG	=	Gas Generator
GPS	=	Global Positioning System
GK	=	General Kinetics Inc.
H_2O_2	=	Hydrogen Peroxide
MEMS	=	Micro-Electro-Mechanical Systems
N_2H_4	=	Hydrazine
RESUS	=	Rescue System for Submarines
RCS	=	Reaction Control System
UAV	=	Unmanned Aerial Vehicle
VTOL	=	Vertical Take Off and Landing
WMD	=	Weapons of Mass Destruction

I. Introduction

Rocket propellant driven gas generators (GG) find application primarily in aerospace and defense systems where short operational duration and high power density are a requirement. These requirements are a natural fit for liquid monopropellant GGs which has historically been covered by hydrogen peroxide and hydrazine. Recently a GG using 82-81% H_2O_2 was developed and tested for low temperature start and operation. This paper provides a brief overview of some recent cold environment testing (further details can be found in Ref. 1) and provides a few examples of possible applications.

II. Low Temperature Testing of 82% Hydrogen Peroxide Gas Generator

A. Apparatus

Hot fire testing was conducted at Purdue University's Zucrow Labs during December 2007 & January 2008. The test apparatus was a pressure fed test stand and a horizontally mounted test article. The test stand comprises a 14 gallon (53 liter) run tank with a 1.0 inch (2.54 cm) horizontal exit run line into a 0.25 inch (0.635 cm) ball valve which acts as the fire valve. Gaseous Nitrogen was used for both purge gases and as the primary pressurant in the run tank. The gas generator is P/N: GK-PD039-201-003 (see Figure 1) and has aft penetrations (four, equally spaced) for measurement of chamber pressure and chamber temperatures.

The test plan included gas generator wear-in followed by performance mapping of a single GG over various operating parameters which included low temperature propellant and hardware start. After performance mapping the GG was then endurance tested at the nominal conditions for a total accumulated time of 20 minutes. Nominal test conditions are shown in Table 1. Subsequent to the endurance testing it was found that there was sufficient propellant to further investigate the cold limits of the device.

Table 1 Nominal Gas Generators Test Conditions

Parameter	Value (English)	Value (SI)
Chamber Pressure	~1400 psia	~96 bar
Oxidizer Flow Rate	1.40-1.45 lbm/s	0.64 kg/s
GG Start Temperature	85+/-10 °F	~30 °C
H_2O_2 Temperature	85+/-5 °F	~30 °C
H_2O_2 Concentration	81-82% wt	

In summary a single GG was hot fire tested with:

- Wear-In

- Performance Mapping
- Endurance Testing
- Cold Limit Testing

The next section primarily covers the test performed during the Cold Limit portion of the test campaign. Derived parameters are adjusted for temperature effects on theoretical performance.

B. Cold Limit Experimental Test Results

Initial performance mapping tests suggested that the GG could operate with fluid temperatures below 35 °F (1.7 °C) and as such the final set of “Cold Limit” tests were conducted to investigate this. A natural lower barrier to investigate would be to get as close as possible to the freezing point of the H₂O₂ solution. Figure 2 shows the liquid-solid phase diagram for H₂O₂-H₂O solutions. As can be seen from the figure the minimum eutectic temperature occurs at a concentration of roughly 62% H₂O₂ around -67 °F (-55 °C). For the present test data the range of H₂O₂ tested was between 82-81% wt. Table 2 shows the range of freezing point as read from the data found in Figure 2. In particular for the final tests the solution was 81.3% H₂O₂ and as can be seen from Table 2 this translates into a freezing point between roughly -4 °F (-20 °C) and -7 °F (-21.7 °C). For operational simplicity and for a good round number lower target temperatures for the fluid and the hardware (GG) were put at 0 °F (-18 °C).

Table 2 Freezing Points Experimentally Determined Limits of 82-81% H₂O₂ Solutions²

H ₂ O ₂	Lower Curve	Upper Curve
81.0%	-23.2 °C (-9.8 °F)	-20.7 °C (-5.3 °F)
81.3 %	-6.5 °F	-4.6 °F
82.0%	-21.4 °C (-6.5 °F)	-19.4 °C (-2.9 °F)

Prior tests (wear-in, performance mapping & endurance) had established a baseline of understanding of the nominal performance of the GG. The primary parameters of interest derived from measured data are: start time (time from initial chamber pressure rise to 90% of steady state), C* efficiency, catalyst bed pressure drop (difference between GG inlet pressure and chamber pressure), chamber pressure roughness (3 sigma zero to peak of mean). It was determined that the start times are between 450-350 ms, C* efficiencies > 98%, pressure drop around 50 psid and roughness < 1.5%. All of these parameters are indicative of a well performing GG and as such if significant deviations were noted during testing for the cold limit, the testing would then indicate the lower limit. All of the prior tests were conducted with propellant above 35 °F (1.7 °C) which produced an exhaust temperature around 1000 °F (538 °C). Hence the first test to determine the cold limit was to lower the fluid to around 20 °F (- 6.7 °C) and heat up the GG to around 150 °F (65.5 °C), which would help the start condition. Subsequent tests decreased the fluid temperature and then followed by lowering the GG start temperature until performance significantly deviated.

Figures 3 & 4 show the measured pressure and temperature response from the 10 second steady state run of test with 0 °F fluid and 100 °F GG start temperature. The figures show smooth operation with no deviation from nominal performance other than the reduced exhaust gas temperature.

The final test was to find the lower limit on temperature of 0°F/0°F on H₂O₂ and GG start temperature. Unfortunately, the actual H₂O₂ was a little higher, at around 5 °F. Figure 5 shows the GG prior to test with frost on the outside of the housing and nozzle. Figures 6 & 7 show the pressure and temperature response from the test in which the start transient has two spikes. The maximum peak is only about 20% greater than steady state values. Prior performance mapping showed that reduced valve rates can be used to reduce and likely eliminate the mild hard starts. Hence, it is concluded that the GG will start and operate nominally and is fully functional at start conditions of 0 °F & 0 °F for H₂O₂ and GG temperature. Or rather, that the lower operating temperature limits on hardware and fluid is just above the freezing point of the fluid.

C. Comparison to Other Liquid Monopropellant Systems

The results from the Cold Limit tests discussed in the previous section seemed to be a new record for low temperature operation of hydrogen peroxide. A short literature review was conducted for comparison. The only other liquid monopropellant of significant historical use, hydrazine, was also investigated for comparison purposes. Table 4 shows the results of the literature search.

Items of note concerning the comparisons:

- Limited to US systems as the data was readily available. Russia uses a significant amount of 82% H₂O₂ but is not included here as the authors know little of their operational limits.
- All data is for catalytic decomposition of the monopropellants. Liquid, non catalytic gas generators are not considered.
- All hydrazine data is with Shell 405 as the catalytic material.

Inspection of the hydrazine portion of Table 3 suggests that the temperature of the fluid can be successfully driven to 5-10 °F above the freezing point. However, the lower limit for the catalyst is somewhere around 70-100 °F. As noted by the TRW study: “The results indicated that ignition delay increased rapidly below 100 °F ... and the ignitions were accompanied by large overpressures”⁵ Also starting from the lower temperature of 70-100 °F appears to have detrimental effect on the Shell 405 catalyst as noted in the Aerospace Corp study: “Some early work at the The Aerospace Corporation in a small scale reactor indicated that both low catalyst bed temperature (<70 °F) and low propellant temperature (40 °F) increased ignition delay time, resulting in large overpressure spikes and pulverization of the catalyst”⁵. As such for missions which require a great many pulses, the hydrazine catalyst bed lower limits are generally greater as suggested by Reference 4 & 5 at anywhere from 200 to 600 °F.

Table 3 Comparison of Hydrazine and Hydrogen Peroxide Lower Operating Limits

System	Fluid	Freezing Pt Fluid	Fluid Lower Limit	Hardware Lower Limit	Comment
Shuttle APU	N ₂ H ₄	34 °F (1.3 °C)	45 °F	190 °F	Ref 4
TRW	N ₂ H ₄		-	>100 °F	1967 Study, Ref 5
Aerospace Corp	N ₂ H ₄		40 °F	70 °F	1969 Study, Ref 5
Pioneer Jupiter Probe	N ₂ H ₄		-	> 70 °F	Ref 5
Fleetsatcom	N ₂ H ₄		-	> 600 °F	Ref 5
Project Mercury	90-91% H ₂ O ₂	11 °F ² (-11.7 °C)	35-50 °F Flood-out Limit	35-50 °F Flood-out Limit	1960 Study, Ref 6 Matched Fluid & Hardware Temps
X-1B	90-91% H ₂ O ₂		> Freezing	Trickle Preheat	Ref 10
X-15	90-91% H ₂ O ₂		Heated Possible > 59 °F	Heated Possible > 59 °F	Ref 9
Scout	90-91% H ₂ O ₂		40 °F	Probable Pulse Preheat	Ref 8
FMC	90-91% H ₂ O ₂		> 50 °F	> 50 °F	Ref 11
GK-Sandia	81.3% H ₂ O ₂	-5 °F (-20.6 °C)	~ 0 °F (-17.4 °C)	~ 0 °F (-18 °C)	Present Study Comparison Only

The historical H₂O₂ applications noted in Table 3 utilize 90-91% H₂O₂ and have lower fluid temperature limits of roughly 20-30 °F above the freezing point. It appears that utilizing separate thermal conditioning of the H₂O₂ and the catalytic device was not studied. Additionally, alternate methods of heating the catalytic devices were employed such as trickle preheat on X-1B. Reference 10 states that the feed lines were fed from the mother craft with a flow rate of 0.05 lbm/s with 80 +/-10 °F H₂O₂ such that the system stayed above freezing before the X-1B reached altitude of use for the RCS thrusters. Further Reference 8 suggest by the mass properties that H₂O₂ was used to pulse preheat the thrusters on stages 2 & 3. Although not explicitly stated Reference 9 suggests that the entire system was kept above 59 °F using heaters to guard against the cool liquid oxygen onboard the vehicle. And finally, FMC standard design criteria calls for keeping both fluid and catalytic device above 50 °F.

Hence it seems that the present experimental study has established a new low record for operation with hydrogen peroxide, that of being just above the freezing point for both fluid and catalytic device conditioning. In addition, the device has demonstrated mild hard starts, which based upon historical evidence might not be possible with hydrazine.

III. Possible Applications for Low Temperature H₂O₂ Gas Generators

General applications where this type of technology might be useful are those missions where monopropellant hydrazine would be the preferred propulsion power source except where the toxic effects of hydrazine are

undesirable. Additionally, for some missions the exhaust products from hydrazine decomposition (ammonia, hydrogen & nitrogen at ~1700 °F – for gas generators Ref. 17) may also be undesirable. In the subsequent subsections a few examples of these missions will be provided and discussed and compared to hydrogen peroxide based systems. In general the missions where substitution of hydrogen peroxide for hydrazine would be beneficial are those with repetitive human interaction or repetitive environmental interaction.

From the test data presented in the prior section it shows that hydrogen peroxide systems can be designed and operated with minimum start temperatures corresponding to the roughly the freezing point for various concentrations of hydrogen peroxide. Table 4 provides a quick reference of the expected minimum operating temperature without the use of heaters for typical hydrogen peroxide concentrations.

Table 4 Comparison of Typical Hydrogen Peroxide Concentrations and Expected Lower Operating Limits Without the Use of Heaters

H ₂ O ₂ Concentration	Expected Lower Operating Limit
70%	-40 °F
82%	-5 °F (Experimentally Proven to 0 °F)
90%	11 °F
98%	30 °F

As an example of this low temperature utility might be the use in atmospheric flight where temperature constraints at cold soak would be the atmospheric temperature. Table 5 shows the temperature of the air versus altitude. As an illustration the Predator unmanned aerial vehicle has an operational ceiling of 25,000 ft (Ref. 18) which in comparison to Tables 5 and Figure 2 would suggest that a functioning system utilizing roughly 77% hydrogen peroxide concentration would not require provisions for heaters or heating of neither the hydrogen peroxide propellant nor the catalyst bed.

Table 5 Comparison of Altitude versus Air Temperature (Ref. 12)

Altitude	Air Temperature
10k ft	23 °F
20k ft	-12 °F
30k ft	-48 °F
40k-70k ft	-70 °F
90k ft	-57 °F

A. Mini-Sniffer III

1. *Prior Art*¹³⁻¹⁵

The Mini-Sniffer program occurred in the mid 1970's and involved a remotely piloted, pusher propeller vehicle flown from the NASA Dryden Center. The program had three vehicles with the first two (Mini-Sniffer I & Mini-Sniffer II) being flight test vehicles and utilized a gas powered air-breathing combustion engine. The third and final vehicle was the Mini-Sniffer III which was designed to carry a 25 lbm payload to 70,000 ft for 1 hour duration or climb to 90,000 ft and glide back. Because of the rarified atmosphere the Mini-Sniffer III utilized a hydrazine monopropellant reciprocating engine throughout the entire flight envelope. The hydrazine powered engine is often referred to as the Akkerman engine – named for the designer. The Mini-Sniffer III made one flight which a maximum altitude of 20,000 ft because of a hydrazine leak (much more exacting detail of the flight is to be found in Ref. 13). The Mini-Sniffer III was designed to measure natural and man-made upper atmospheric pollution. Figures 8 & 9 show the Mini-Sniffer III on the lake bed at Dryden with the later showing the ground support crew in full self contained suits as protection against hydrazine.

2. *Utility with Low Operating Temperature H₂O₂ System*

The Mini-Sniffer III program provided critical proof of concept for a non-air breathing engine to be used for upper atmospheric investigations. While the use of hydrazine is better from a performance perspective swapping for a low temperature hydrogen peroxide system provides some advantages listed below:

- Afterburning – Two of the exhaust products of hydrazine decomposition (hydrogen & ammonia) will further undergo combustion with the oxygen in the air (note that the Mini-Sniffer III utilized hydrazine decomposition from take off to altitude). In the case of hydrogen the combustion would produce water and would be of little concern for this application, with the one caution, that accumulations of hydrogen gas (perhaps explosive) would need to be accounted for during ground testing, etc. In the case of the ammonia combustion with the air it is possible to produce nitrogen oxides (or further reaction with water to nitric acid) which might not be beneficial if the intent of the onboard sensor was to “sniff” for man-made nitrogen oxide pollutants. In addition caution would necessitate avoidance of accumulations of unreacted ammonia and air mixtures for the same explosive potential as that for hydrogen. In the case of the hydrogen peroxide system the exhaust products would be water and oxygen – presenting no further hazard, nor man-made pollution.
- Steam Engine – The Akkerman engine was piston type reciprocating engine run off of a pressurized plenum of decomposed hydrazine. Essentially a steam engine without the steam. If the pressurized plenum were charged with hydrogen peroxide decomposition products (superheated steam and oxygen) then the vast body of knowledge associated with steam engines could be drawn upon for materials, efficiency tuning and standard equipment. This would lower the cost associated with the engine and decrease any development time.
- Atmospheric Contamination – As previously noted in the above bullet concerning afterburning there is some potential to create nitrogen oxides and potentially nitric acid. Although both are likely to occur in low concentration – both are undesirable from a sensing perspective. In addition the hydrazine itself might leak (which indeed it did during the only Mini-Sniffer III flight - Ref. 13) and contaminate the environment – undesirable from a ground operations perspective (requiring self contained suits – see Figure 9 and potentially explosive hydrazine/air cloud) and again from a sensing perspective. In contrast hydrogen peroxide has a vapor pressure much lower than water and would not form an explosive cloud at atmospheric conditions. In addition because trace amounts of hydrogen peroxide are found naturally in the atmosphere release from a leak would not necessarily be environmentally damaging. The decomposition products of hydrogen peroxide (oxygen and water) are of course found in the environment.
- Freezing Point – The hydrazine in the engine of the Mini-Sniffer III was heat exchanged with the engine cooling oil. It is unclear from Ref. 13 why this was done but it seems it was to keep the hydrazine from getting cold. As noted in Table 3 the lower operating limit for hydrazine is approximately 40°F. Because the vehicle was to operate at the extremes of the atmosphere where the temperature is as low as -70 °F (Table 5) it was necessary to keep the hydrazine heated. Lower operating temperature capacity enables the possible elimination of the heat exchanger system or other cold soak options. Further enabling longer durations at lower temperature environments.
- Personal Protective Equipment – As can be seen from Figure 9 the ground crew was required to wear self contained breathing apparatus while the hydrazine propellant was loaded on the vehicle. This was to protect the ground crew from the toxic effects of hydrazine should a leak or spill occur even though the total loaded amount of hydrazine was relatively small. In comparison hydrogen peroxide systems only require full body chemical splash protective equipment (Ref. 20).
- Carbazic Acid (Carbohydrazide) – Hydrazine is known to react with carbon dioxide to form carbazic acid. The acid in pure form is a white crystalline solid and is often the source of hydrazine feed system internal contamination causing valve and injector tube plugging. In addition for terrestrial applications interaction with the atmospheric carbon dioxide will lead to locally corrosive environments and leads to an additional environmental toxin – including a special note “may cause long-term adverse effects to the aquatic environment” (Ref. 3 & 28).

These advantages seem to significantly outweigh the performance differences between the two propellants and would even result in slightly longer duration for the same propellant tank volume (~20% performance loss and ~10% smaller tank volume on comparison of 98% hydrogen peroxide to neat hydrazine (Ref. 16))

B. FINDER (Flight Inserted Detector Expandable for Reconnaissance) Mini-UAV

1. Prior Art

As mentioned previously in Section III above the Predator ceiling and possible use of a hydrogen peroxide based propulsion system would be possible at 77% hydrogen peroxide without the use of heaters or heating system. This is not to suggest that the Predator should be powered by hydrogen peroxide. A better use would be to provide power/propulsion for stored assets on the Predator that could be used to engage a surface target (or air target). To date the major stores have been: laser & GPS guided bombs, Hellfire missiles, BAT submunition and FINDER (Flight Inserted Detector Expandable for Reconnaissance) mini-UAV (Ref. 22). Of these the FINDER is the only Predator payload that is specifically designed for intelligence gathering beyond the Predator's capability. It seems that this is the first step toward an entire family of UAVs that carry out more specialized missions than the 'mother' UAV and closer or into the target of the intelligence gathering. In the case of the FINDER this mini-UAV was designed to fly (after release) collect air samples over and after an attack of an enemy WMD installation - providing the war fighter real time data on the toxic levels in the air. The FINDER uses an air breathing propulsions system much like the Predator burning an aviation fuel with an airspeed of roughly 45 mph (Ref. 23).

2. Utility with Low Operating Temperature H₂O₂ System

The concept of deploying other specialized UAV's from a "mother ship", such as the FINDER, opens up a vast array of potential applications. One of these might be the same mission that the FINDER is designed for but also include a longer duration between sampling. At present the FINDER is design to stay aloft and take data for a 2 hr period before landing. If the FINDER were required to obtain updated information about the previous location that it sampled it would need to be redeployed via Predator or catapult (both requiring human interaction). What might be useful is if the FINDER were to land and wait until commanded and then fly up and obtain data in the same location. The FINDER propulsion system is not designed for such a mission but a rocket based Vertical Take Off and Landing (VTOL) UAV would be capable of such a feat. Such a rocket based VTOL UAV was built and flown (albeit tethered in a wind tunnel and outdoor environment) in the early 1960's by the US. The vehicle was a 1/5 scale model of a VTOL jet powered aircraft being investigated at that time. The scale model plan form is shown in Figure 10 and weighs approximately 40 lbm dry. The propulsion was provided by a main hydrogen peroxide monopropellant rocket and successfully hovered and flew at level speed up to 60 mph (Ref. 21). Note that this rocket VTOL scale model is roughly the same size and shape as the FINDER. Substitution of the existing FINDER propulsion with a low temperature hydrogen peroxide rocket VTOL system provides some advantages listed below:

- Freezing Point – The diesel fuel for the FINDER probably have a fairly low freezing point (<-20 °F) but would probably have a hard time getting the required activation energy to kick start the combustion reaction at temperatures much below 0 °F. The hydrogen peroxide based system would have no real advantage from a freezing point perspective other than it has now been proven possible to operate at the lower temperatures. In addition the hydrogen peroxide system is catalytic in nature and hence does not require an additional source of energy to start the combustion reaction like a hydrocarbon/airbreathing propulsion would (combustion activation energy & forward flight).
- VTOL – The hydrogen peroxide propulsion system is capable of VTOL and as such can fulfill much more generic missions than the FINDER could. In general the VTOL mini-UAV would be capable of precision landing making the generic mission more akin to a perch, stare & lurch. The lurch of sensing the air is a mere subset of capabilities. In addition, given the ability of hydrogen peroxide to be safely stored for years (Ref. 16) the stare portion of the mission can be much longer than the existing FINDER and allows possible repositioning of sensors.
- Atmospheric Contamination & Afterburning – These reasons are similar to the information provided above as related to the Mini-Sniffer III. Hence if the mission is to sense the contamination or substances in the air it is simpler if the exhaust of the propulsion system didn't add any pollutants.
- Plume Signature – In the applications where enemy sensors might be looking for IR signatures of carbon dioxide (presence of combustion) the hydrogen peroxide device would be "invisible" due to the exhaust being oxygen and water.
- Smaller Scale – At propulsion system scales below that noted in the FINDER the thermal phenomena associated with combustion becomes much more difficult to start and sustain with efficiencies dropping

off significantly. This is not true for catalytic based systems such as the hydrogen peroxide based monopropellant which is not significantly affected in efficiency even down to MEMS scale. (Ref. 24).

C. RESUS (Rescue Systems for Submarines)

1. Prior Art

For more than 25 years the navies of Germany and others around the world employ the RESUS system for emergency rescue of their submarines. This is accomplished by the use of gas generators to blow the main ballast in less than 20 sec, thus enabling the entire submarine to the surface. The gas generators are modular and part of a system on the submarine that can be programmed to fire during pre-determined emergency conditions or by triggering one of many onboard remote start devices. The number of gas generators to fire is dependent on depth but the system number is sufficient in size to surface from depths greater than 400 m. There are two different propellant utilized for the gas generators: one containing hydrazine (a monopropellant system including pressurant and catalyst bed) and the other being loaded with a solid rocket propellant (Ref. 25). The hydrazine utilized in the gas generator is diluted with 6% water per Reference 25 or 8% per Reference 26. In either case this dilution is for freezing point suppression which would be around 15-20 °F (Ref 3, 17). The total solid propellant gas generator mass is almost double that for the hydrazine system and hence hydrazine is probably preferred for smaller packaging and the lower exhaust gas temperatures (Ref. 25).

2. Utility with Low Operating Temperature H₂O₂ System

If a low temperature hydrogen peroxide system were used instead of the existing systems it would have one major advantage:

- Oceanic Pollution - The hydrazine system represents a potentially toxic release into the ocean system in the event of a leak or rupture of the hydrazine storage tank. This might occur accidentally or as a result of combat operations. In the event that the system is operated as intended the effluents are not nearly as toxic. Hydrogen peroxide on the other hand is already present in trace amount in the ocean (Ref. 27).

IV. Conclusion

Recent experimental work utilizing 81-82% hydrogen peroxide on a new gas generator has yielded the following results and ruminations on possible applications:

- Successful start and operation with 0 °F & 0 °F for H₂O₂ temperatures and gas generator start temperatures with no loss in performance.
- The 0 °F low test limit is just above the freezing point of 82% H₂O₂ and appears to be a new record for low temperature operation of a liquid propellant monopropellant.
- Possible low temperature hydrogen peroxide gas generator applications include:
 - Propulsion for very high altitude vehicle missions – similar to Mini-Sniffer III
 - Propulsion for very low altitude reconnaissance (similar to FINDER) and potential for perch, stare & lurch missions using VTOL mini-UAV
 - Propellant for gas generator in submarine emergency ballast blow systems – similar to RESUS
- Advantage summary for using low temperature hydrogen peroxide gas generator systems:
 - Eliminates toxic effects of hydrazine based systems.
 - Eliminates toxic and corrosive effects of Carbazic Acid formation.
 - Reduced complexity by eliminating heater/heating requirements on propellant & gas generator.

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²²SPG Media Limited, “Predator RQ-1 / MQ-1 / MQ-9 Reaper – Unmanned Aerial Vehicle (UAV), USA”, URL: <http://www.airforce-technology.com/projects/predator/> [cited May 22, 2009].

²³Naval Research Laboratory, “NRL’s Finder UAV: A Countproliferation Asset”, URL: <http://www.nrl.navy.mil/content.php?P=03REVIEW205> [cited May 25, 2009].

²⁴Wernimont, Eric J., “Monopropellant Hydrogen Peroxide Rocket Systems: Optimum for Small Scale”, 42nd AIAA Joint Propulsion Conference & Exhibit, AIAA-2006-5235, Sacramento, CA, July 2006.

²⁵Astrium N.V., “RESUS – Rescue System for Submarines”, URL: <http://cs.astrium.eads.net/sp/Trauen/resus/index.html> [cited May 03, 2009].

²⁶Krueger, Karsten, “Filling Tanks with Hydrazine”, ‘Proc. 3rd European Workshop on Hydrazine’, Cagliari, Sardinia, Italy, 9 June 2004 (ESA SP-556, October 2004).

²⁷Yuan, Jinchun, Shiller, Alan M., “The Distribution of Hydrogen Peroxide in the Southern and Central Atlantic Ocean”, *Deep Sea Research Part II: Topical Studies in Oceanography*, Vol. 48, Issue 13, pp 2947-2970, 2001.

²⁸Acros Organics N.V., “Material Safety Data Sheet - Carbohydrazide”, ACC# 70881, Revision #4, June 19, 2008.



Figure 1 – 82-81% H₂O₂ Gas Generator P/N: GK-PD039-201-003. GG is ~3 Inches (7.6 cm) in Diameter. Bottom is Exhaust End, One of the Four Instrumentation Ports are Shown In Photo.

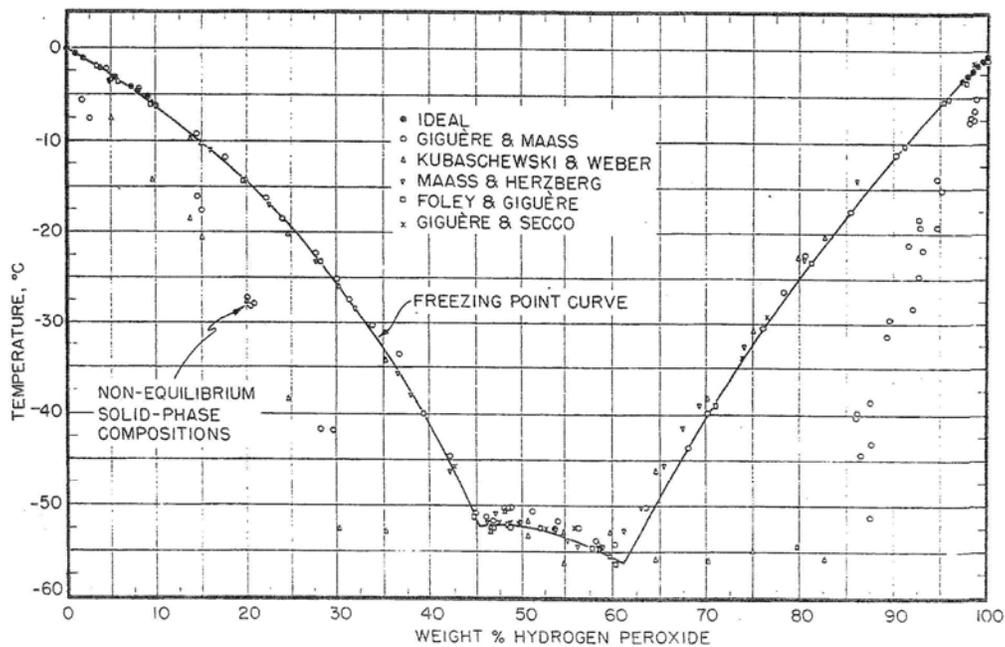


Figure 2 – Freezing Point of H₂O₂-H₂O Solutions, Ref. 2

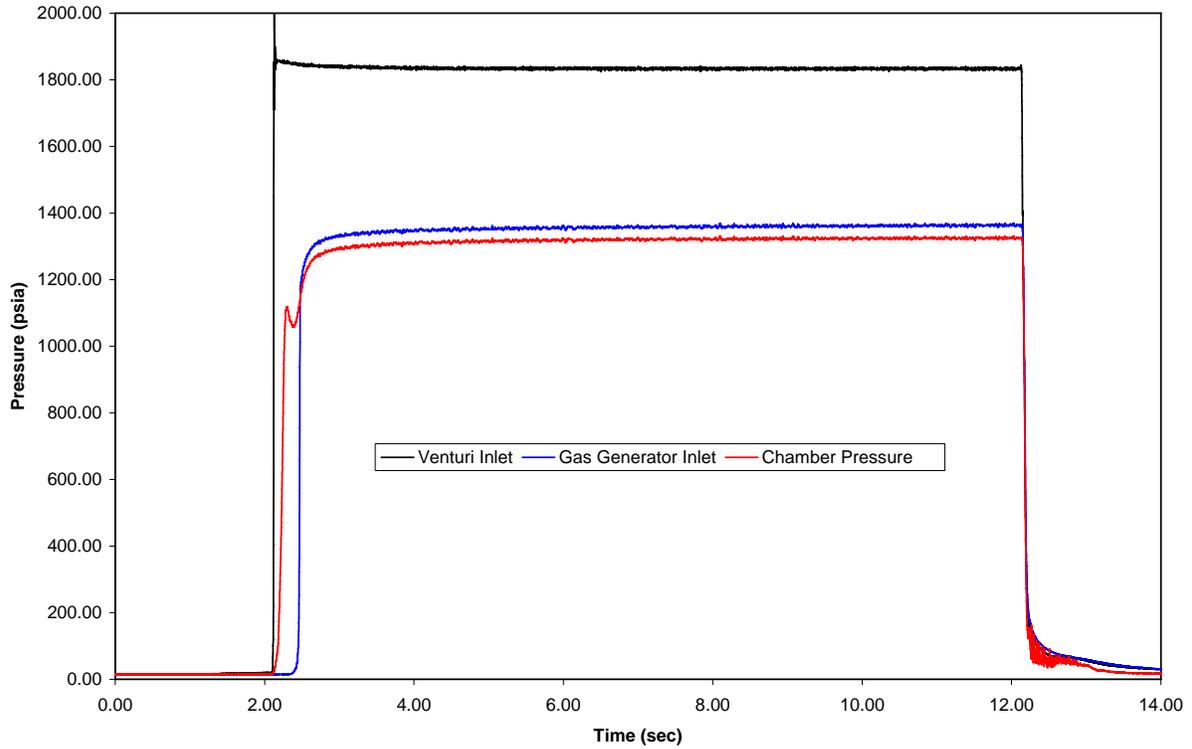


Figure 3 – Pressure Trace From Cold Limit Test with H₂O₂ Temperature ~ 0 °F and GG Start Temperature ~ 100 °F.

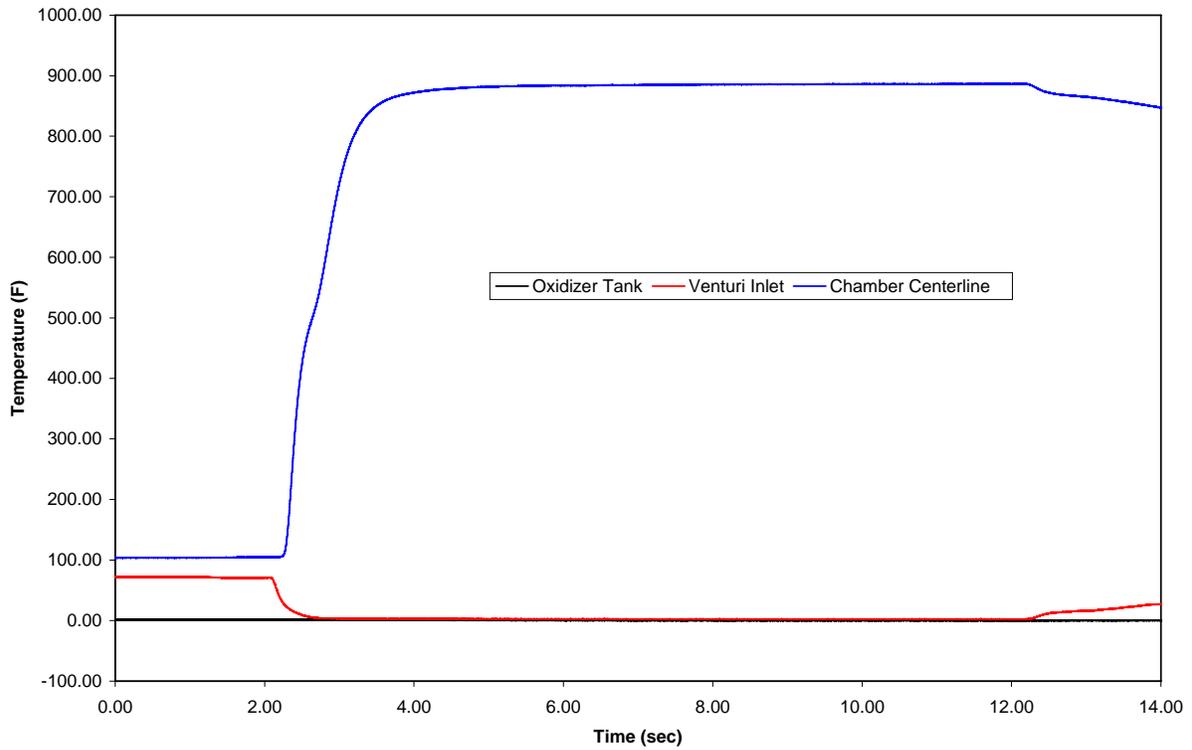


Figure 4 – Temperature Trace From Cold Limit Test with H₂O₂ Temperature ~ 0 °F and GG Start Temperature ~ 100 °F.

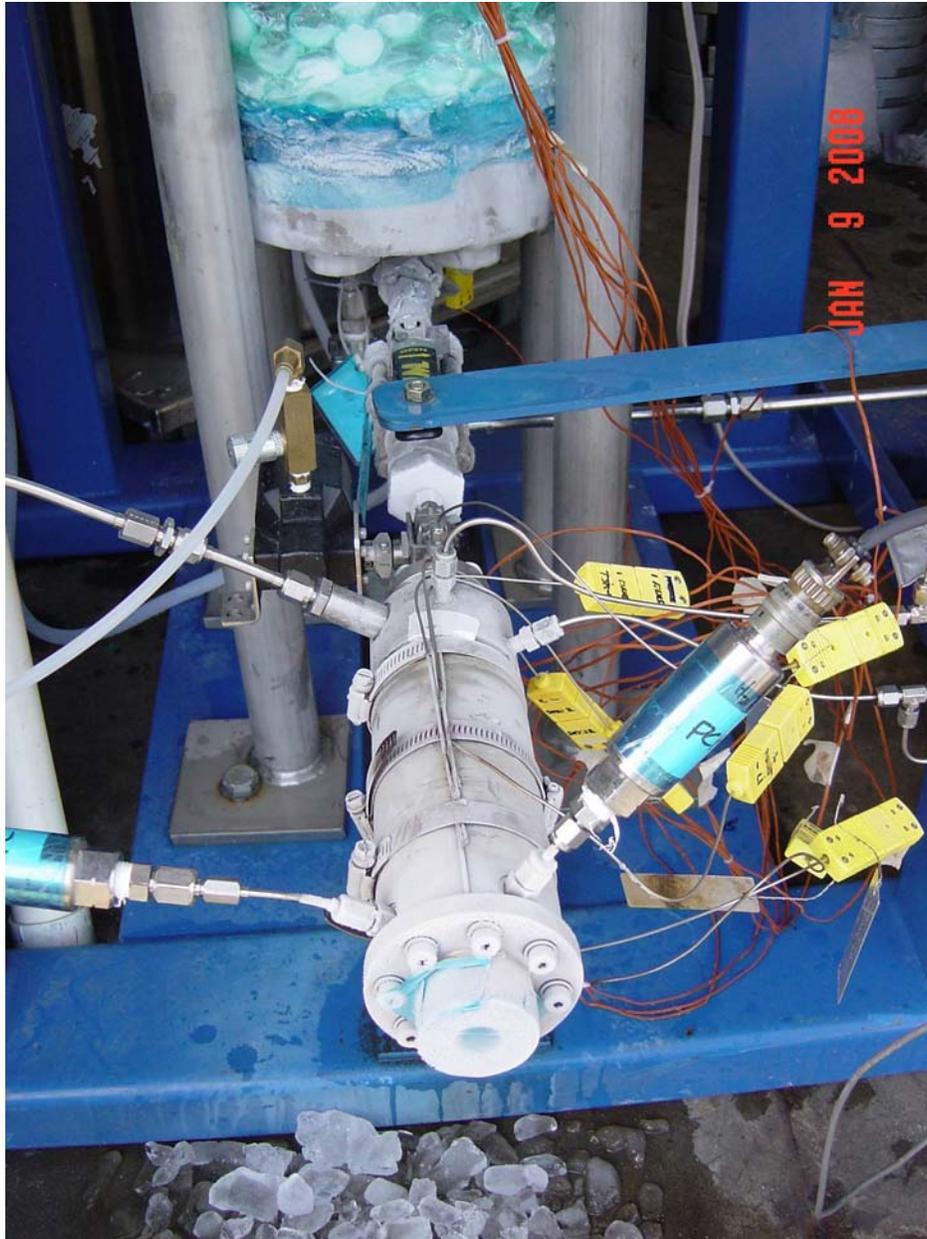


Figure 5 - GG Temperature Conditioned to ~ 0 °F Prior to Final Test (Fluid Temperature ~ 5 °F). Note The Frost On The Feed System and the GG. Also Note Tape Over the Nozzle Exit to Prevent Same Conditions on Interior of GG.

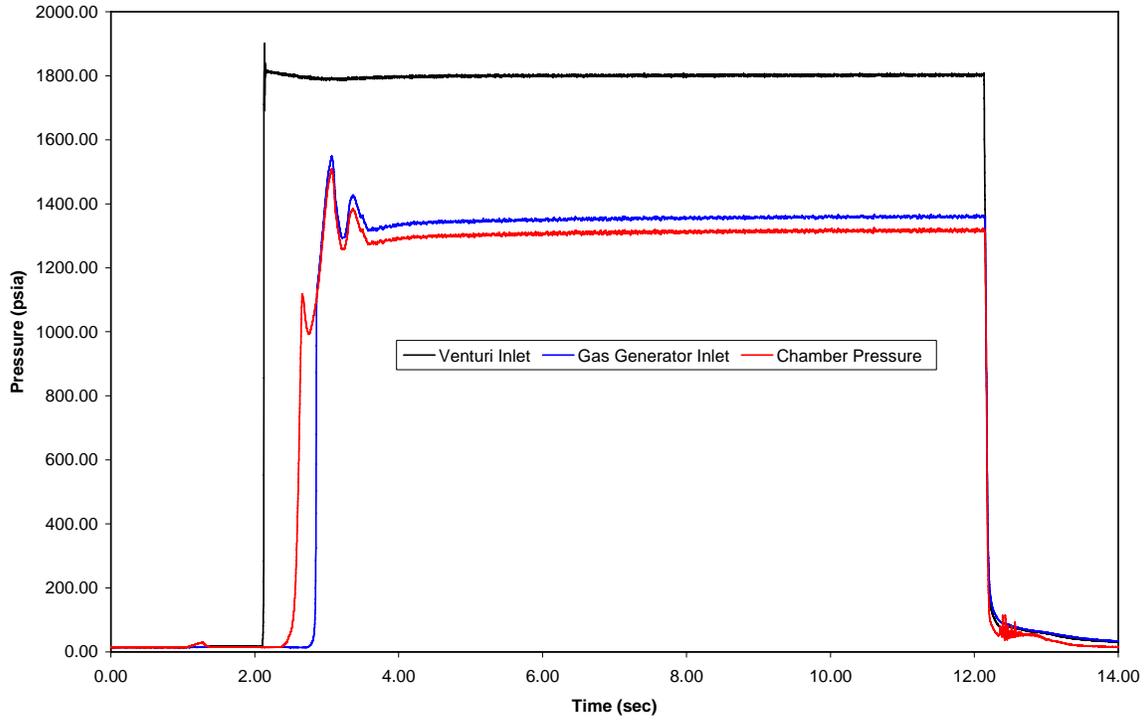


Figure 6 – Pressure Trace From Cold Limit Test with H₂O₂ Temperature ~ 5 °F and GG Start Temperature ~ 0 °F.

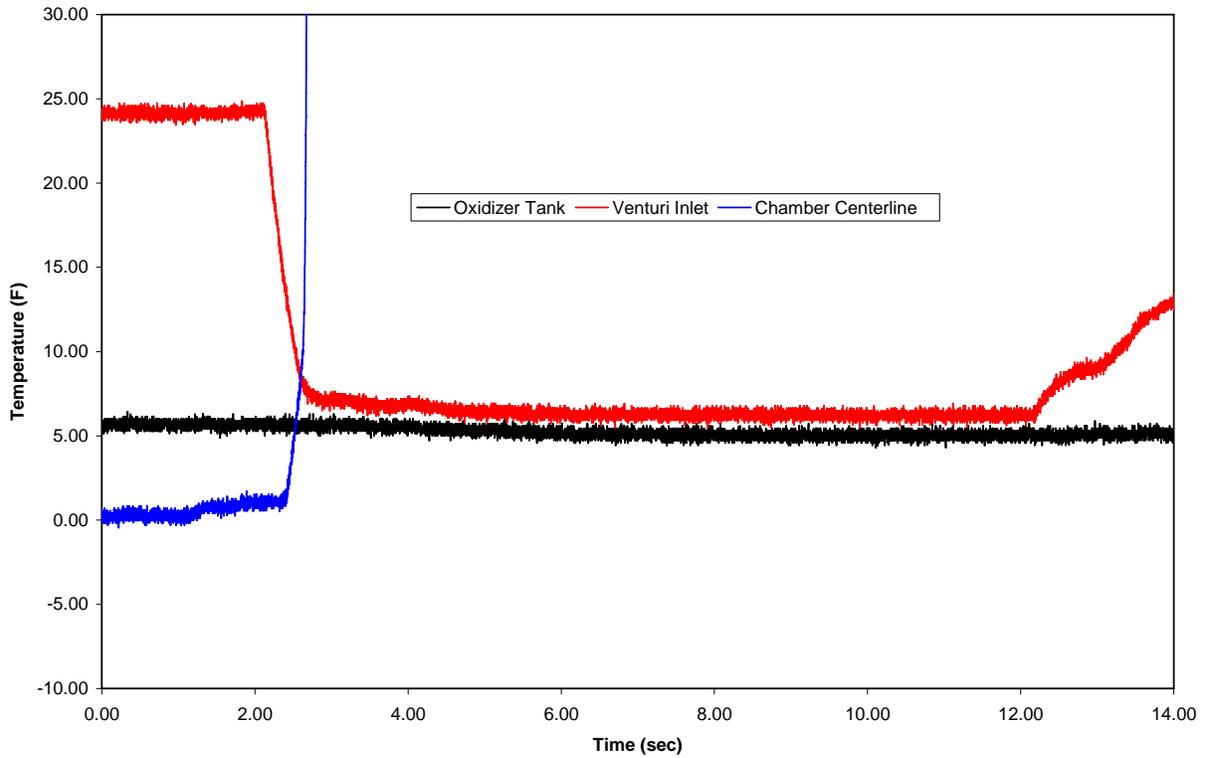


Figure 7 – Temperature Trace From Cold Limit Test with H₂O₂ Temperature ~ 5 °F and GG Start Temperature ~ 0 °F.



Dryden Flight Research Center EC76-6242 Photographed 1976
Mini Sniffer III NASA photo



Figure 8 – Mini-Sniffer III Remotely Piloted Upper Atmospheric Pollution Sensing Aircraft (Ref 14). Utilized a Hydrazine Monopropellant Reciprocating Engine and had a Wingspan of ~18 ft.



Dryden Flight Research Center ECN-6134 Photographed 1976
Mini Sniffer III NASA photo



Figure 9 – Mini-Sniffer III Showing Ground Support Crew Wearing Self Contained Suits Because the Engine was Powered by Hydrazine, Very Hazardous Material (Ref 15).

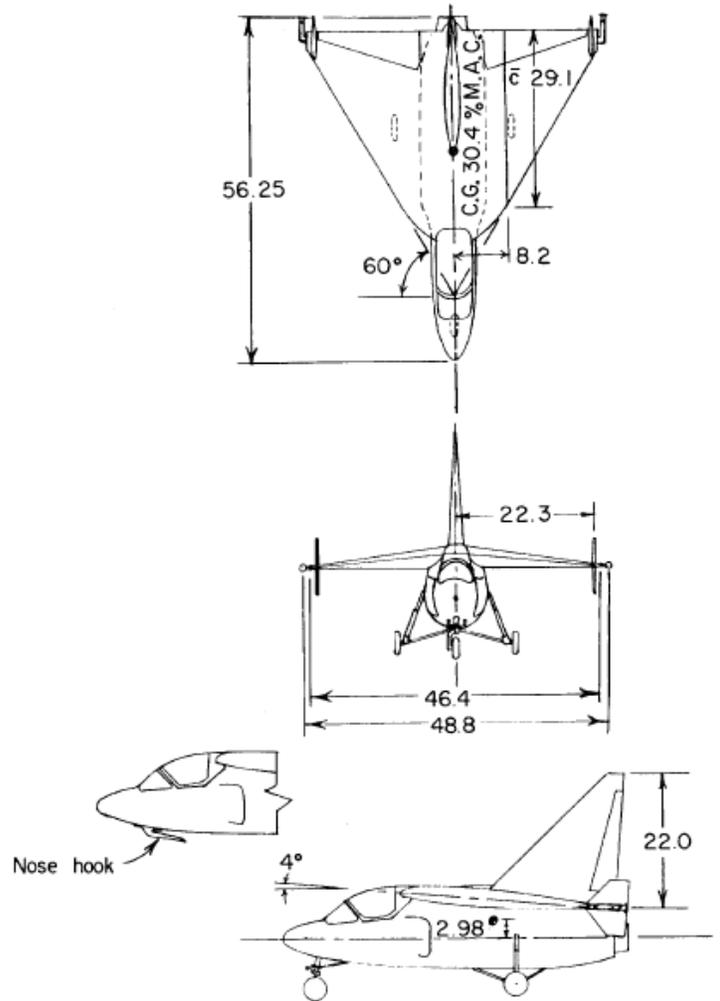


Figure 10 – Planform of a 1/5 Scale Model (of Jet-Powered Aircraft) Used for Hovering and Transition Flight Studies in 1961 - Dimensions in Inches. Model was Powered by Hydrogen Peroxide Rocket – Dry Mass Around 40 lbm (Ref. 21).



Figure 11 – Cutaway View of the Liquid Hydrazine Gas Generator RESUS (Rescue System for Submarines) System for Emergency Ballast Displacement in Submarines. Hydrazine Mass per Gas Generator is Approximately 137 lbm. Gas Generator Manufactured by EADS Astrium and Deployed in German Submarines for More than 25 Years. (Ref. 25).