NITROUS OXIDE / HYDROCARBON FUEL ADVANCED CHEMICAL PROPULSION: DARPA CONTRACT OVERVIEW*

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ABSTRACT

This work, in response to DARPA BAA 99-22, topic title "Small Scale Propulsion Systems," focused on the development of a nitrous oxide (N_2O) / propane (C_3H_8) rocket engine (NOP), that utilizes catalytic decomposition of N_2O as an ignition system for propane. This propellant combination is proposed as an alternative to the present space propulsion systems that use hypergolic or cryogenic liquids, or solid propellants. Phase I work has resulted in a successful demonstration of the key technologies associated with the development of such a propulsion system. In particular, rocket performance for the NOP propellants and catalytic decomposition of nitrous oxide were demonstrated. The work began with two parallel efforts: the experimental evaluation of rocket performance using nitrous oxide and propane as propellants, and an experimental evaluation of various catalysts for the decomposition of nitrous oxide. The development of a catalytic reactor to efficiently decompose N_2O for propane autoignition was central to this research effort. Experiments to demonstrate rocket ignition using the catalytically decomposed nitrous oxide began in late January 2001. These rocket tests were performed using improved rocket hardware (NOP Rocket 2), an improved thrust stand and a new atmospheric pressure test stand, (Test Stand 2) constructed at the Johnson Research Center on the campus of UAH in Huntsville, Alabama. Pitot pressure surveys and radiometric measurements were conducted by AEDC to independently measure thrust and provide spectral signature data. This work resulted in a patent being granted the author (US Patent # 6,779,335 "Burning Nitrous Oxide and a Fuel").

INTRODUCTION

The development of a nitrous oxide (N_2O) / propane (C_3H_8) rocket engine (NOP) was explored under the DARPA Phase I contract. This propellant combination is proposed as an alternative to the present space propulsion systems that use hypergolic or cryogenic liquids, or solid propellants. Phase I work has resulted in a successful demonstration of the key technologies associated with the development of such a propulsion system. In particular, rocket performance for the NOP propellants and catalytic decomposition of nitrous oxide were demonstrated. This report summarizes the design, development and testing of a NOP rocket system and outlines work required to further develop this concept to the point that a flight weight prototype could be fabricated if DARPA elects to fund a Phase II project or alternate funding sources are found.

Also included in the report are generalized mission analyses to help determine future uses for such a propulsion system. Details associated with the individual propellants, their properties, and handling qualities are discussed. One of the main benefits this technology exploration has verified is that nitrous oxide can be considered as a cold gas propellant, monopropellant, and oxidizer for a bipropellant.

PROBLEM IDENTIFICATION

A serious limitation on the ability of the commercial aerospace industry to place into and keep satellites in Low-Earth-Orbit and support manned spaceflight at economical prices is the choice of propellants and propulsion technologies used for rocket boost, attitude control systems (ACS), reaction control systems (RCS), orbital maneuvering systems (OMS), and auxiliary power units (APU). Present systems are either liquid propellants that are hypergolic or cryogenic, or solid propellants that are single use only, are unthrottleable, and are explosive in nature. A proposed solution to the problem is to select propellants for a chemical propulsion system that are readily available, are easier to handle, non-toxic, produce high performance, and provide significant reduction in cost of operations.

High operating costs are a result of occupational safety requirements associated with the handling of toxic, hypergolic propellants and of added complication of operating a cryogenic propellant system. This cryogenic system also adds considerable dry weight, further reducing the payload weight fraction. By using nontoxic, benign propellants that are relatively safe to handle, low cost can be realized through simplified ground operations.

RESULTS AND DISCUSSION

The technological innovation explored exploited several unique properties of the propellants, propane and nitrous oxide, for a chemical rocket propulsion system. These self-pressurizing propellants have a distinct advantage over current systems that use hydrazine as a monopropellant and monomethylhydrazine and nitrogen tetroxide (MMH/NTO) as bipropellants. They are standard liquefied industrial gases and are classified by the U.S. Department of Transportation as simple asphyxiates, with propane as a flammable gas and nitrous oxide as a mild oxidizer. They are neither highly explosive nor hazardous to work with or handle. The proposed chemical liquid propulsion system, using these environmentally benign propellants, is economically advantageous to current hypergolic or cryogenic systems. They possess commercial availability at low prices and are easy to handle, thereby producing a significant reduction in operating costs.

UNIQUE FEATURES OF NOP PROPELLANTS

A unique feature of nitrous oxide facilitates auto-ignition of the propane without the use of hypergolics. Nitrous oxide can be catalytically decomposed using a wide variety of catalysts, including platinum, iridium, rhodium, tungsten carbide, copper, cobalt, and gold. The decomposition process is exothermic resulting in nitrogen and oxygen at 2988 ^{o}F, for complete decomposition. This hot oxidizer will ignite propane (and most hydrocarbon fuels) on contact and will facilitate sustained combustion in a rocket combustion chamber. Using this technique, auto-ignition and rigorous and complete combustion can be accomplished using stable, non-toxic, storable propellants. Along the same lines nitrous oxide could be decomposed and used as a monopropellant similar to hydrazine and hydrogen peroxide.

In addition to these qualities, nitrous oxide and propane both store as high-pressure liquids. This facilitates self-pressurization, which eliminates the need for a pressurant system. Although high-pressure storage (750 psia for nitrous oxide, 125 psia for propane) increases tank weight, this can be mitigated with the use of a variety of low-weight, high-strength composite materials. Although the vapor pressure for propane is quite low, it can be pressurized with nitrous oxide utilizing a single tank with a diaphragm.

Ethylene is being considered as a replacement fuel for propane since its vapor curve and critical conditions are similar to that of nitrous oxide. Ethylene would improve the specific impulse over propane by several seconds, and is a candidate for future development of this technology.

Nitrous oxide and propane also have relatively low freezing temperatures as compared to hydrazine and MMH. This eases problems associated with line freezing in orbit. Freezing point temperatures as well as a host of other properties for nitrous oxide and propane are shown, compared to those of hydrazine, MMH, and NTO, in Table 1. Although the storage density for the NOP propellants is lower than that of the hypergolic propellants, the benefit comes from the stability of the liquids, the lower freezing point conditions, and self-pressurization.

	N_2O	C_3H_8	C_2H_4	N_2H_4	MMH	N_2O_4	H_2O_2
Critical Temp (F)	97.2	114.5	49.3	716.4	561.0	316.0	
Critical Pressure (psia)	1048.2	983.2	729.7	2128.3	1195.0	1465.0	
Freezing Point (F)	-130.9	-305.0	-271.8	36.0	-61.2	15.7	12.6
Boiling Point (F)	-126.9	-43.2		237.6	189.9	70.2	286.2
Storage density (lb_m/ft^3)	47.9	44.2	35.3	62.9	54.8	90.3	86.0
Stability	Stable	Stable	Stable	Hypergolic	Hypergolic	Hypergolic	Unstable[i]
Toxicity	-	-	-	Toxic	Toxic	Toxic	-
Decomposition	Exothermic	-	-	Exothermic	Exothermic	-	Exothermic
Catalyst	Shell 405			Shell 405			Silver

Table 1: Properties of liquid rocket propellants

Table 2 shows a comparison of performance for candidate propellant combinations, including both bipropellant and monopropellant systems with nozzle expansion to vacuum conditions. It is evident from Table 1 and Table 2 that the NOP propellant combination has comparable rocket performance and more benign qualities than MMH/NTO, although it is at the price of a slightly lower storage density.

	NOP	MMH/NTO[ii]	H_2O_2/Kerosene	N_2O	Hydrazine[iii]	Peroxide
I_{sp} (s)	300	292	273	187	-	182
I_{sp} (s) Vac	312	339	319	192	230	187
C* (ft/s)	5234	5874	5494	3496	3073	3344
T_c (R)	5699	5850	5247	3195	1010	2207

Table 2: Rocket Performance Comparison

Although the NOP rocket concept deals specifically with nitrous oxide and propane as propellants, the greater theme is one of using nitrous oxide as an oxidizer and ignition source for use alone as a monopropellant or with a fuel as a bipropellant. The concept is based on the ability to catalytically decompose nitrous oxide into a hot nitrogen/oxygen mixture, and use this mixture to ignite and burn a fuel. This catalytic decomposition has was successfully demonstrated in a Phase I effort under a DARPA/TTO BAA 99-22, using a number of catalysts including the iridium based Shell 405, which has a rich space flight heritage as a hydrazine catalyst. A schematic diagram of such a proposed system is shown in Figure 1. The nitrous oxide passes over the catalyst reactor before entering the combustion chamber. Fuel is injected into the combustion chamber and thermally autoignites the propane, or other hydrocarbon of choice.
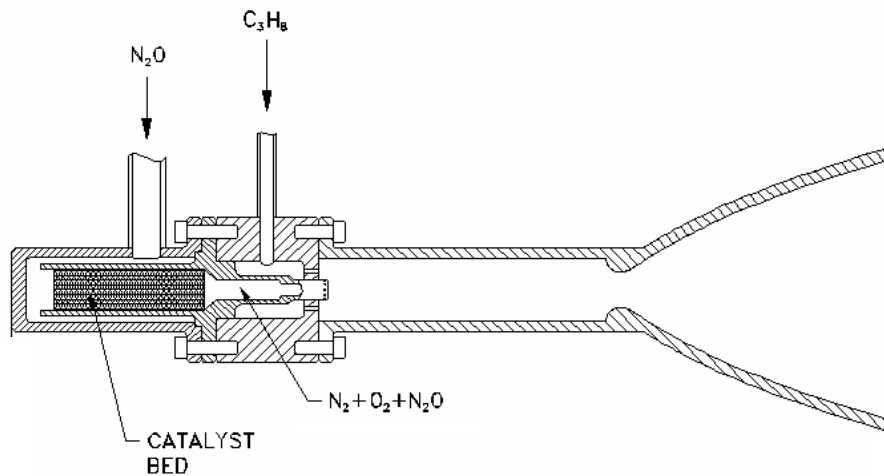
Figure 1: Conceptual Drawing of NOP Rocket Flight Hardware

This work suggests that a nitrous oxide / hydrocarbon propellant combination is viable alternative to the MMH/NTO bipropellant, which is the mainstay for current systems. Nitrous oxide has already been successfully used as an oxidizer for bipropellants in hybrid rockets and has extensive use as a performance enhancer in auto racing.

NITROUS OXIDE MONOPROPELLANT

Since nitrous oxide decomposes exothermically it can also be used as a monopropellant. This monopropellant could serve as a replacement for hydrazine monopropellant rockets, or as an alternative to cold gas thrusters. Nitrous oxide is listed as a candidate propellant for cold gas thrusters[iv] and has already been used as a propellant for a resistojet on the UoSat-12 (designed and built by Surrey Satellite Technology Limited[v] (SSTL) and Polyflex, Inc.[vi]). With the minimal added catalyst weight, a nitrous oxide cold jet thruster can nearly triple its specific impulse as a warm jet thruster. Such a system would be of tremendous use for microsatellites / minisatellites or minor orbit adjustments since chemical rockets suffer reduced thrust-to-weight ratio at small scales (Figure 2).
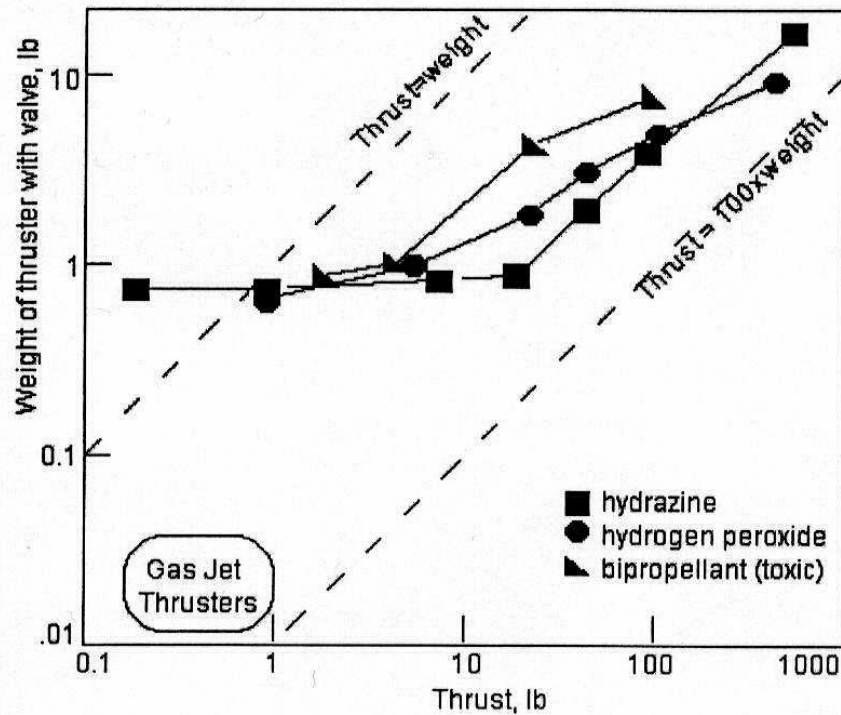
Figure 2: Thrust-to-Weight Ratio as a function of rocket scale.[vii]

The SSTL resistojet is a 125mN sized thruster that has flown on the UoSat-12 satellite. The resistive element has a 100W power requirement and produces 127s of specific impulse. Nearly complete nitrous oxide decomposition is possible using a 600W heater. This would result in higher thrust and a 182 s specific impulse[viii]. This level of nitrous oxide decomposition is possible by catalytic reaction without the expense of high power requirements.

Surrey Satellite Technology Limited has also been exploring the idea of using catalytically decomposed nitrous oxide for a monopropellant rocket[ix] and as an igniter/oxidizer for a kerosene bipropellant rocket[x]. Although they have not yet performed rocket tests using catalytically decomposed nitrous oxide, they have tested over 50 different catalysts. Tests showed nitrous decomposition using a variety of catalysts (including Shell 405) with light-off temperatures as low as 392°F. They made no attempt to develop low light-off temperature catalysts and instead have focused on catalyst stability issues at excessively high temperatures. SSTL's previous resistojet work and future research and development plans indicate their recognition of the potential benefit of nitrous oxide as a rocket propellant and of catalytic decomposition as a low-power alternative to resistive heating and ignition. Additional trade studies by Zakirov[xi,xii] indicate tremendous benefit for nitrous oxide use as a monopropellant and cold gas thruster and underscores the added benefits of developing a multi-modal propellant system where nitrous oxide is used for all small satellite propellant needs.

Nitrous oxide has added benefit as a space propellant in that it stores as a liquid and injects as a gas. This is important for attitude control (AC), since liquid injection rockets cannot provide the shorter pulse times required for an ACS mission. Liquid storage gives tremendous weight benefit since a liquid

tank can hold multiple times its own weight in propellant, whereas the same is not true for gas storage systems.

NITROUS OXIDE AS AN ALTERNATIVE TO HYDROGEN PEROXIDE

With similar goals in mind, hydrogen peroxide is being considered more and more as both a monopropellant and oxidizer for a bipropellant, for space applications and upper-stage booster rockets[xiii]. We propose the NOP rocket concept as a viable alternative or even a complementary technology as it has some advantages over peroxide as well as some disadvantages (Table 1 and Table 2). Concurrent development of the two technologies is ideal in that many of the challenges are the same and the expanding knowledge base can mutually support both.

The resurgence of hydrogen peroxide as a potential rocket propellant is based partially on the promise of new technologies that can solve the long-standing technical issues associated with its use[xiv]. In particular, improvements to the silver catalyst beds are required for high temperature operation. The silver catalyst used for peroxide is also prone to "poisoning" by contaminants and stabilizers in the peroxide. Stabilizers are required to avoid inadvertent decomposition, which occurs during long periods of storage. Although "poisoning" can affect most catalysts, this is less likely to occur with nitrous oxide since it does not require stabilizers for long-term storage. Peroxide vapors can be explosive and shock sensitive in the presence of contaminants. Highly concentrated hydrogen peroxide, such as is required for efficient propellant use, is almost as toxic as hydrazine based on IDLH, and the OSHA PEL and ACGIH TLV values governing occupational exposure are actually much lower than those of NTO.

Other work seeks out non-toxic, storable fuels that become hypergolic in the presence of peroxide. Ignition for our proposed propellant combination is provided by the high-temperature products of the nitrous oxide decomposition and not by the hypergolic nature of propellants. A similar approach to ours was also in development for hydrogen peroxide rockets by Beal Aerospace Technologies Inc. before they shut down in October of 2000.

MULTI-MODAL SPACE PROPULSION SYSTEM

Due to the versatility of nitrous oxide as both a monopropellant and oxidizer for a bipropellant system, the potential exists to set up a multi-mode propulsion system, which will improve space mission capability by reducing the dry weight overhead. A single propellant system serving all space propulsion missions from attitude control to orbital maneuvering would reduce the component count, system weight, and cost. Lower dry weight can be converted into higher payload weight fraction or ΔV.[xi]

PROPELLANT SYSTEM FOR SELF PRESSURIZING LIQUIDS

Most propellants commonly used today have relatively low vapor pressure (lower than the rocket chamber pressure) and consequently have to be pressurized. This is accomplished in one of several ways. Turbo pumps are used for launch vehicle applications. The pumps are driven using onboard propellant and form part of the thermodynamic cycle for the system. For space applications, expulsion systems are used to pressurize the propellant and drive it out of the propellant system. Expulsion

systems are either blow-down or regulated. Both versions use high pressure gas (either helium or nitrogen) to pressurize the liquid propellant.

For blow-down systems the pressurant gas is stored in the same tanks with the propellant. As the propellant is consumed tank pressure decays, as does thrust. Regulated systems keep a very high pressure source of pressurant gas, which is regulated down to the required tank pressure. As the propellant is consumed, the regulator maintains a constant tank pressure, and correspondingly constant thrust. Blow-down systems are used mainly for monopropellant thrusters, while regulated systems are used for bipropellant thrusters. Expulsion systems lower the useful tank volume, and, in the case of regulated systems, add considerable dry weight. Blow-down systems can occupy over 20% of the tank volume. Regulated systems require a lower ullage volume (~3%), although a separate high-pressure tank is required to store the pressurant gas.

In contrast to these systems the NOP propellants are self-pressurizing due to their relatively high vapor pressures (higher than the rocket chamber pressure). Consequently, they do not require separate expulsion systems and the entire tank volume can be used to store propellant. The vapor pressure of nitrous oxide is approximately 750 psi and that of propane is 125 psia at ambient temperature.

For a self-pressurizing system the vapor pressure is maintained in the tanks until all of the liquid propellant is consumed. By taking a ratio of the vapor to liquid densities of nitrous oxide, we could see that constant pressure and thrust conditions can be supplied using 83.1% of the propellant. The remaining 16.9% remains as a high-pressure gas and can be used with decaying conditions as a blowdown system. The metering orifices would now operate in a choked fashion and could therefore still be used to meter flow rate. With 7.1% mass still remaining in the tanks, there would be insufficient pressure remaining to meter the flow using the choked orifice. The system would continue to work until approximately 3.5% mass is left remaining in the tanks, although with increasingly decaying performance.

The self pressurizing system has both advantages and disadvantages as compared to the other systems mentioned. Although regulated systems can provide constant tank pressure for the entire propellant mass, such systems add considerable dry weight and complications. Blow-down systems suffer pressure decay over the spacecraft's entire operational lifetime and could occupy over 20% of the tank volume. In comparison, the NOP self-pressurized propellants utilize the entire tank volume, allowing for up to 20% more propellant mass. The self-pressurized system provides constant tank pressure for over 80% of its operational life, and then transitions to a blow-down system with as little as 3.5% unusable propellant. A self-pressurizing system would incur higher tank weight, although this could be mitigated by material choices.

The vapor pressure of propane is slightly low in order to be used as a true self-pressurizing propellant. For the case of a NOP system, high-pressure nitrous oxide vapor would be used as a pressurant gas for the propane. Issues associated with maintaining mixture ratio for the bipropellant case will require some research. Ethylene is also being considered as a propane replacement due to its higher vapor pressure.

IDENTIFICATION OF OPERATIONAL SYSTEM PAYOFFS

The NOP rocket offers a non-toxic, environmentally benign propellant combination that is storable in space over long periods of time and offers comparable specific impulse to current systems. Table 2 compares the performance of nitrous oxide / propane with MMH/NTO and hydrogen peroxide / kerosene. Nitrous oxide monopropellant is also compared with hydrazine.

The non-toxic nature of the NOP propellants will serve to reduce operating costs due to the handling issues associated with the hypergolic propellants currently in use for space applications. The NOP propellants are benign and not highly reactive. They remain so until the nitrous oxide is catalytically decomposed and combined with the fuel. Exhaust products consist mainly of nitrogen, water, and carbon dioxide.

The NOP propellants are storable over long periods of time without degradation. Inadvertent decomposition is one of the main technical obstacles for hydrogen peroxide use in space propulsion systems.

POTENTIAL CUSTOMERS FOR THE TECHNOLOGY

The rocket propellants studied in under this contract could be used for satellite applications with the intended objective of providing economical service in a LEO (Low Earth Orbit) environment. Space applications will include auxiliary power units, attitude control systems, reaction control systems, and orbital maneuvering systems. These applications appear feasible using the proposed propellants and ignition scheme. Potential weight savings exist by using the same propellant combination for all satellite rocket systems (i.e. multi-modal propulsion system). Any larger derivatives would target requirements for the upper stage of launch vehicles for routine placement of satellites in LEO.

This work suggests future concentration on the satellite propulsion market for both technical and marketing reasons. Technically, this rocket combination is well suited for use as a space propellant and upper stage booster, although it is probably not dense enough to be advantageous as a first stage booster over solids and cryogenic propellants. The satellite market is also rapidly growing. Competition will create a need for better and cheaper propulsion solutions.

Other potential customers exist in the areas of upper stage launch vehicles, low and medium altitude BMD interceptors, and RATO systems for the UAV market. A potential application as a pilot and torch igniter for hypersonic air-breathing propulsion systems opens up another potentially large future market. Operational ramjets and scramjets are expected on hypersonic weapon systems within the next ten years. Operational vehicles using air-breathing propulsion systems are in the works, with the eventual goal of low-cost access to LEO. Application of catalytically decomposed nitrous oxide to high altitude re-light of gas turbine engines is also being considered.

DESIGN AND DEVELOPMENT APPROACH AND OVERVIEW

The work under this DARPA BAA 99-22 contract, dealt with a demonstration of the nitrous oxide / propane rocket to evaluate rocket performance and ignition using catalytic decomposition of nitrous oxide. The work began with two parallel efforts: the experimental evaluation of rocket performance using nitrous oxide and propane as propellants, and an experimental evaluation of various catalysts for the decomposition of nitrous oxide. Once these two efforts were completed, they were combined to demonstrate rocket ignition using the catalytically-decomposed nitrous oxide.

The catalyst research was performed at the University of Alabama at Huntsville, (UAH), and was focused on obtaining a candidate catalyst for use in rocket tests and on finding the optimum catalyst material (or materials) for use in a future space-qualified prototype. This work showed that the Shell 405 catalyst successfully decomposes nitrous oxide with moderate light-off temperatures. Shell 405 catalyst has an extensive history of use in space as a hydrazine catalyst material.

Experiments to demonstrate rocket ignition using the catalytically decomposed nitrous oxide began in late January 2001. These rocket tests were performed using new rocket hardware (NOP Rocket 2) and a new atmospheric pressure test stand, (Test Stand 2). The new rocket hardware features a new fuel injection scheme, a copper heat sink design, and a nozzle design that is traceable to a full area ratio design that is verified by CFD analysis. Test Stand 2 features an improved thrust stand design and adequate room to perform the planned pitot pressure surveys and radiometric measurements, conducted by AEDC.

In the following sections an overview of the design and development of the NOP Rocket 2 test article and Test Stand 2 will be the main focus. However, prior to NOP Rocket 2, a series of tests were conducted at Test Stand 1 at the Johnson Research Center at UAH, with the NOP Rocket 1 test article. Descriptions of Test Stand 1 and a brief discussion of the NOP Rocket 1 motor are also presented.

ROCKET TEST ARTICLE 1 AND 2 DESIGN

The NOP rocket utilized nitrous oxide (N_2O) as the oxidizer and propane (C_3H_8) as the fuel. The chamber pressure is 150 psia for this 50 lb_f rocket, and a fuel-rich propellant combination is used to maximize performance. According to common practice for space-based thrusters, a pressure drop between 20-30% of chamber pressure is taken across the injectors, requiring an injection pressure of approximately 180 psia. Since the vapor pressure of propane at 70 °F is only 109.6 psi the propane needs to be pressurized for this application. This was accomplished using nitrogen pressurant for the ground-based testing, and can be accomplished using the nitrous oxide as pressurant in space, via a suitable diaphragm.

To measure rocket performance using specific impulse (I_{sp}) and characteristic exhaust velocity (c*), accurate measurements of thrust and propellant (fuel and oxidizer) flow rate are essential. Measuring the flow rate of N_2O and C_3H_8 requires using a subcritical venturi, with the fluid in the liquid state to avoid two-

phase flow. In order to achieve this during the ground testing, both propane and nitrous oxide are pressurized to 1000 psia.

The nitrous oxide is injected as a two-phase fluid (-25 °F, 175 psia), while the propane is injected as a liquid (70°F, 195 psia). The rocket design involved the design of the injector for N_2O and C_3H_8, design of the combustor with an appropriate L* (characteristic combustor length) and design of a rocket nozzle for sea level static conditions and space conditions. Work was also accomplished on the design of the injector, combustor, and rocket nozzle.

TEST ARTICLE 1

The NOP Rocket 1 test article has a nominal L* = 3 m, for a combustor geometry of 2.125" inner diameter and a nozzle A_e/A^* of 2.21, with a throat diameter of 0.616" and an exit diameter of 0.916". Various combustor designs with L*'s equal to 1, 2 and 3m for NOP Rocket 1, were evaluated on Test Stand 1, with the conclusion that the optimal L* was between 2m and 3m. A photograph of the NOP Rocket 1 test article is shown below in Figure 3, on Test Stand 1. The combustor overall length was 12.25".
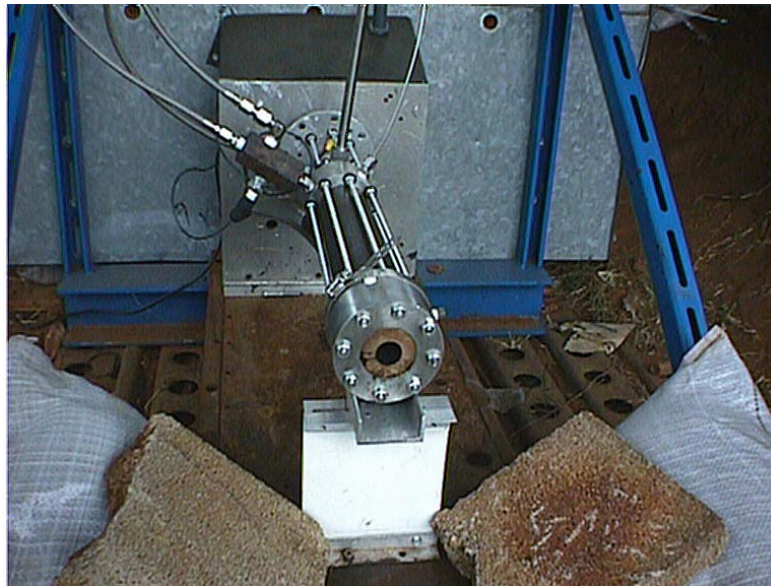
Figure 3: Photograph of NOP Rocket 1 motor shown mounted on Test Stand 1 at the Johnson Research Center at UAH.

TEST ARTICLE 2

Based on data and experience with testing Test Article 1, it was recognized that the combustor design must provide for adequate mixing between fuel and oxidizer as well as provide sufficient residence time required to mix and burn the propellants efficiently. The area ratio on the subsonic side of the nozzle, for NOPR1 was 11.9 and for NOPR2 was 4.4, for a combustor Mach number of approximately

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0.13. This area ratio was chosen as a compromise between residence time and velocity (which promotes atomization). The combustor for NOPR2 is made of Glid-Cu, a Cu-0.15% alumina matrix alloy, and carbon-steel for NOPR1.

Selection of the appropriate combustor length L* was also based on testing done at the UAH with the NOP Rocket 1 design. The criterion for combustor length selection is maximum c* efficiency, where c* efficiency η_{c^*}, is defined as:

$$\eta_{c*} \equiv \frac{P_c A^* / \dot{m}}{c^*_{theoretical}} \qquad (3\text{-}1)$$

Where $c^*_{theoretical}$ is obtained from a NASA chemical equilibrium program[xx] and is a function of P_c, , mixture ratio and reactant composition.

A characteristic combustor length L* is defined as the length that a chamber of the same volume would have if it were a straight tube with cross sectional area A* and had no converging section:[xv] L* is given by:

$$L^* \equiv \frac{V_c}{A^*} \qquad (3\text{-}2)$$

where V_c is the combustor chamber volume ($\pi D_c^2 L_c / 4$), L_c is the combustor geometric length, D_c is the combustor diameter and A* is the nozzle throat cross-sectional area.

For sea level conditions, the nozzle was truncated at an area ratio, A_e/A^* of 2.45 for the supersonic region, to achieve perfect expansion to the ambient conditions. This configuration was tested at the rocket Test Stand 2. The full nozzle configuration would require a vacuum chamber for testing. Table 3 summarizes the rocket design for NOP Rocket 2 for both sea level and vacuum conditions.

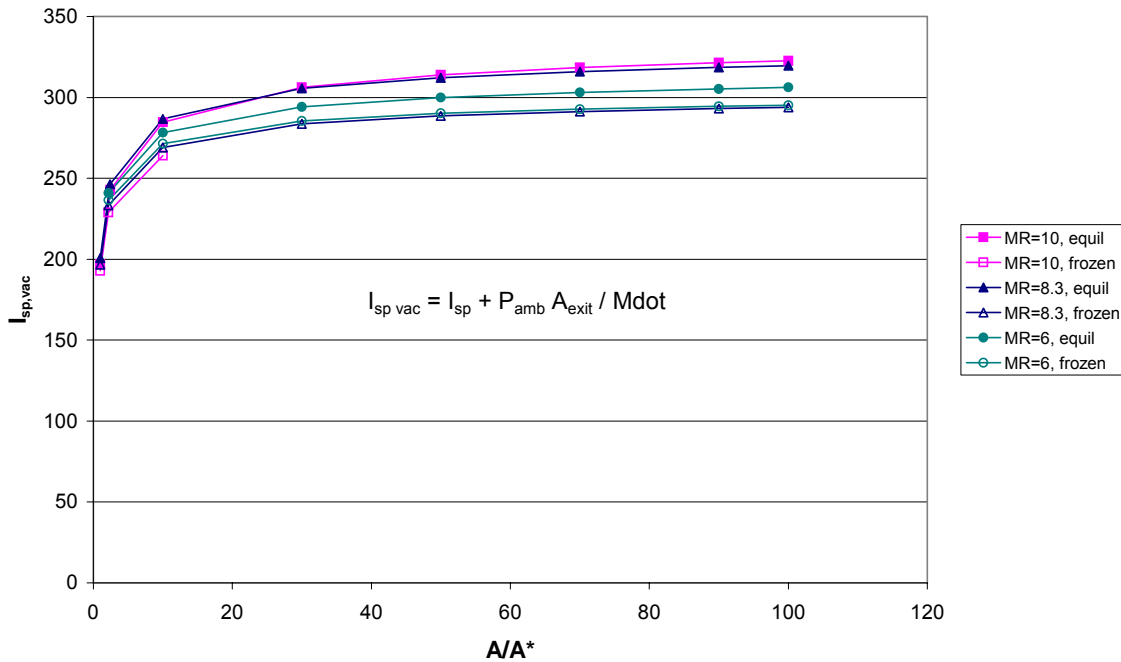|	Sea Level	Vacuum
Chamber Pressure, P_c (psia)	150	150
Total Propellant $\dot{m}$ (pps)	0.164	0.164
Mixture Ratio	10.0	10.0
L_c (in)	8"	TBD
Throat Area, A* (in^2)	0.178	0.178
A/A* (subsonic)	4.4	4.4
A/A* (supersonic)	2.45	50

Table 3: NOP Rocket 2 Design Parameters

The subsonic A/A* = 4.4 refers to a typical contraction ratio for the combustor area to throat area. One Dimensional Equilibrium analysis shows that the vacuum specific impulse attains a maximum of 314 sec at an area ratio of A/A*=50, with a thrust coefficient of about 1.8 for a mixture ratio of 10.0, Figure 4.

The concept being tested utilizes decomposed N_2O (i.e., a high temperature mixture of N_2, O_2 and N_2O) as a pilot to ignite the propane fuel. Chemical kinetics calculations using LSENS and GASP software were performed to determine the rates of the combustion reactions.

$$I_{sp\ vac} = I_{sp} + P_{amb} A_{exit} / Mdot$$

Legend:
- MR=10, equil
- MR=10, frozen
- MR=8.3, equil
- MR=8.3, frozen
- MR=6, equil
- MR=6, frozen

Figure 4: Vacuum specific impulse as a function of nozzle area ratio for various mixture ratios, for both equilibrium and frozen flow calculations.

ROCKET TEST STAND

Work has been performed using an existing atmospheric test stand (Test Stand 1), which was used for the Alabama Space Grant work. A new rocket test stand (Test Stand 2) was designed and constructed for rocket performance and rocket ignition testing using the catalytic N_2O decomposition reactor as an ignition source. This new rocket test stand features palletized propellant systems, improved propellant system instrumentation, an improved, more robust thrust stand, and adequate room for the rocket exhaust pitot survey equipment and radiometric measurements performed by AEDC.

The new experimental set-up for Test Stand 2 is designed to obtain more accurate measurements of thrust, propellant mass flow rates, chamber pressure, propellant system pressures and temperatures, as well as catalytic reactor pressure and exit temperature, than Test Stand 1. The following subsections describe Test Stand 2 in more detail.

<u>LAYOUT</u>

The new rocket test stand, Test Stand 2 is situated on the UAH campus next to the Test Stand 1 (see Figure). The rocket engine and palletized propellant systems are encased in a steel reinforced concrete bunker to provide adequate safety for operation on campus.

(a)
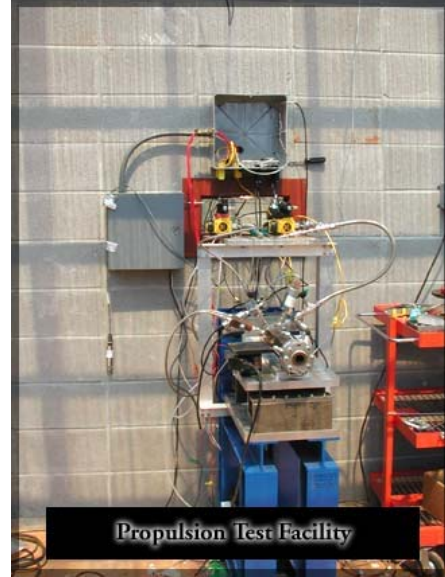
(b)

Figure 5: (a) Test Stand 2 during initial construction at the Johnson Research Center at UAH, and (b) newly operational thrust stand.

Schematics of the palletized propellant system are shown below in Figure 6. Note that both the nitrous oxide and propane systems are similar in layout, except for minor differences in venturi size, metering valve size, and storage tank volume. The idea behind using the palletized approach is to add some modularity to the facility in the event of future work.

The basic idea behind the propellant system layout is to provide the user with a safe and self-contained methodology for loading and pressurizing N_2O and C_3H_8 for use in the ignition circuit (spark ignition or catalyst reactor) and rocket engine feed-systems. The propane and nitrous oxide are first loaded into their respective run tanks. Tank T-1 is a nitrogen pressurization tank, that is used to further pressurize the N_2O and C_3H_8 run tanks (T-2), to ensure that both propellants are in the liquid state at least through the venturi, thus assuring accurate mass flow rate measurements, Section 0. The propellants experience a large pressure drop through the metering valve, (p~400-700 psi), which adjusts the flow to provide the required P across the injector. There are various type 'K' thermocouples and pressure transducers located throughout the system. A nitrogen purge circuit is also used to purge the lines before and after the rocket firing sequence is engaged.
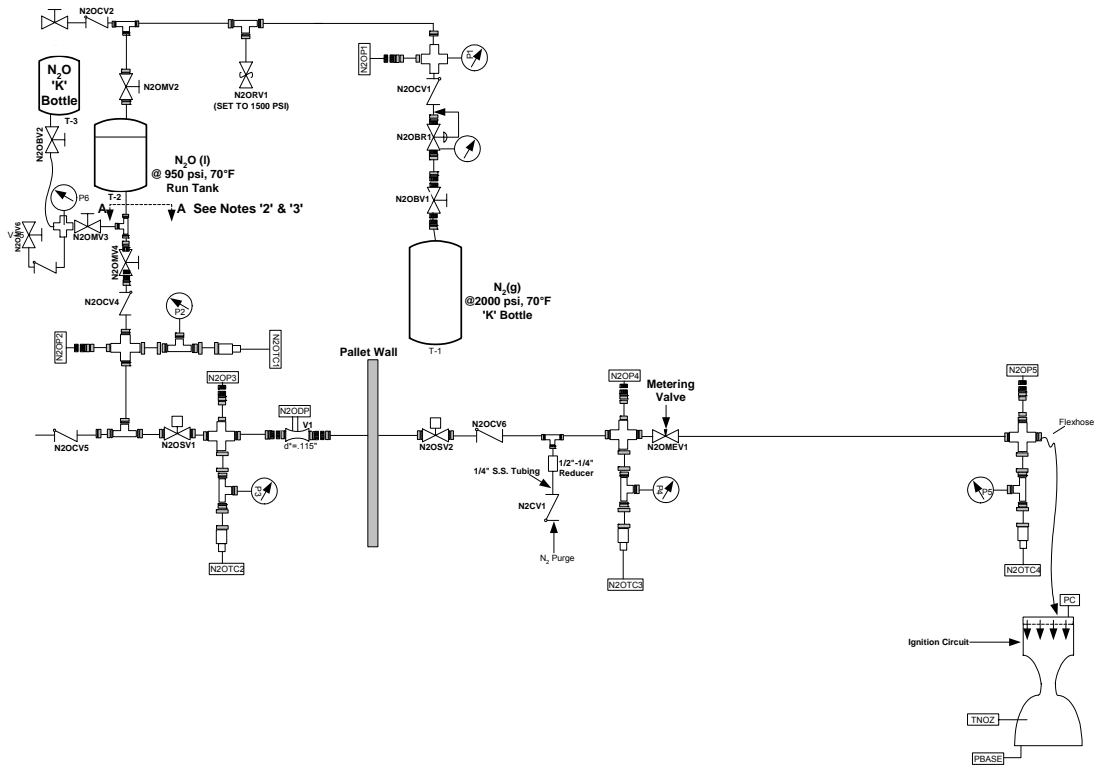
Figure 6. Test System Schematic

MEASUREMENTS

Measurements are made of rocket thrust, propellant mass flow rates, chamber pressure, and a variety of system pressures and temperatures.

To measure rocket engine thrust, a new thrust stand was designed and fabricated at GASL, Inc. The engine is mounted on a pendulum-type stand, supported by flexures. The thrust stand is designed to isolate any induced vibrations in the system and transmit only the engine thrust through the load cell. We used a SENSOTEC Model 43 compression-only load cell, which is a "pancake" type load cell and has a 0-100 lb_f range with a 4-20 mA output to increase S/N ratio. A dead weight calibration system is integrated into the stand. Traceable weights are used for calibration, providing a preload on the load cell. There are no hard pipe connections to the stand; all connections are made with flex-hoses perpendicular to the thrust direction, to minimize any nonlinear resistive forces that may affect thrust measurements.

The N_2O and C_3H_8 flow rates are measured in the liquid state using an unchoked venturi. The following equation is used:

$$\dot{m}(pps) = \left(\frac{C_d A_{geom}(in^2)}{12} \right) \sqrt{2 g_c \Delta P(psia)\rho\left(lb_m/ft^3\right)} \qquad (3\text{-}3)$$

Based on Equation (3-3), to measure flow rate a differential pressure transducer is required for each venturi, as well as a static temperature and a total pressure measurement upstream of the venturi throat.

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Since the state of the propellant is liquid, curves showing density as a function of upstream venturi temperature for various upstream venturi pressures were generated. Thus, to obtain mass flow rate, three measurements are required: upstream static temperature, upstream static pressure and pressure differential, p, across the venturi. A discharge coefficient of $C_d = 0.995$ is used, in accordance with ASME MFC-3M-1989[xvi]; however, the discharge coefficient can also be measured through calibration. The venturi diameters for measuring N_2O and C_3H_8 flow rates are d=0.115" and d=0.054", respectively. The venturis were sized to provide a pressure differential of about 25 psid for a nominal N_2O flow rate of 0.233 lb_m/sec and nominal C_3H_8 flow rate of 0.043 lb_m/sec.

All system pressures were measured with SENSOTEC transducers and all temperatures were measured with OMEGA thermocouples (type K).

Measurements of thrust, flow rates, system pressures and temperatures allow rocket performance parameters, such as specific impulse I_{sp}, and characteristic exhaust velocity, c* to be calculated. In addition to these measurements, AEDC will perform an independent determination of thrust using a rocket exhaust pitot survey. Also, AEDC will conduct radiometric measurements that involve UV-VIS-IR spectral coverage using several spectrometers and infrared images. These measurements are used to determine rocket exhaust temperature and plume composition. Integration and testing of the N_2O catalyst reactor is now required to complete the NOP rocket system.

CATALYST REACTOR DESIGN, TESTING AND RESULTS

In the following sections the catalyst development, material selection process and catalyst preparation are discussed. A description is also given of the various experimental set-ups and testing that were required to evaluate a suitable catalyst candidate for ignition of the NOP rocket.

CATALYST DEVELOPMENT

The development of a catalytic reactor to efficiently decompose N_2O for propane autoignition is central to this research effort. The effort has two goals: to develop a catalytic reactor for the NOP rocket ignition testing and to research all candidate catalyst materials to search for an optimum material (or combination of materials) for a space prototype rocket engine.

Nitrous oxide decomposes exothermically with adiabatic decomposition temperature reaching $\approx$ 1640°C, (2984°F).[xvii] This decomposition is accelerated by a catalyst. Free oxygen available by nitrous oxide decomposition can then be combusted with a wide variety of fuels. Studies have been conducted to develop catalysts that accelerate its decomposition. The ideal chemical reaction for the decomposition of nitrous oxide results in the formation of nitrogen and oxygen according to the following reaction equation.

$$N_2O(g) \rightarrow N_2(g) + \frac{1}{2} O_2(g) + Heat. \qquad (4-1)$$

However, heat input is required to initiate the decomposition reaction. In the case of thermal decomposition, the activation energy barrier for nitrous oxide is about 250 kJ/mole. There are other intermediate chemical reactions that can lead to oxides of nitrogen, such as NO and NO_2, that are undesirable if complete decomposition is to be achieved.

In order to attain homogenous reaction rates, the gas must be heated above its auto-decomposition temperature, unless a heterogeneous surface such as a catalyst is incorporated. Catalysts are designed to lower the activation energy barrier, thus allowing the decomposition to occur at much lower temperatures. The principal catalytic action can originate from charge donation into the anti-bonding orbitals, weakening the N-O bond and thereby lowering the activation energy and thus the reaction temperature.

In the following sections the catalyst material selection process, the various catalyst experimental set-ups, and the procedures for the catalyst preparation are discussed.

CATALYST MATERIAL SELECTION PROCESS

The search for a catalyst material followed a logical path through the periodic table, considering the commonly known catalytic elements, including platinum (Pt), palladium (Pd), rhodium (Rh), and iridium (Ir). Various catalyst combinations were tested, over a range of initial pressures and reactor lengths. These catalysts include a platinum monolith, granular tungsten carbide, rhodium (0.17% granular), gold, platinum/palladium monolith, iridium (granular) and a Shell 405-Ir based catalyst bed. Each of these catalysts was preheated to various temperatures (122°F, 303°F, 398°F, 401°F and 662°F) using a linear temperature controller to determine the minimum light-off temperature. Catalyst activation requires a minimum initial temperature, with activation increasing as temperature increases. Instabilities occur at temperatures above a given value, which is material dependent.

The crystalline solids of primary catalytic interest, called aluminosilicates, incorporate Al, Si, and O. Naturally occurring minerals and many solids prepared in the laboratory exemplify this class. Zeolites are microporous inorganic compounds, mainly aluminosilicates, which exhibit crystal structures containing pores and voids large enough to permit the diffusion of organic molecules. Because of such unusual crystal structure, zeolites were widely employed as molecular sieves and for ion exchange as they commonly contain relatively loosely bound cations (i.e. positive ions) in their pores, which can be readily exchanged with other cations from solution. As polymers become more highly cross-linked and rigid, they lose this solution-like character, and their physical properties approach those of inorganic solids. However, it is in the field of heterogeneous catalysis that the most important applications of these materials can be found. Certain positions on the inner walls of the zeolite micropores can behave as active sites where catalytic conversions can take place. Moreover, since the micropores are very uniform and in the same size range as small molecules, zeolites can exhibit specificity and selectivity in adsorbing or rejecting molecules based upon differences in molecular shape, size and polarity. The diffusion and adsorption steps precede the chemical reactions at the active sites. Because the zeolites have well-defined crystalline structures, the catalytic groups in them are relatively well understood.

ZSM-5 zeolite is a medium-pore zeolite with ellipsoidal tubular pores with maximum aperture of 0.56 nm. This zeolite has received great interest because of its optimum performances as a solid acid catalyst in various industrial processes. The active sites are located both at the external surface of the crystallites and in the micropores. Often the internal surface developed by the porous channels is much larger than the external surface. The internal to external surface area ratio affects both the activity and the selectivity of the zeolite when it is used as a catalyst. The presence of molecules in the pore channels may drastically reduce the activity of zeolites and modify the selectivity in limiting the accessibility of the

internal active sites to the reactants. Metal cation loaded zeolites have recently received great attention due to their activity in the decomposition and reduction of nitrogen oxides. These solids are very complex due to the presence of two distinct phases, the one crystalline (zeolite) and the other that can be amorphous or crystalline (metal oxide), having different chemical compositions and physio-chemical properties among others, is the microstructure.

Metals loaded zeolites have been used as catalysts for a wide range of chemical reactions, such as hydrogenation, oxidation, isomerization and cracking of various feedstocks. For the selective catalytic reduction of nitrous oxide with hydrocarbons, transition metal ion exchanged zeolites are generally more active than the relevant supported catalysts since zeolites can disperse the metal at the atomic level. Recently, many studies have focused on the direct decomposition of nitrous oxide. Sivaraj *et al.*, 1988, Egerton *et al.*, 1974 and Swamy *et al.*, 1992 had reported that several metal oxides, mixed metal oxides and perovskites showed some activity for nitrous oxide decomposition, but the reaction rates were too low to have any significance. Sobolev *et al.*, 1993 has reported on studies conducted on several metal zeolites towards nitrous oxide decomposition. In 1992, Li and Armor reported that selected metal exchanged zeolites, principally copper, cobalt, rhodium or palladium on ZSM-5 were very active for N_2O decomposition. In 1998, Kannan and Swamy reported that calcined copper, cobalt or nickel hydrotalcites were effective catalysts, the activity of the catalyst being strongly affected by the temperature at which the hydrotalcite is activated. It has been reported that the catalytic activity of copper and cobalt based catalysts were higher than noble metal-exchanged catalysts such as rhodium and ruthenium. However, most of these studies have been carried out in the absence of hydrocarbons.

This research focused on the catalytic activity of copper and cobalt based catalysts for the direct decomposition of nitrous oxide, but mainly on the activity for the selective reduction of nitrous oxide in the presence of propane. Vannice,[xviii] 1999, showed that low temperature catalytic decomposition of ppm levels of nitrous oxide in the presence of hydrocarbons is possible. At high concentrations of nitrous oxide, previous researchers have found that the high adiabatic flame temperature of 1640^oC caused the catalytic metal to literally vaporize from the support, reactively combine with the ceramic support (sinter), or even melt the ceramic support leading to eventual failure or deactivation. These types of phenomena have also been observed during this research. In 1990, Iwamoto *et al.* and Held *et al.* have shown that the most effective catalyst for this reaction is Cu-ZSM-5. However, this catalytic system suffers from several disadvantages. It appears that the Cu-ZSM-5 catalyst does not show high temperature stability for practical use. In comparison, a catalytic system of Co-ZSM-5 is proposed to be much more attractive. Armor and Farris demonstrated its higher hydrothermal stability, and stated that the loss of catalytic activity due to water vapor is completely reversible. In this research endeavor, tests were carried out on copper and cobalt based zeolite catalysts. However based on this brief overview it is important to note that other researchers in the field do not incorporate promoters. The purpose of the promoter is to alter the chemical behavior of the catalytic metal (cobalt, cobalt-copper and copper) to control their absorptive chemistry towards one of the two reactants (nitrous oxide and propane or propylene). Promoters are often added in an attempt to reduce the auto-ignition temperatures of the reactants, i.e. light-off temperatures.

Iridium, platinum, rhodium, ruthenium, copper and cobalt based catalysts have shown promising activity for the stoichiometric catalytic decomposition of nitrous oxide at low temperatures ($<250^oC$). Based on both a review of the literature and experimentation, it was found that cobalt deposited on ZSM-5 exhibits activity in the thermal decomposition of nitrous oxide. Since zeolites have both acidic and basic sites in their structures, addition of alkali promoters like lithium, sodium, potassium, cesium and rubidium alters their basicity bringing about changes in the adsorption properties of the base metal, cobalt in this

case. For a catalyst to effectively lower the activation energy of a chemical reaction, at least one of the reactive species must be chemically adsorbed onto its surface, termed chemisorption. This adsorption dissociates or significantly alters the chemical bonds, generating reactive species that can be stabilized at the catalytic surface. These chemical species are in many cases similar to those that would be generated during the auto-decomposition of nitrous oxide, but at much lower operating temperatures.

The initial focus of this research was to determine the adsorption behavior, and catalytic activity of different catalysts towards nitrous oxide decomposition. Based on the data obtained from these experiments a pre-screening process was adopted with the objective of focusing on catalysts that would show high levels of activity towards the selective catalytic reduction of nitrous oxide with minimum preconditioning requirements. Catalysts with a base metal such as platinum, palladium, iridium, gold, rhodium, copper and cobalt were selected and tests conducted to determine their relative activities.

During the latter part of our research into catalyst materials, work focused on the development of lower temperature and reduced cost catalytic nitrous oxide reduction approaches. The cobalt, cobalt-copper and copper catalysts were prepared and tested in laboratories at UAH by incipient wetness techniques, while others were available commercially. The incipient wetness, or capillary impregnation technique[xix] utilizes the process whereby a precursor salt is dissolved in an amount of water equal to the water pore volume, determined by slowly adding water to a carrier until it is saturated. Once dried, the carrier pore structure is assured to contain the required amount of catalytic species.[xix] Those catalysts with a 1-1 notation contained an equal volume fraction of the catalytic metal(s) and sodium promoter deposited on the specified substrate.   The catalysts were then reduced at 275°C (oxidation temperature) under flowing compressed air in an oxidation reactor to oxidize the metal nitrate and sodium carbonate promoter. Most catalysts include a promoter to from a co-precipitate phase.

Currently, the research effort headed by UAH continues examining the light-off temperature of the catalysts mentioned above and new versions that show increasingly lower bed temperatures required for decomposition. For example, catalysts prepared using cobalt appear to have greater activity than copper based catalysts. ZSM5 based catalysts appear to have greater activity than Y-Sodium zeolite. Results from the various catalyst materials used in the prototype reactor design showed several candidates that ultimately proved successful in our testing. The exact "recipe" or "recipes" that are the best candidates for commercialization is a trade secret and under review for patent protection.

NOP ROCKET PERFORMANCE TEST RESULTS

During this development program, experiments were conducted for the purpose of assessing rocket performance, determining the optimum L* for the given injection scheme, and evaluating rocket ignition using catalytic decomposition of nitrous oxide. These steady state performance tests were performed in the atmospheric test stands (Test Stand 1 and 2) at UAH on a rocket with a truncated nozzle (NOP Rocket 1 and 2). The rocket test article was a copper heat sink design consisting of a preliminary injector design, combustor and nozzle components. To compensate for the non-optimal injector, combustor L* was set sufficiently large to accommodate atomization, evaporation, mixing and combustion. It should be noted that the NOP Rocket 2 was tested at Test Stand 2, but combustion instabilities, perhaps due to inappropriate L*, coupled with a non-optimal injector, mitigated use of this rocket in favor of NOP Rocket 1. The performance data presented in this section is therefore for the NOP Rocket 1 test article evaluated on Test Stand 2.

The rocket engine (NOP Rocket 1) was tested with L*= 1, 2, and 3m. At L*=1m, NOP Rocket 1 showed degraded performance. The L*=3 m was used for this injection scheme, and L* can only be reduced by improving the injector design. The swirl injector was chosen for these concept development tests since it provides reasonable performance without the expense of complex machining processes. A more elaborate injection scheme will be developed as a step to higher technical readiness levels (TRLs).

Heat transfer losses experienced during ground testing will be mitigated in a prototype rocket by designing to maintain a higher wall temperature. By using flight materials instead of heat sink copper, proper use of coatings and insulation, and possibly regeneratively heating the fuel, a c* efficiency of 96% should be achievable, along with correspondingly higher specific impulse approaching that of the theoretical values.

A compilation of results from the tests is shown in Figure 7 through Figure . These plots display some of the performance data and typical rocket performance parameters generated from the reduced data. For comparison purposes, plots of the theoretical vacuum $I_{sp,vac}$, I_{sp}, and c*, obtained from a NASA chemical equilibrium code[xx], are presented. Initial results are promising, showing rocket performance consistent with theoretical prediction taking into account the effects of heat transfer and nozzle area ratio.

Figure 7 shows a plot of specific impulse versus mixture ratio. The data are displayed with symbols and uncertainty bars, while theoretical predictions are displayed by various colored lines. Heat loss was calculated and included with the theoretical predictions. One method used the Bartz analysis[xxi], where a heat loss of 586.7 Btu/lb$_m$ for N_2O and C_3H_8 each was calculated for a wall temperature of 150°F and used to generate the heat loss curves in 7-10, and 12. The second method assumed a lumped capacitance model for the combustor and rocket nozzle, with an estimated 377.8 Btu/lb$_m$ for the heat loss, for N_2O and C_3H_8 each. It is evident from these plots that heat loss to the cold heat-sink rocket model can account for the difference between the ideal rocket performance and that measured. Other losses not accounted for in the theoretical predictions include total pressure loss in the combustion chamber, non-axial thrust losses due to flow angularity at the exit of the truncated nozzle, and incomplete combustion.

Figure 7 shows the I_{sp} as a function of mixture ratio for L*=2m and 3m for both Test Stand 1 and 2. The L*=3m NOP Rocket 1 tested on Stand 2 displays about a 7% drop in I_{sp} compared with the Test Stand 1 tests with the same rocket. Reasons for this difference may be attributed to uncertainties in mass flow rate and thrust measurement taken at Test Stand 1. The maximum I_{sp} measured at Test Stand 1 is 181.5 sec at an MR=4.89, compared with a maximum I_{sp} of 171.85 sec at MR=6.83, measured at Test Stand 2.

From Figure 8, the maximum $I_{sp,vac}$ measured at Test Stand 1 (210.4 sec) was at a L*=2m and MR=5.44, with a fairly "clean" chamber pressure trace, without large pressure oscillations and chugging observed at the higher mixture ratios (6<MR<8.68). The maximum $I_{sp,vac}$ measured at Test Stand 2 (204.1 sec) was at a L*=3m and MR=6.83.

Figure 9 shows that at the A/A* of 2.21, the experimental data is within 18% of the theoretical curves, which do not account for heat losses, and within 11% of the theoretical data that does account for heat losses, as calculated by using Bartz analysis.[xxi] At the design area ratio of 50, for space propulsion

applications, the NOP rocket, with lower heat losses than the heat sink test article, and improved injector design should approach the theoretical vacuum I_{sp} of 312 sec for MR=8.3.

Figure 10 shows a plot of c* versus the mixture ratio where the c* varied from 4460 ft/sec at MR=4.89 to 4866 ft/sec at MR=8.68. Heat loss calculations (via the Bartz analysis[xxi]) used in adjusting the theoretical c* curves, correlate well with the experimental c* data for the Test Stand 2. The c* efficiencies, between 82% and 93%, reflect a combination of all system losses, including heat loss and non-optimal propellant injection (affecting atomization, vaporization, mixing, and combustion). As shown in Figure 11 for Test Stand 1, η_{c*} varied from 87.9% at MR=4.89 to 92.7% at MR=5.44; and for Test Stand 2, η_{c*} varied from 81.8% at MR=6.82 to η_{c*}=93.2% at MR=8.68.

Figure 12 shows the variation in the NOP Rocket 1 thrust coefficient (article 1, evaluated on test Stand 1 and 2) as a function of mixture ratio for two combustor lengths, L* (2m and 3m). The average thrust coefficient measured on Test Stand 1 is 1.21, compared with a theoretical value (neglecting heat losses) of 1.27, and a measured value of 1.14 on Test Stand 2, compared with a theoretical value (neglecting heat losses) of 1.26.

Data is shown for L* of 2m and 3m and indicates no real change in performance between the two combustor lengths, with respect to I_{sp}, $I_{sp,vac}$, c* and η_{c*}. However, L* and mixture ratio are not the only factors affecting engine performance. Increasing N_2O mass flow rate above a given value leads to larger chamber pressure oscillations and a decrease in c* efficiency. As the mass flow rate of N_2O increases from $\dot{m}_{N2O}$=.232 lb$_m$/sec (η_{c*}=.887) to $\dot{m}_{N2O}$=.265 lb$_m$/sec (η_{c*}=.818), P_c oscillations increase from ~17 Hz (+/- 4.55 psia standard deviation) to ~ 28 Hz (+/- 13.1 psia standard deviation).
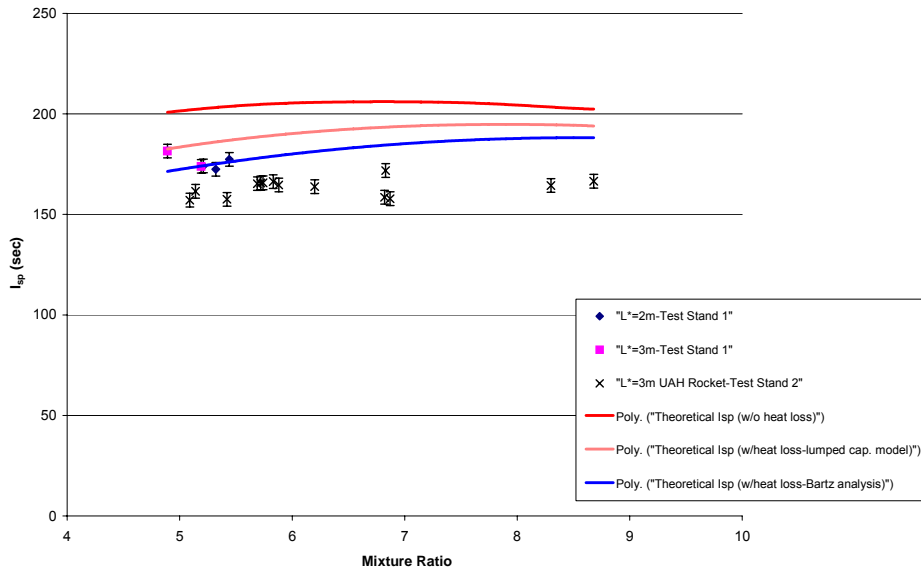
Figure 7: Specific impulse I$_{sp}$ as a function of mixture ratio (two different combustor L*).
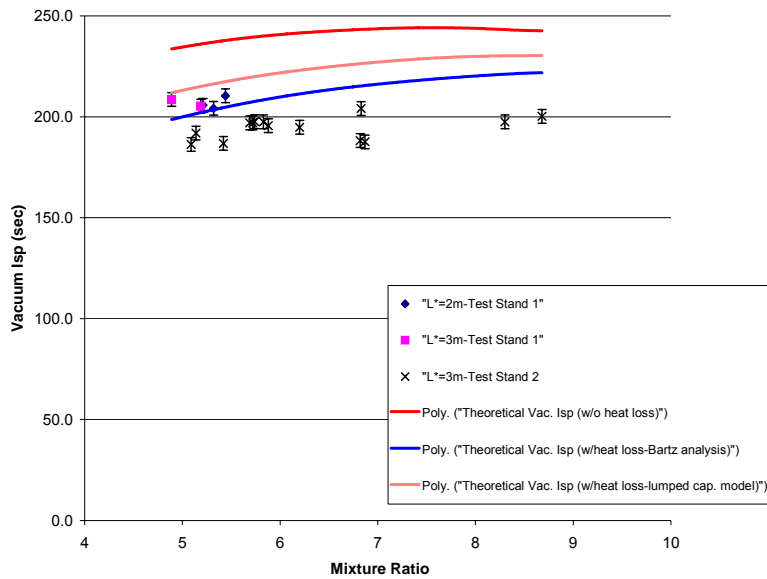
Figure 8: Vacuum I$_{sp}$ versus mixture ratio (two different combustor L*) @ sea level A/A*.

$$I_{sp\,vac} = I_{sp} + P_{amb}\,A_{exit}\,/\,Mdot$$

Legend:
- MR=8.3, equil
- MR=6, equil
- "Expt'l Data-Test Stand 2,MR=6.2"
- "Expt'l Data-Test Stand 2,MR=8.3"
- "Theor. Isp Vac.(w/heat loss-Bartz analysis);MR=6.2"
- "Theor. Isp Vac.(w/heat loss-Bartz analysis);MR=8.3"
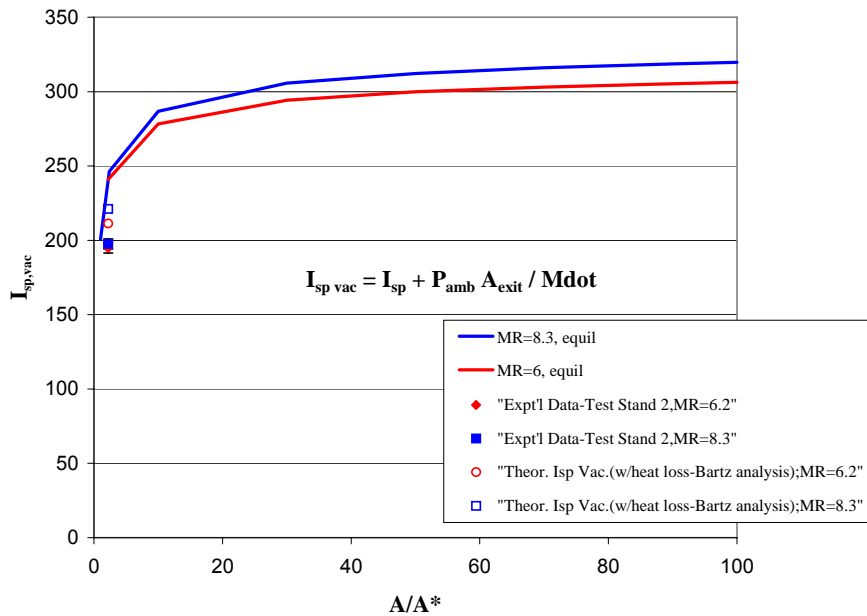
Figure 9: Theoretical and experimental data for vacuum I_{sp} as a function of A/A*.

Legend:
- "Avg.M.R. L*=2m-Test Stand 1
- "Avg.M.R. L*=3m-Test Stand 1"
- "L*=3m-Test Stand 2"
- Poly. ("Theoretical c* (w/o heat loss))
- Poly. ("Theoretical c* (w/heat loss-Bartz analysis)")
- Poly. ("Theoretical c* (w/heat loss-lumped cap. model)")
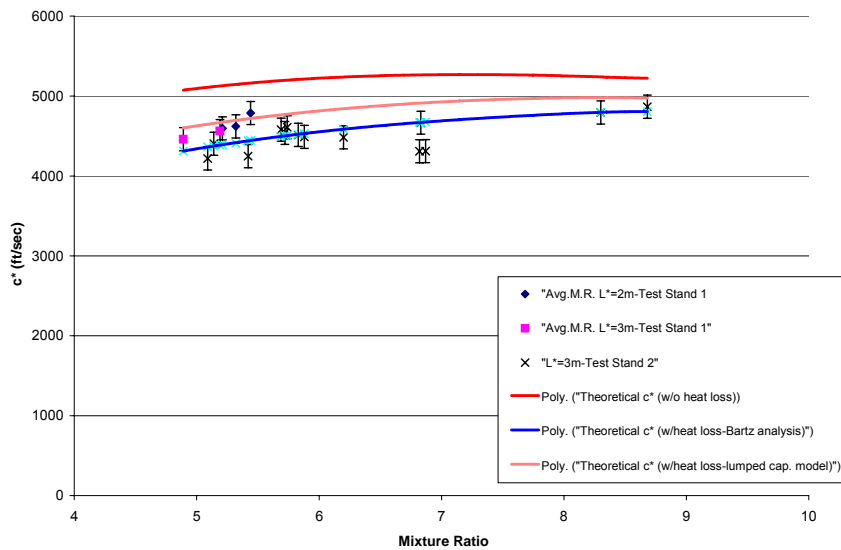
Figure 10: Rocket c* as a function of mixture ratio (two different combustor L*).

Figure 11: Rocket c* efficiency as a function of mixture ratio (two different combustor L*).
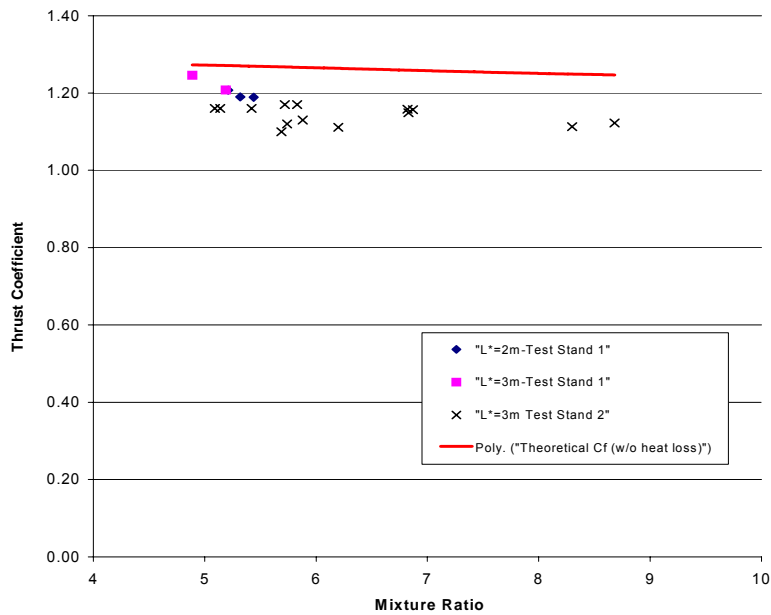
Figure 12: Rocket thrust coefficient as a function of mixture ratio (two combustor L*).

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CONCLUSIONS

A new rocket test stand facility, equipped with palletized propellant feed systems, 1000 lbs$_f$ thrust stand, and data acquisition systems, was built to test a nitrous oxide/propane (NOP) rocket engine. The NOP rocket was tested over a range of mixture ratios (4.89<M.R.<8.68). A unique ignition concept using catalytically decomposed nitrous oxide to auto-ignite propane, was explored and various catalyst materials were evaluated. Shell-405 and cobalt based ZSM-5 showed promising reactivity, demonstrating sufficient decomposition of N_2O to ignite hydrocarbon fuels. Laboratory experiments with the catalyst reactor have shown that N_2O catalytic decomposition is achievable at 400 °F for pure nitrous oxide flowing over Shell 405, and, with the use of trace amounts of a hydrocarbon (e.g. propane or propylene), this temperature is lowered to approximately 200 °F. Recent catalyst "recipes" show even lower temperatures and shorter decomposition reaction times in addition to robust longevity.

In addition to developing the catalyst ignition system, NOP rocket performance was experimentally determined to match well with theoretical predictions, with proper modeling of heat losses. This work shows that a respectable vacuum I_{sp} of over 300 seconds can be achieved with this rocket engine technology.

Radiometric measurements were also used to determine rocket exhaust temperature and plume composition and plume pitot probe measurements provided another method for verifying thrust data. Future work will focus on demonstrating NOP rocket ignition using catalytically decomposed N_2O, and on exploring the use of catalytic decomposed N_2O for monopropellant rockets as well as torch igniters.

A traversing, water-cooled rake with a single, integral spherical nose tip designed with a stagnation point pressure sensing tube was used to obtain pitot pressures during test firings of the nitrous oxide/propane engine at UAH on 15 March 2001. The probe assembly survived the firings with no melting or erosion. Data were obtained on Runs 2, 4, 8, 9, and 10. However, the chamber pressure varied to such an extent on Runs 2, 4, and 8 to preclude further analysis of this data. The chamber pressure was relatively steady during Runs 9 and 10, and the data from these runs were used to determine thrust for comparison to the thrust stand measurements using the procedure described above. The pitot pressure derived thrust as either between the minimum and maximum thrust stand values over the time of the rake traverse, or slightly above the maximum. The base pressure was shown not to be important in these comparisons. In general, the pitot pressure derived thrust values agreed with the thrust stand data to better than 5%. However, the variations in chamber pressure (and thus thrust) are too great to draw firmer conclusions about the validity of the pitot pressure method.

Optical data was taken of the NOP rocket tests on 27 March 2001 for both catalyst ignition and spark plug ignition. The data include UV thru MWIR spectra, and MWIR and LWIR imagery. The imagery shows flow details such as the Mach cell structure and mixing layer of the exhaust plume, as well as indications of the presence of soot. The spectral data allow the identification of specific emitters including CO_2 and H_2O as well as hydrocarbon fragments in the infrared, Na and K in the visible wavelengths, and NO, CH, C_2, and OH in the UV.

In conclusion, the use of nitrous oxide and propane as a rocket propellant combination has many potential applications for which it is well suited. This propellant combination is highly reactive when

catalyzed and combined, yet benign and nontoxic in storage. Its storage density and specific impulse are suitable for many missions currently employing hypergolic, toxic, or cryogenic propellants. The benign nature of the propellants holds promise for reducing launch costs due to that incurred as a result of the volatile nature of current rocket propellants.

The alternative uses for nitrous oxide as a monopropellant lead to other space applications where nitrous oxide is highly competitive with existing systems. The ability to decompose nitrous oxide with the same flight proven catalyst that has decomposed hydrazine in space for decades paves the way for an easy transition to its use. The undeniable superiority of nitrous oxide as a cold gas propellant over both nitrogen and helium completes the package, making possible a true multi-modal propulsion system that uses the same propellants for all space applications.

It is the belief of the authors that the NOP propellants should be pursued with continued research that targets the most appropriate mission applications. This applied research should be paralleled by a scientific effort to understand and maximize the capabilities of catalytic decomposition of nitrous oxide. The ability to control these reactions will accommodate better reactor design for real systems.

ACKNOWLEDGEMENTS

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