NITROUS OXIDE MONOPROPELLANT GAS GENERATOR DEVELOPMENT

K. A. Lohner and Y. D. Scherson
Department of Mechanical Engineering
Stanford University
Stanford, CA

B. W. Lariviere
Pratt & Whitney Rocketdyne
Canoga Park, CA

B. J. Cantwell and T. W. Kenny
Stanford University
Stanford, CA

ABSTRACT

Research is ongoing at Stanford University on the catalytic decomposition of nitrous oxide as a monopropellant for propulsion and power applications. A capable test facility has been constructed, and a robust subscale test article has been fabricated to carry out these experiments. Several different catalyst beds have been hot fire tested in this facility since the research began in mid-2006. High steady-state c* efficiency has been demonstrated at bed loadings up to 15 kg/m^2/sec, and hot fire durations on a single catalyst bed have exceeded one hour, showing no signs of degradation.

Three different device configurations have been tested, demonstrating a path to scaling-down the device to MEMS-fabricated micro-scale thruster, as well as scaling-up to a powerful gas generator.

NOMENCLATURE

A_o	=	flow control orifice throat area
A_s	=	surface area of test article
A_t	=	test article chamber throat area
c*	=	characteristic exhaust velocity
C_d	=	discharge coefficient
C_F	=	thrust coefficient
F	=	thrust
h_g	=	convective heat transfer coefficient
I_{sp}	=	specific impulse
$\dot{m}$	=	mass flow rate
P_1	=	upstream pressure
P_c	=	test article chamber pressure
P_{crit}	=	static pressure at orifice throat
$\dot{Q}$	=	heat transfer rate
S.S.	=	steady-state
T_c	=	test article chamber temperature
T_{skin}	=	surface temperature of test article
T_{surr}	=	ambient temperature of surroundings
Y	=	expansion factor
ε	=	emissivity of test article
ρ	=	density of the gas
σ	=	Stefan-Boltzmann constant

INTRODUCTION

There is renewed interest within academia, industry and government agencies in storable, non-toxic propellants for a variety of aerospace applications. Of particular interest – due to its simplicity, low-cost, and safety – is a catalytic gas generator device capable of decomposing monopropellants such as nitrous oxide and/or very lean nitrous oxide / fuel mixtures.

Building off of previous work that has been performed at Surrey Space Center[2,3,4,5,6], GASL[7], and Tsinghua[8], preliminary studies have indicated that scaling such a device down to the meso- or micro-scale could enable benefits in thrust-to-weight, start-up transients, cost, and robustness, while still yielding a high level of performance[9]. A basic schematic for such a device is shown in Figure 1. The modular design allows for its use in a wide range of propulsion and power applications, such as a(n):

- Compact pressurization source for a propellant tank.
- Reliable, simple, and reusable igniter for a larger rocket engine.
- Portable hot gas generator for a variety of applications, including power generation.
- Oxidizer source for an auto-ignitable bipropellant liquid or hybrid rocket engine.
- Storable, self-pressurizing monopropellant thruster propulsion system for satellites and other spacecraft (attitude control, station-keeping, nano-satellite propulsion, and thrust vector control), as a replacement for toxic hydrazine thrusters or power-consuming electric propulsion systems (0.1 to 10 N of thrust).
- Compact life support system; the exhaust from N2O decomposition forms a fully breathable gas mixture of nitrogen and oxygen.

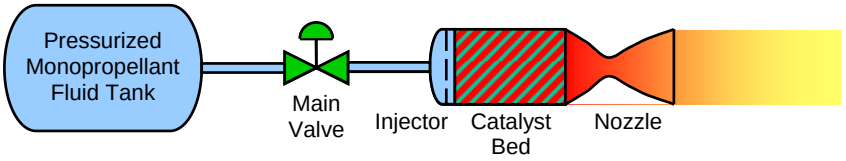


Figure 1. Basic schematic of a monopropellant gas generator.

Nitrous oxide is a non-toxic chemical that is stable at normal conditions, and it is compatible with common structural materials. It can be stored as a compressed gas or as a liquid over a wide temperature range. The storage pressure of the liquefied gas is approximately 51 atm (750 psi) at 25°C. Commonly known as laughing gas, nitrous oxide is a 'green propellant' that is easy handled and stored. The decomposition of nitrous oxide results in the formation of nitrogen and oxygen:

$$N_2O \rightarrow N_2 + \tfrac{1}{2}O_2 + 1864\,kJ/kg \quad (1)$$

This decomposition can be accelerated by a catalyst, reducing the preheat temperature requirement to as low as 200°C to initiate decomposition[2]. Nitrous oxide decomposes exothermically with an adiabatic decomposition temperature of approximately 1640°C. Theoretical c* performance of the monopropellant is 1106 m/sec at 7 atm chamber pressure. Research has shown that after an initial input of heat to initiate the catalytic decomposition, the reaction can become self-sustaining[2]. The free oxygen released by nitrous oxide decomposition can also be combusted with a wide variety of fuels when used in a bipropellant system.

Goals for the research being performed at Stanford include:

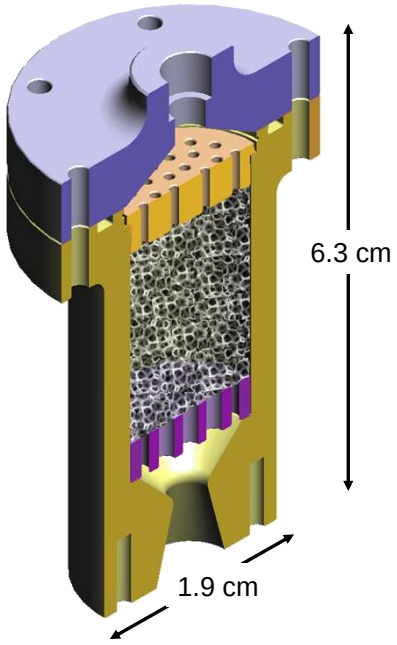
- Minimizing the preheat temperature requirement for the reaction initiation.
- Minimizing the thermal capacitance of the system to enable fast start-up transients.
- Determining optimal catalyst bed length while minimizing the pressure drop and the amount of catalytic material required.
- Optimizing the bed loading parameter.
- Maximizing the c* efficiency of the reaction.
- Maximizing the exhaust gas temperature for application as an igniter or hot gas generator.
- Demonstrating long-duration decomposition trials (greater than 1 hour).
- Demonstrating re-start capability.

SUB-SCALE DEVICE

Initial work began with the design, fabrication, and testing of a 1.27 cm (0.5 inch) diameter axisymmetric metallic gas generator device to explore the operational parameters of the reaction.

DESIGN

A cutaway 3-D model of the subscale device is shown in Figure 2 as well as a table of the operating conditions and dimensions to which it was designed. The construction of the device largely employed high temperature oxidation-resistance superalloys and refractory metals. It was designed to be radiation-cooled so that is stays below the material strength limits at pressure. The 2-piece flange was sealed by use of a copper crush gasket. The catalysts used in this investigation are proprietary metal oxide and ceramic materials.



Design Point Operating Conditions

Chamber Pressure	24 atm
Chamber Temperature	1300 °C
Mass Flow Rate	5 gram/sec
Throat Diameter	1.8 mm
Thrust	8 N
Specific Impulse	167 sec

Figure 2. Cutaway 3-D model of subscale gas generator (left) and the associated design point operating conditions (right).

Temperature and pressure ports were welded to the inlet and chamber of the test article (see Figure 3). The thermocouples were inserted through the thermal stand-off tubes so that the tips protruded through to the flow centerline. The catalyst material was supported on the upstream and downstream sides by porous metal discs, which were in turn constrained by a retaining ring.

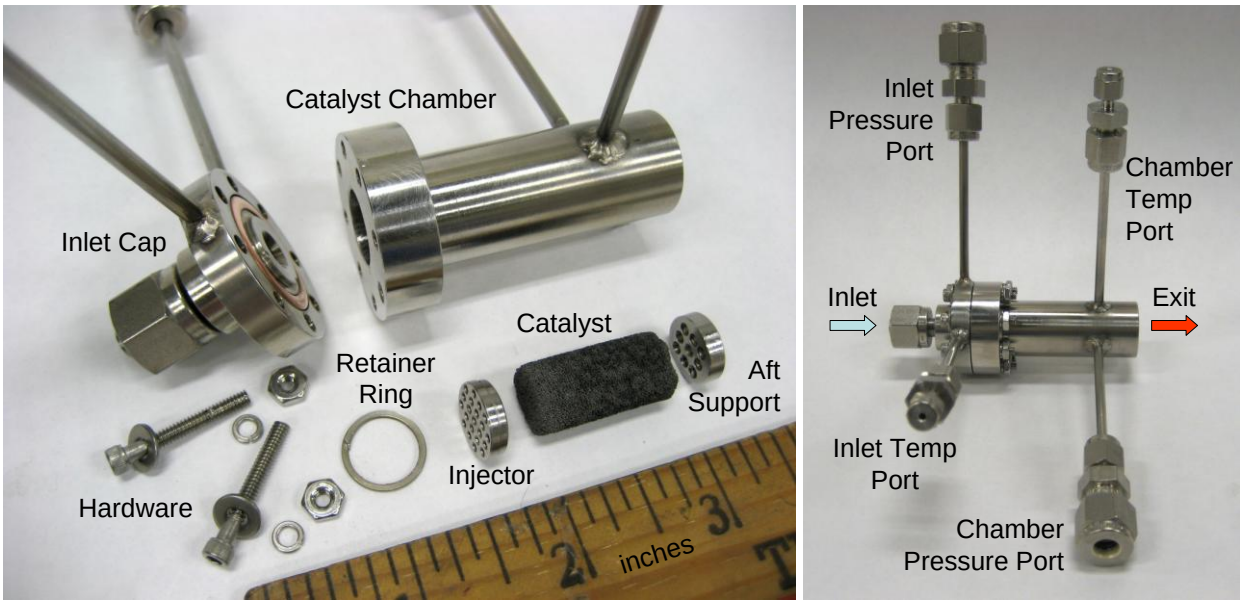


Figure 3. Completed subscale gas generator hardware shown disassembled (left), and assembled (right).

TESTING

Several different catalyst beds have been hot fire tested in this facility since the research began in mid-2006. The test procedure consists of preheating the catalyst bed with a glow plug immediately upstream of the test article until sufficient activation energy exists to initiate the reaction. Once the exothermic decomposition begins, a prescribed set of flow rates and chamber pressures are obtained by throttling the supply pressure upstream of the sonic orifice. The objectives of the test matrix were to determine the decomposition efficiency and bed loading limits, both the upper and lower values. Bed loading represents the mass flow rate of the fluid per unit cross-sectional area of catalyst bed.

At the highest bed loadings, the test article glows bright yellow in the central section and a very faint plume can be discerned (Figure 4). The test article is carefully examined after each test for signs of degradation and/or thermal fatigue. The design of the test article allows for easy disassembly and re-packing with new catalyst material when needed.

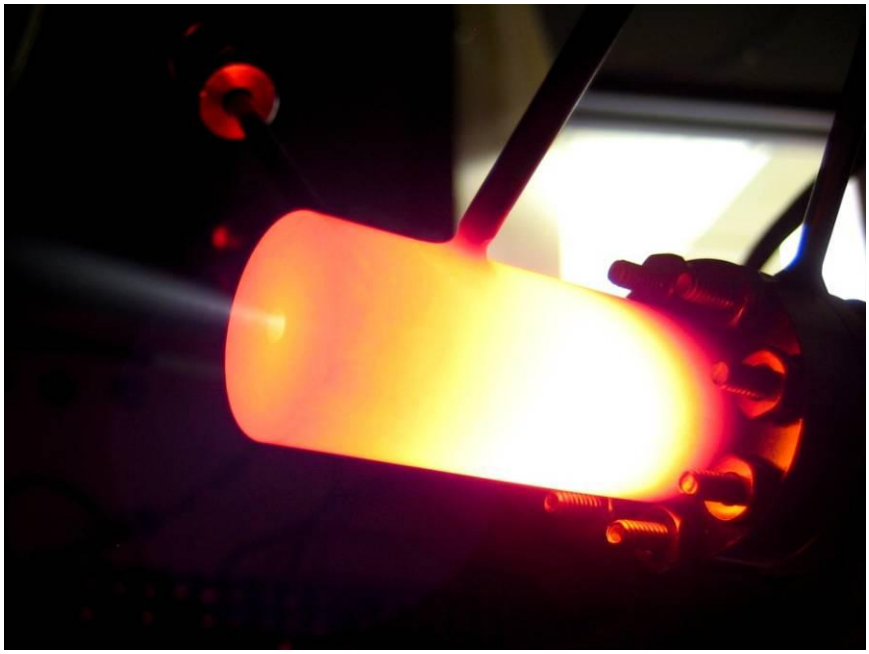


Figure 4. Close-up photograph of sub-scale catalyst bed operating at high bed loading.

For each time slice collected by the data acquisition system, instantaneous density is calculated based on the measured feedline pressure and temperature using the NIST database. This value is used to calculate the mass flow rate of the nitrous oxide, per the following equation:

$$\dot{m} = Y \cdot C_d \cdot A_o \sqrt{2 \cdot \rho \cdot (P_1 - P_{crit})} \tag{2}$$

Characteristic exhaust velocity is calculated over discrete areas of each test using the equation below:

$$c^* = \frac{P_c \cdot C_d \cdot A_t}{\dot{m}} \tag{3}$$

Thrust is calculated by the following equation, where the thrust coefficient, C_F, is determined by Chemical Equilibrium with Applications (CEA) software to be 1.25 for this design:

$$F = C_F \cdot P_c \cdot C_d \cdot A_t \tag{4}$$

Bed loading is an important parameter because the larger the bed loading limit, the smaller the catalyst bed required for a given propulsion level. This has strong weight-saving implications, particularly for on-orbit satellite propulsion systems, where both volume and mass are critical. Figure 5 plots c* efficiency and chamber temperature as a function of the bed loading parameter for various tests performed at Stanford. Radiation cooling of the test article at these temperatures results in significant heat loss to the surroundings, lowering the apparent c* efficiency. Calculations were made to correct for this effect.

As can be seen, the c* efficiency tends to drop off at bed loadings above 15 kg/m^2/sec, and chamber temperature appears to be at a maximum at bed loadings of approximately 10 kg/m^2/sec. At lower bed loadings, the heat loss to the system dominates and chamber temperature suffers as a result. At higher bed loadings, the reaction begins to quench as the decomposition front is pushed downstream through the catalyst bed.

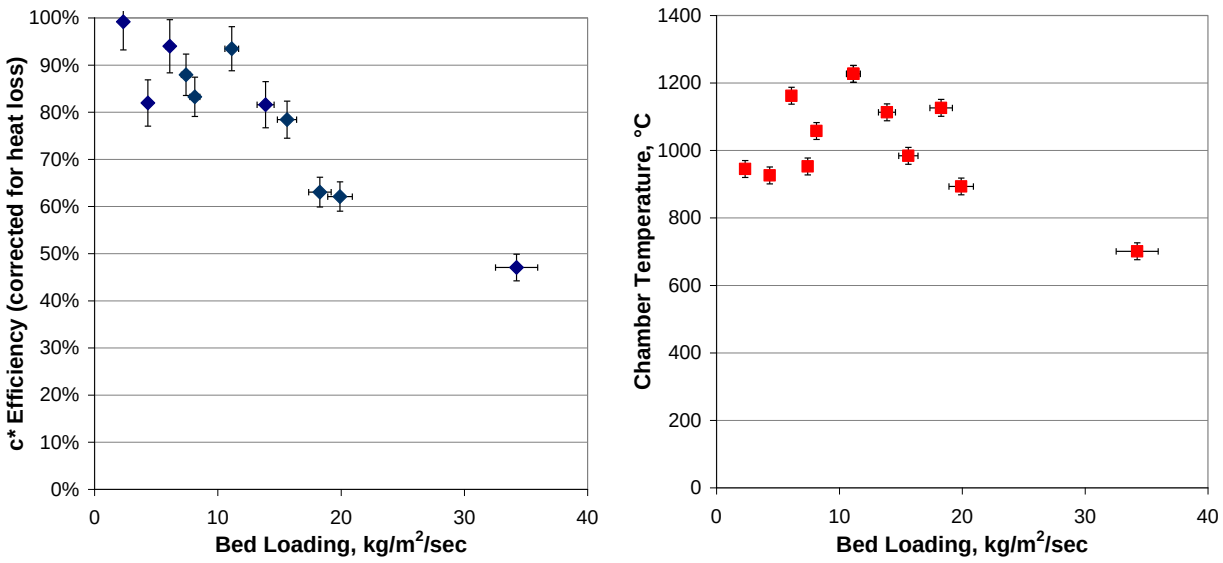


Figure 5. c* efficiency corrected for heat loss plotted versus bed loading (left), and chamber temperature plotted versus bed loading (right).

2-D PLANAR DEVICE

Based on the results of the sub-scale axisymmetric metallic device, a new device was fabricated and tested to explore the feasibility of an un-cooled MEMS-fabricated micro-gas generator.

DESIGN

The new MEMS-scale device was fabricated from monolithic silicon carbide (Figure 6). It allows for high temperature, high efficiency steady-state operation (thermally insulated). Additionally faster start-up transients may be achieved due to lower thermal mass combined with a close-coupled resistively-heated metal pre-heat coil.

This 5 cm long by 3 cm wide by 2 mm thick device housed a noble-metal-on-alumina pebble catalyst bed, restrained on the aft end with silicon carbide foam. The rectangular cross-section throat was sized to produce 3.4 atm (50 psia) of chamber pressure at a max flow rate of 0.5 gram/second. Kovar metal fluidic interconnects and instrumentation ports were brazed and bonded to the silicon carbide chamber with a ceramic bonding agent. A metal wire resistor coil was imbedded in the inlet plenum to provide the initial pre-heat to initiate the reaction. A thin graphite foil gasket was used seal the two halves of the device. Aluminum oxide felt was wrapped around the outside of the silicon carbide to insulate the reaction, and Hastelloy-X® clamps were used to hold the device together, as shown in Figure 7.

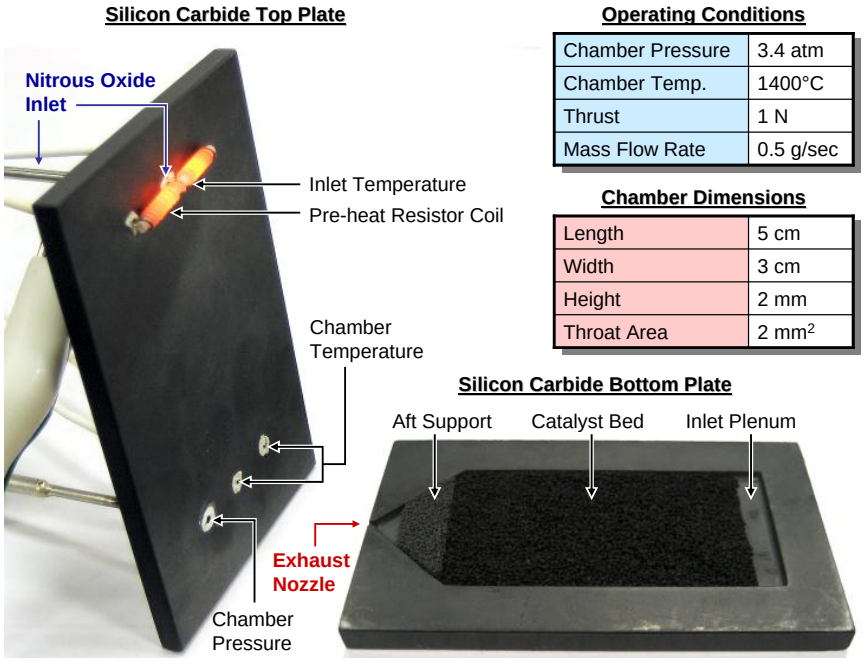


Figure 6. As-fabricated SiC device.

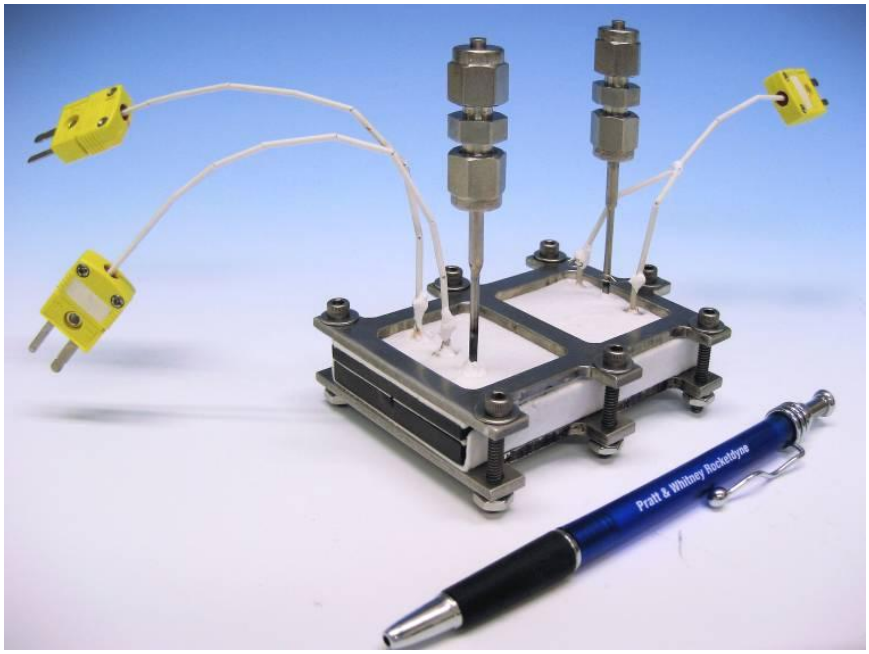


Figure 7. As-assembled SiC device.

TESTING

The assembled device was mounted to a thrust plate and plumbed into the same test stand as used in earlier testing[1]. Performance was as-predicted at mass flow rates up to 50% of the design condition. At chamber pressures above 2 atm, the high thermal and pressure gradients within the system caused sealing and structural problems. Nevertheless, good long-duration steady state data was

obtained at low power levels that confirmed the feasibility of this device configuration and material system (Figure 8).

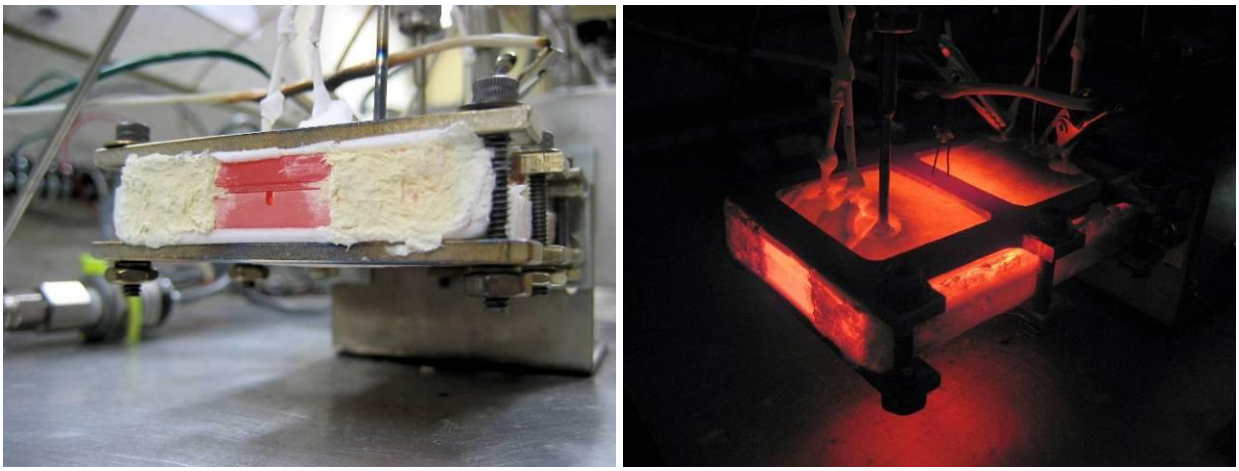


Figure 8: Hot fire testing of the silicon carbide 2-D planar device.

Twelve total tests were performed with this device, all using noble-metal-on-alumina pebble catalyst. Temperature and pressure test data is plotted in Figure 9 for a representative steady-state test. In this test, a bed loading of 5 kg/m^2/sec was sustained for a 13 minute duration, decomposing nitrous oxide at a c* efficiency of 71% (uncorrected for radiation heat loss). Initial bulk catalyst preheat temperatures of approximately 400°C were required to initiate the reaction before it became self-sustaining. This required approximately 100W of power to be supplied to inlet resistor at the beginning of the test. Steady-state chamber temperatures of over 800°C were achieved.

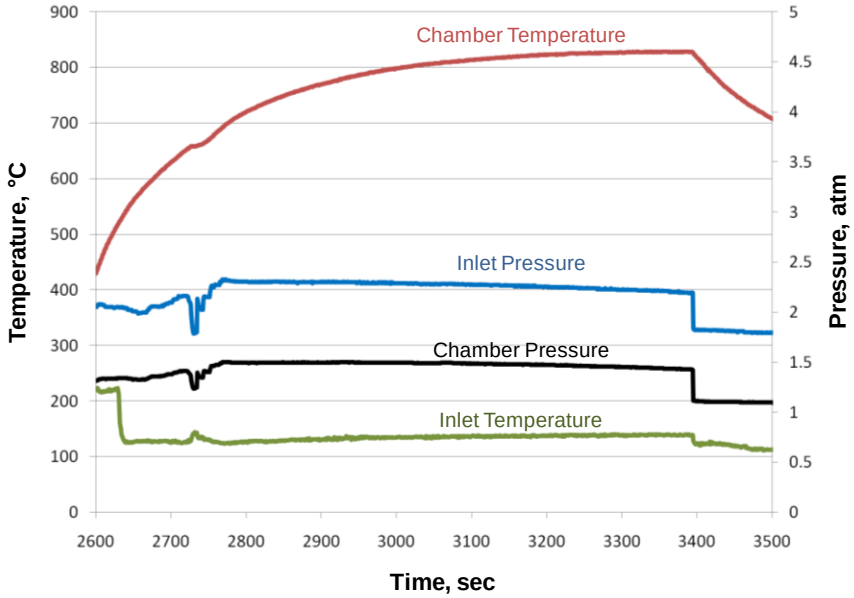


Figure 9. Silicon carbide planar device test #6 – pressure and temperature vs. time.

SCALED-UP DEVICE

In order to output a higher level of power and prove out applicability as a tank pressurization scheme, a 2.54 cm (1 inch) diameter scaled-up device was developed.

DESIGN

This device was designed to use the most optimal material system as determined through the subscale testing. Again, a noble-metal-on-alumina pebble-based catalyst system was selected so as to minimize the amount of active oxidation that occurred at high temperature (Figure 10).

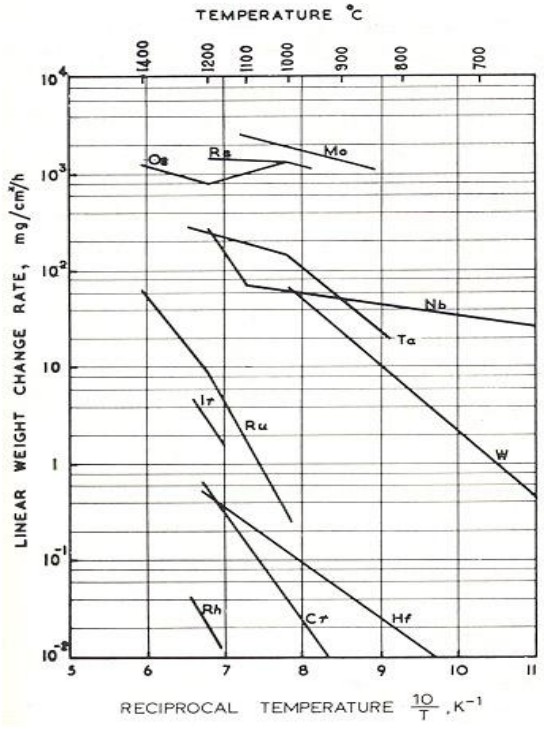


Figure 10. Oxidation of the refractory metals.

Scaling up the design of the sub-scale device, the 2.54 cm (1 inch) diameter catalyst bed was housed within a Hastelloy-X main chamber with a throat diameter of 2.54 mm (0.100 inches) (Figure 11). The design point was chosen to produce a chamber pressure of 17 atm (250 psia) at a bed loading of 15 $kg/m^2/sec$. A split ring flange and graphite face seal was used to seal the chamber up against the inlet flange. A Bosch Duraterm® ceramic glow plug was used to provide the initial pre-heat for the reaction. The catalyst was restrained on the aft end by a refractory ceramic foam disc supported on a ceramic distribution plate. Instrumentation ports and fluidic interconnects were welded onto the main body.

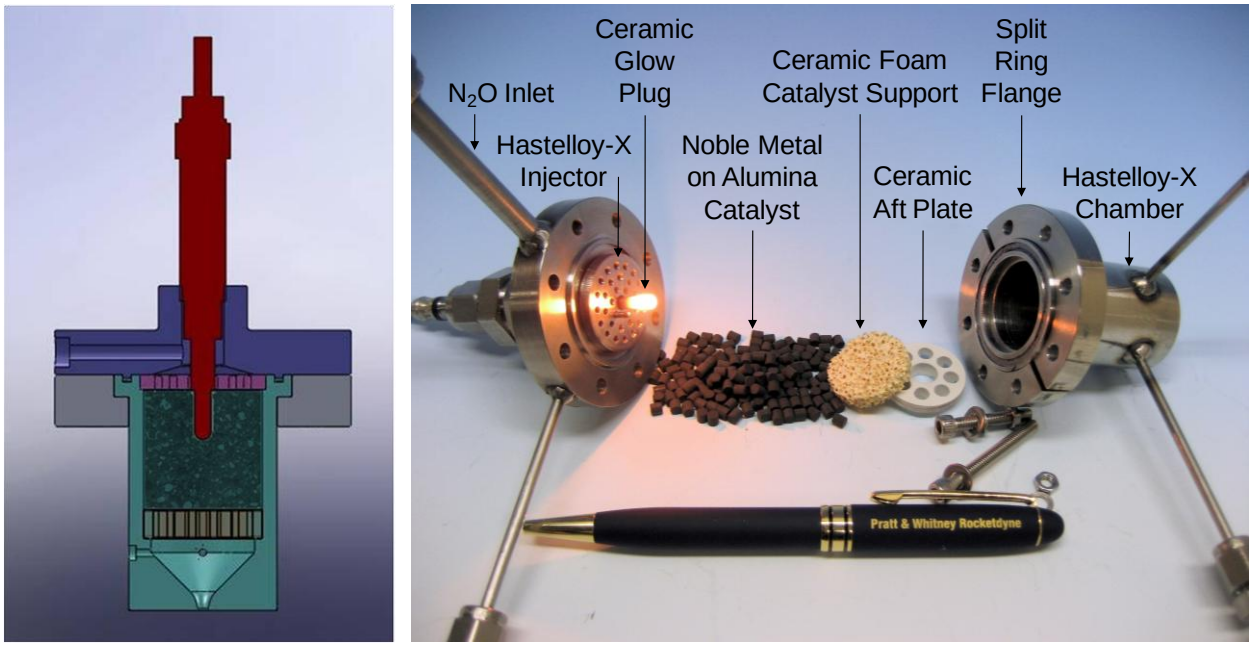


Figure 11. Design and pre-assembly of the scaled-up 2.54 cm (1 inch) diameter catalyst gas generator.

TESTING

In a similar fashion to the previous 2 device configurations, this gas generator was instrumented and plumbed into the test stand (Figure 12). The location and power density of the ceramic glow plug has provided a successful means for initiating the self-sustaining reaction with as little as 30 W supply power and local catalyst temperatures as low as 300°C. Once initiated, the glow plug power is turned off and the flow rate of the nitrous oxide is ramped up.

The test campaign is currently in progress, but to-date, high decomposition efficiency has been obtained at flow rates up to 50% of the design point, resulting in chamber pressures up to 5.3 atm (78 psia). A representative test data plot is shown in Figure 13. This particular test is at a bed loading of 5 $kg/m^2/sec$ and is operating at a c* efficiency of 81% (not corrected for radiation heat loss). As can be seen, the power supplied to the glow plug is shut off immediately after the reaction is initiated. Figure 14 shows a photograph taken during this hot fire test.

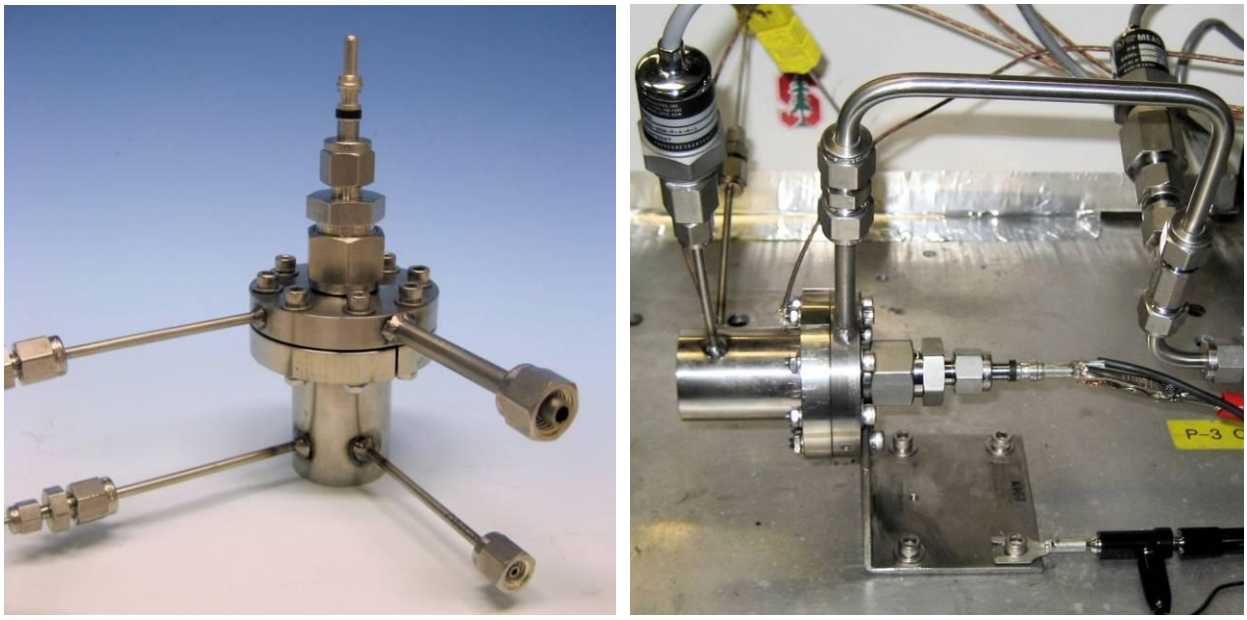


Figure 12. Assembled hardware instrumented and plumbed into the test stand.

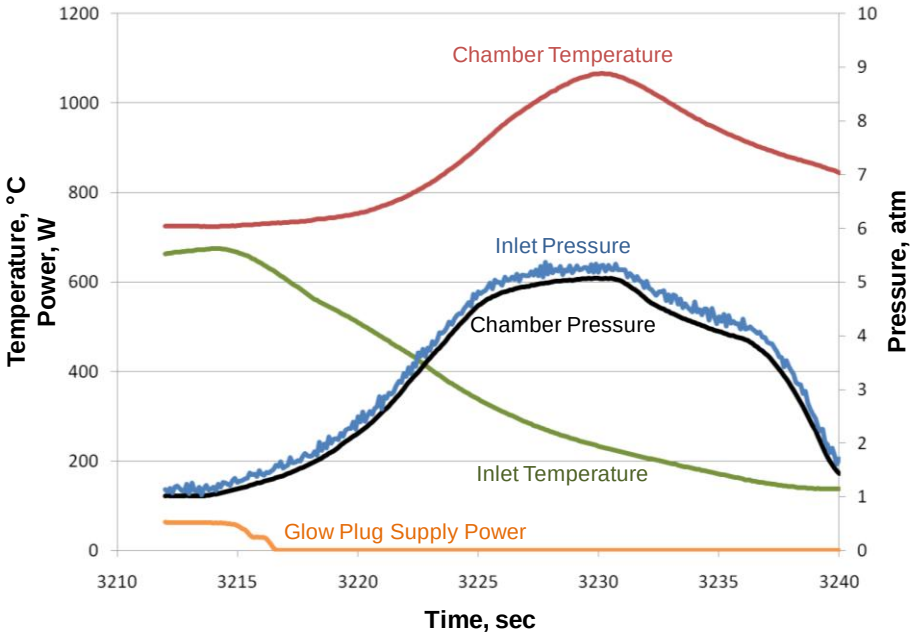


Figure 13. Scaled-up device test #102 – pressure, temperature, and power vs. time.

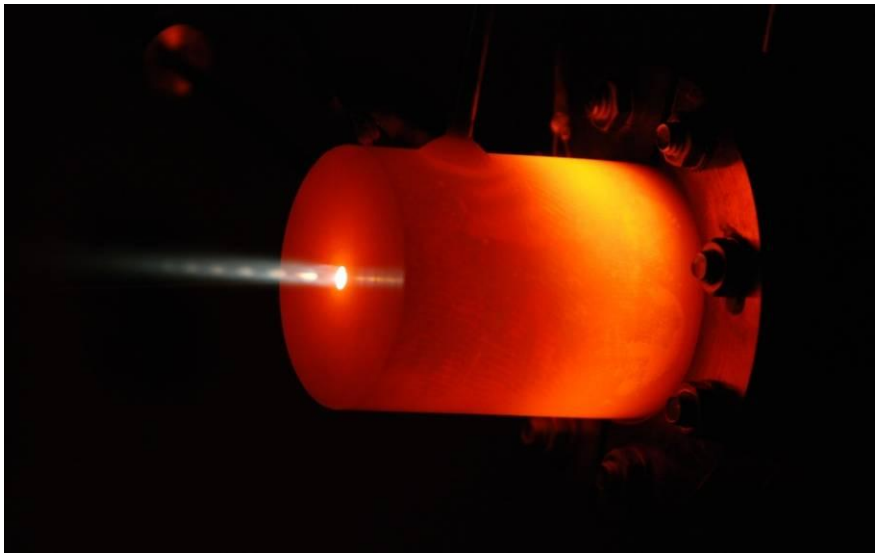


Figure 14. Scaled-up gas generator operating at 5.3 atm chamber pressure with 1060°C exhaust plume.

SUMMARY AND CONCLUSIONS

Research is ongoing at Stanford University on the catalytic decomposition of nitrous oxide as a monopropellant for propulsion and power applications. A capable test facility has been constructed, and a robust subscale test article has been fabricated to carry out these experiments. Tests to date have validated the extensive research performed at Surrey and by Zakirov, and have demonstrated some increased capability in terms of higher bed loadings, up to 4 times those previously reported, at acceptable decomposition efficiency. Other critical aspects of a subscale nitrous oxide monopropellant thruster demonstrated thus far include:

- Sustained thrust levels up to 2 N.
- Steady-state hot fire durations on a single catalyst bed of over 1 hour, showing no signs of degradation.
- Multiple re-starts and thermal cycles on a single catalyst bed, including hot re-starts that require no additional pre-heat.
- Bed loadings up to 15 $kg/m^2/sec$.
- Low catalyst bed pressure drop, typically 10% of chamber pressure.
- Efficient operation at chamber pressures over 5 atm.
- Chamber temperatures up to 1225°C.

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REFERENCES

1. Lohner, K.A., et al, ***Design and Development of a Sub-Scale Nitrous Oxide Monopropellant Gas Generator***, AIAA 2007-5463, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, OH (8-11 July 2007).

2. Zakirov, V.A., Lawrence, T.J., and Sweeting, M.N., ***An Update on Surrey Nitrous Oxide Catalytic Decomposition Research***, SSC01-XI-2, Proceedings of the 15th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT (13-16 August 2001).

3. Zakirov, V., Sweeting, M., Goeman, V., and Lawrence, T., ***Surrey Research on Nitrous Oxide Catalytic Decomposition for Space Applications***, 14th AIAA/USU Conference on Small Satellites (2000).

4. Wallbank, J.R., Sermon, P.A., Baker, A.M., Courtney, L., and Sambrook, R.M., ***Nitrous Oxide as a Green Monopropellant for Small Satellites***, 2nd Int. Conf. on Green Propellants for Space Propulsion, Cagliari, Sardinia, Italy (7-8 June 2004).

5. Gibbon, D., Paul, M., Jolley, P., Zakirov, V., Haag, G., Coxhill, I., Sweeting, M., and EIoirdi, R., ***Energetic Green Propulsion for Small Spacecraft***, 37th AIAA / ASME / SAE / ASEE Joint Propulsion Conference, Salt Lake City, Utah (8-11 July 2001).

6. Gibbon, D., and Baker, A.M., ***Development of 50 – 100 milliNewton level Thrusters for Low Cost Small***, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana (7-10 July 2002).

7. Tyll, J., and Herdy, R., ***The Nitrous Oxide – Propane Rocket Engine, Final Report for BAA 99-22***, GASL TR No. 387, Ronkonkoma, NY (August 16, 2001).

8. Zakirov, V., Li, L., and Ke, G., ***N2O Propulsion Research at Tsinghua: 2003***, 2nd Int. Conf. on Green Propellants for Space Propulsion, Cagliari, Sardinia, Italy (7-8 June 2004).

9. Wernimont, E.J., ***Monopropellant Hydrogen Peroxide Rocket Systems: Optimum for Small Scale***, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, California (9-12 July 2006).

10. Lohner, K., Dyer, J., Doran, E., Dunn, Z., and Zilliac, G., ***Fuel Regression Rate Characterization Using a Laboratory Scale Nitrous Oxide Hybrid Propulsion System***, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA, Sacramento, CA (July 2006).

11. Zhu, S., Wang, X., Wang, A., Conga, Y., and Zhang, T., ***A Novel Ir-Hexaaluminate Catalyst for N2O as a Propellant***, Chem. Commun., pp. 1695–1697 (2007).