Surrey Research on Nitrous Oxide Catalytic Decomposition for Space Applications

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Abstract. Nitrous oxide is introduced as a rocket propellant for small satellites. The reasons for using this propellant on small spacecrafts are discussed. Potential space applications of nitrous oxide are listed. A nitrous oxide catalytic decomposition technique is suggested for restartable spacecraft propulsion. Theoretical performance of a nitrous oxide monopropellant thruster is shown. Basics of nitrous oxide catalytic decomposition are given. Operating principles of a nitrous oxide monopropellant thruster are described. The design of the test apparatus and the set-up for nitrous oxide decomposition are given. Up-to-date achievements of nitrous oxide decomposition research at Surrey are reported. Future design features of nitrous oxide monopropellant thrusters are discussed. A conclusion about future research on nitrous oxide catalytic decomposition is given.

Introduction

Advanced communications, remote sensing and science missions require propulsion for small satellite attitude control, station-keeping and orbit manoeuvring. Launched as secondary payloads, small satellites are subjects of unique propulsion system integration requirements and constraints. Volumetric constraints, for example, make the use of nitrogen for conventional cold-gas propulsion inefficient due to low non-liquefied gas storage density. The electric power constraint (an average of <50W per orbit) restricts application of existing electric propulsion on board small spacecraft. The high cost of conventional mono- and bipropellant systems is usually prohibitive for these low-cost spacecrafts. Since toxic and flammable liquid or explosive solid propellants are involved, substantial conventional propulsion cost reduction is unlikely. In addition, dominating heat losses out of reaction chamber and flow friction losses in the nozzle throat lower performance of conventional thrusters at the low thrust levels of interest (<1N). Moreover, propulsion dry mass fraction increases upon scaling the system down. This often makes integration of compound propulsion on board small spacecraft unfeasible. Therefore, novel approaches are required for efficient small satellite propulsion.

One of the approaches is an application of new propellant. Nitrous oxide has been identified as such a propellant at the University of Surrey. This gas is a non-toxic chemical, stable at normal conditions, and compatible with common structural materials. It can be stored as a liquid or compressed gas through the wide temperature range theoretically limited by its triple point (-90.8°C) [1] on the lower and thermal decomposition temperature (520°C) [2] on the upper end of the scale. However, the recommended practical storage temperature range is from -34 to 60° C. It will be discussed in detail in future publication. [3] Storage density of this liquefied gas is ~745kg/m^3 at 20°C while its vapour pressure is about 52bar. Nitrous oxide decomposes exothermically with adiabatic decomposition temperature reaching ~1640° C. The decomposition can be accelerated by a catalyst. Free oxygen available by nitrous oxide decomposition can be combusted with a wide variety of fuels.

Therefore, nitrous oxide can be used for wide range of space power and propulsion devices including:

- cold-gas thrusters
- monopropellant thrusters
- resistojets thrusters
- bipropellant thrusters
- gas-generators
- turbine drives
- source of breathing oxygen for spacecraft emergency life-support

Thus, it is possible to design a simple, multi-mode propulsion system using this self-pressurising propellant and capable of all necessary functions for successful mission accomplishment. Total dry mass fraction for such a system will be lower in comparison to an alternative system combining conventional propulsion. Since different function type thrusters share the same propellant, the flexibility in the firing strategy is gained in orbit. This important advantage leads to relaxed spacecraft velocity change requirements for each particular propulsion function. Therefore, the number of mission scenarios may be increased. The further advantages of nitrous oxide propulsion are discussed in recent publication. [4]

Recent experience of storing nitrous oxide on-board the *UoSAT-12* mini-satellite for more than one year indicates that:

- Storage of the gas in-orbit is not a problem
- No expulsion system is required
- Minimum safety overheads and application of common materials for system design both provide a potential for low-cost system

To employ nitrous oxide as a rocket propellant it is suggested to take advantage of its catalytic decomposition.

Decomposition

Nitrous oxide catalytic decomposition is considered at Surrey as a key-technology for mono- and bipropellants restartable in orbit.

In the past nitrous oxide decomposition has been extensively studied, both in the presence, and in the absence, of catalysts. [5-38]

The decomposition of nitrous oxide results in formation of nitrogen and oxygen according to the following reaction equation:

$$\mathbf{N_2O(g) \rightarrow N_2(g) + \tfrac{1}{2}O_2(g) + Heat}$$

At standard conditions this exothermic reaction generates ~82kJ of heat per mole of nitrous oxide. [39, 40] However, heat input is required to initiate the reaction. In the case of thermal decomposition the activation energy barrier for nitrous oxide is about 250kJ/mole. [40] Therefore, in order to attain the required reaction rates, the gas must be heated to above 1000°C.

A catalyst lowers the activation energy barrier, and thus the decomposition occurs at much lower temperatures (>200°C). Figure 1 illustrates the advantage of catalytic over thermal decomposition. Textbooks on catalysis and chemisorption often give nitrous oxide decomposition as an example followed by list of catalysts. [41-44]

In the gas flow, if balance between rates of heat generated by decomposition and heat dissipated into surrounding is achieved ($Rate_{heat\ generated} - Rate_{heat\ dissipated} = 0$) then the reaction becomes self-sustaining.

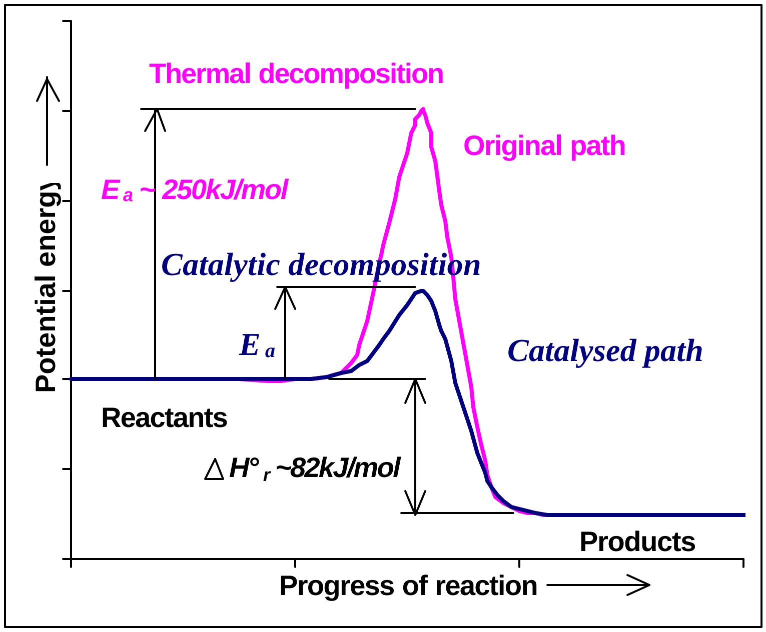


Figure 1. Nitrous oxide decomposition. (E_a – activation energy; DH^{o}_r – reaction enthalpy)

Previous Accomplishments

The research on nitrous oxide decomposition started at Surrey after self-sustaining decomposition was first reported by Timothy J. Lawrence in 1998. Earlier that year a self-sustaining nitrous oxide decomposition was observed in the *Mark-III* resistojet for longer than 18 hours during its vacuum test at the US Air Force Research Lab at *EDWARDS* Air Force Base, CA. The highest recorded specific impulse of that nitrous oxide resistojet was 148s. [45, 46] In 1999 the first (0.1N and 100W) nitrous oxide resistojet thruster *Mark-IV* has been successfully commissioned on board the *UoSAT-12* mini-satellite.

Monopropellant Thruster Concept

The schematics of a nitrous oxide monopropellant thruster employing catalytic decomposition is shown in Figure 2. In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst, which in turn decomposes more nitrous oxide, and generates more heat. The process proceeds with increasing temperature until all of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. This takes a few seconds. The products of the decomposition leave the chamber through the converging-diverging nozzle generating thrust. Once self-sustaining nitrous oxide decomposition is achieved, the electrical power input is no longer required.

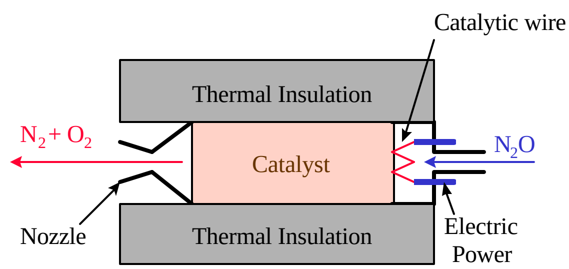


Figure 2. Nitrous oxide monopropellant thruster schematics.

The suggested concept offers significant electrical power savings because:

- It makes use of catalytic decomposition providing considerable input power savings for reaction initiation over thermal decomposition technique employed in a resistojet
- It takes an advantage of self-sustaining decomposition as zero input power main operation mode for a thruster

This is expected to make nitrous oxide propulsion a feasible option for small satellites, extending its application range from mini-satellite (100-500kg) to micro-satellite (10-100kg) platforms.

In Figure 3 theoretical specific impulse performance of nitrous oxide monopropellant thruster was evaluated as a function of chamber temperature using the *USAF ISP* computer code written by Curt Selph. The specific impulse rises monotonically till it reaches value of 206s corresponding to maximum thermodynamic decomposition temperature.

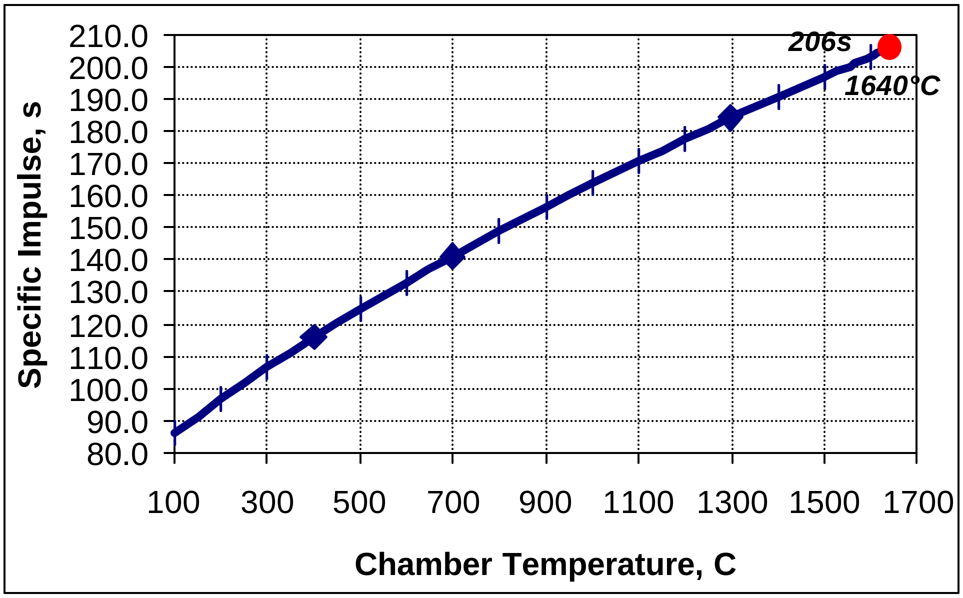


Figure 3. Theoretical specific impulse of nitrous oxide monopropellant thruster as a function of chamber temperature (chamber pressure = 3bar; nozzle expansion ratio = 200).

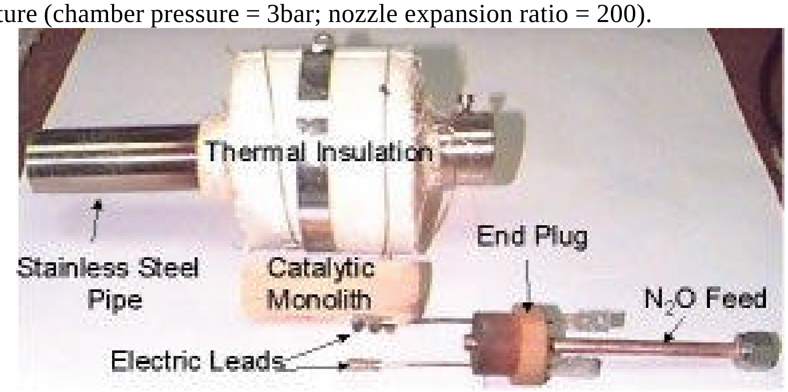


Figure 4. Test design.

Since low thrust levels (<1N) and, thus, low propellant mass flow rates (<0.5gm/s) are of interest, it is suggested to reduce thruster's operating chamber pressure to below 3bar. The lower chamber pressure is desirable for several reasons:

- The famous Le Chatelier's principle [40] can be interpreted as: "for chemical reaction with increasing volume of products lower pressure will shift equilibrium towards reaction products". In other words, lower pressure is beneficial for nitrous oxide decomposition.
- It increases the thuster's nozzle throat to the size that is easy to manufacture.
- It improves thrust efficiency since flow friction losses in the thuster's nozzle throat are reduced.
- Higher nitrous oxide storage tank depletion can be achieved.
- Taking in account low mechanical (due to lower pressure) and moderate thermal (due to "slow" start-up) stresses exerted on thruster's casing it would be possible to use high temperature ceramic materials (such as, for example, alumina) for its design. Application of high temperature ceramics in thruster design will shift operating temperature and, thus, improve the specific impulse performance.

Slight increase in thruster size and mass due to lower operating pressure is not crucial for low-thrust propulsion system, and is a subject of optimisation.

Test Apparatus

As a first step towards the development of flight-qualified thruster the following simple test apparatus was designed. A 190mm-piece of 2.54mm-inner-diameter stainless steel pipe was adopted to house the catalysts. The test apparatus design is shown in Figure 4.

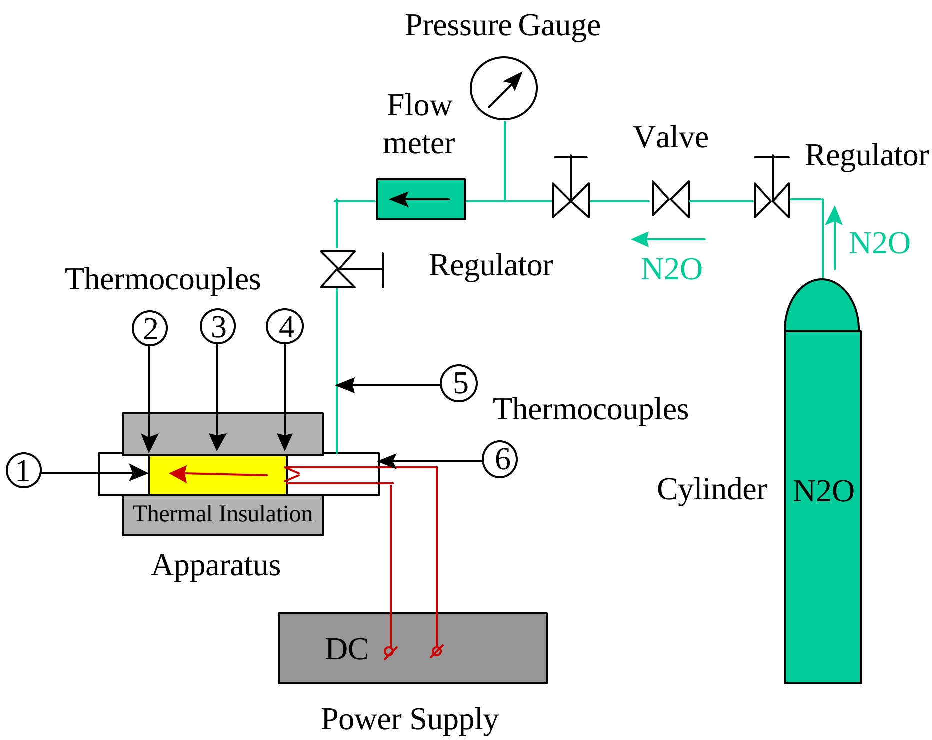


Figure 5. Test set-up schematics.

Experimental set-up for nitrous oxide decomposition research is shown in Figure 5. Nitrous oxide from the cylinder flows though the valve and regulators to the test apparatus where it decomposes on a catalyst before discharging to atmosphere. A pressure gauge and flow meter in the nitrous oxide feed line indicate flow parameters set by the regulators. Direct current power supply is necessary for heating a catalytic wire inside the apparatus. Thermal insulation is used to reduce heat loss from the decomposition chamber. Thermocouple *1* is set to read the temperature of exhaust gases. Thermocouples *2*, *3*, and *4* are set to measure decomposition chamber outside wall temperature. Thermocouple *5* is set in stream of nitrous oxide feed line. Thermocouple *6* measures the outside wall temperature of end plug of the apparatus.

Experimental Results

The potential for the nitrous oxide catalytic decomposition technique has been demonstrated in dozens of experimental tests at *Surrey Space Centre*, U.K. (see Figure 6). During these tests:

- The proof-of-concept was demonstrated.
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts.
- Hot restarts at zero-power input have been repeatedly shown in operation.
- More than 50 different catalysts have been tested.
- A catalyst activation temperature as low as 250°C has been recorded.
- Nitrous oxide mass flow rates above 1.1gm/s have been supported.
- Decomposition temperatures in excess of 1500°C have been demonstrated.
- Electrical power input as low as 24W has been used.
- The time required to heat the catalyst from ambient to activation temperature has been as short as 3min.
- A catalyst lifetime in excess of 76min. was demonstrated.
- Nitrous oxide decomposition was shown to ignite solid fuel (PMMA). A vortex flow “pancake” hybrid rocket motor was successfully ignited by injection of hot gaseous products of the nitrous oxide decomposition into the combustion chamber (see Figure 7).[47] In the test, a well-known hydrazine decomposition catalyst (*Shell 405*) was used to decompose nitrous oxide.

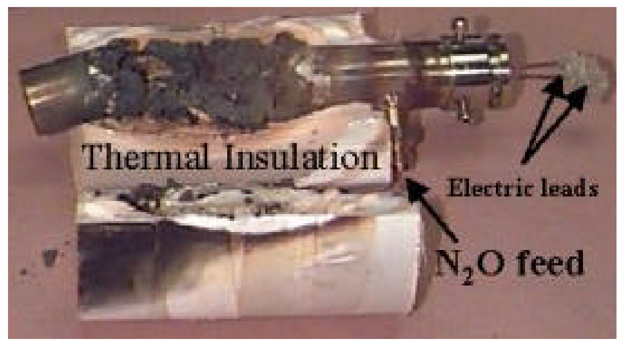
Despite these achievements, two major challenges were revealed. Both of them are associated with choice of high temperature materials.

The first challenge is due to high temperature generated inside decomposition chamber. This temperature is enough to melt stainless steel casing (see Figure 8). Application of refractory materials in the design is presently not considered because they are difficult to manufacture and expensive. Lowering the process temperature is unfavourable because it sacrifices thruster performance. Application of alumina ceramics was found promising for high temperature casing design. However, additional tests comprising both thermal and mechanical stress loads need to be carried out before the final conclusion can be made. The future designs involving ceramics will require careful consideration of thermal expansion coefficients.

Figure 6. Self-sustaining nitrous oxide decomposition on *LCH 212* hydrazine catalyst. The electric leads have been disconnected from power supply after "ignition". No electric power is applied.

The second challenge is associated with high temperature (>1100°C) instability of the catalyst materials. The literature search on nitrous oxide decomposition catalysts provided no answer for the problem. Since practical applications for nitrous oxide decomposition catalysts are currently limited to environmental outlooks rather than power generation the maximum explored temperatures did not exceed 800°C. It is also believed that above this temperature homogeneous (or thermal) decomposition dominates the process. However, it was found that in the case of suggested dynamic system homogeneous decomposition rates at 800°C are not high enough to initiate self-sustaining decomposition; therefore, the need in high temperature catalyst still remains.

Figure 7. A vortex flow "pancake" hybrid rocket motor firing.



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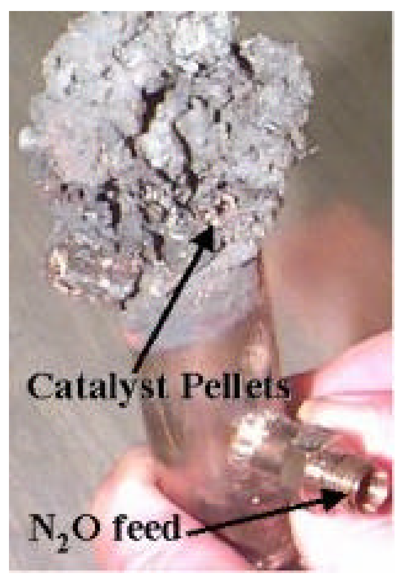

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Figure 8. Test design after firing: a) Stainless steel pipe is melted with iron catalyst and *MICROPORE* thermal insulation; b) Alumina pellets coated by catalyst have survived the heat.

Meanwhile, it was found that above 1100°C the following problems occur:

- Zeolites and silica sinter
- Cordierite matrix does not withstand the temperature
- Iridium and rhodium oxides sublimate
- Nickel, cobalt and iron react with alumina or magnesia substrates forming spinels (complex oxides).

The work on high temperature stable catalysts continues.

Summary

Nitrous oxide has been identified at Surrey Space Centre as a rocket propellant for small satellites. Application of this propellant on small spacecraft is advantageous because:

- All propulsion functions for small satellites can be covered.
- Multi-mode propulsion system can be designed for a small satellite. Such a system will have lower total dry mass fraction and increase the number of mission scenarios due to more efficient propellant management.
- It has potential in providing significant reduction of propulsion system cost.

Previous research regarding nitrous oxide space application proved that:

- It can be stored in orbit.
- It can be used as a resistojet propellant.
- Its self-sustaining decomposition is attainable.

A continuation of earlier efforts, nitrous oxide catalytic decomposition is a focus of current research at Surrey. It is considered to be a key-technique for a novel monopropellant thruster concept. This technique reduces input power requirements for power-constrained small satellites in comparison with a thermal decomposition technique, and, therefore, will be affordable for smaller spacecraft. As a further step, nitrous oxide catalytic decomposition technique is suggested for bipropellant thruster ignition.

As a first approach towards the monopropellant thruster a catalytic decomposer for nitrous oxide has been designed and successfully tested along with supporting infrastructure.

Catalysts for nitrous oxide decomposition exist. They have been proven feasible for heat and thrust generation as well as hybrid rocket motor ignition.

Although the existing catalysts work well, high-temperature stable catalyst materials would further enhance the performance of a monopropellant thruster.

Current research at Surrey is focused on the investigation of the performance of a nitrous oxide catalytic decomposer leading towards the development of a nitrous oxide monopropellant thruster.

The ultimate research goal is to provide theoretical and experimental basis for the development of the first nitrous oxide multi-mode propulsion system for small satellite applications.

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