

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/268483024>

Low Cost Catalysts for Hydrazine Monopropellant Thrusters

Conference Paper · August 2009

DOI: 10.2514/6.2009-5232

CITATIONS

2

READS

53

5 authors, including:



Jose Nivaldo Hinckel

National Institute for Space Research, Brazil

27 PUBLICATIONS **50** CITATIONS

SEE PROFILE

Low Cost Catalysts for Hydrazine Monopropellant Thrusters

José Nivaldo Hinckel*

INPE/DMC, São José dos Campos, SP, 12201-970, Brazil

José A. R. Jorge[†]Turíbio G. Soares Neto[†]Marisa A. Zacharias[†]Jalusa A. L. Palandi[‡]

INPE/LCP, Cachoeira Paulista, SP, 12630-000, Brazil

Hydrazine monopropellant engines are widely used in space missions; mainly in reaction control systems. The most widely used catalyst is the aluminum oxide supported iridium. It is also very expensive. The cost of the catalyst weights heavily, especially in the high thrust, short life thrusters used for roll control of launch vehicles. In this paper we present the results of testing of low cost catalysts in a 35 newton thruster. The catalysts tested were aluminum oxide supported ruthenium and a homogeneous catalyst, tungsten carbide. The test sequence included pre-heated and cold starts, pulsed and continuous firing modes, a range of feed pressure and life cycle that exceed the requirements of roll control systems. The start and energetic performance of the thruster matched very closely the performance of the iridium catalyst.

Nomenclature

C^*	[m/s]	Characteristic Velocity	P_c	[MPa]	Chamber Pressure
C_f		Thrust Coefficient	t_{ig}	[ms]	Ignition time
F	[N]	Thrust	t_{resp}	[ms]	Response time
I_{sp}	[m/s]	Specific Impulse	T_{in}	[°C]	Initial Temperature
P_i	[MPa]	Injection Pressure			

I. Introduction

The development of monopropellant thrusters and performance characteristics are well documented in the literature. Schmitz¹ describes the qualification test sequence for a long life, iridium catalyst, 2 newton monopropellant thruster for a satellite reaction control system. Hinckel^{2,3} describes the development of hydrazine monopropellant thrusters carried out at INPE. Rath⁴ and Pitt⁵ describe the development of a 400 N monopropellant engine.

The life cycle and thrust level requirements of control thrusters, depend strongly on the mission application. The two main applications are in roll control systems of upper stages of launch vehicles and reaction control systems of satellites and space platforms. Thrusters used in roll control systems have a thrust level in the hundreds of newton, accumulated working time of a few hundred seconds and operating life of approximately 600 seconds. The duty-cycle varies from short pulses of hundreds of milliseconds to continuous firings of up to one minute. Thrusters used in reaction control systems of satellites have a thrust of a fraction of one newton to tens of newton, accumulated operating time of a few hours, operating life of 10 to 15 years. The duty-cycle varies from short pulse trains with dozens of pulses to continuous firings with duration up to one hour.

*Senior Researcher, and AIAA Senior Member.

[†]Senior Researcher

[‡]Graduate student

The amount of catalyst loaded is roughly proportional to the nominal thrust of the engine, varying from less than one gram for a 1 newton thruster to 300 grams for 400 N thruster. The catalyst cost consideration is of minor importance in long life thrusters for satellite reaction control systems. For short life, high thrust level engines, for roll control systems, the cost of the catalyst is significant.

In this paper we describe the results of fire test with two catalysts whose production costs are substantially lower than the widely used aluminum oxide supported iridium catalyst. The test were carried out in a chamber designed for nominal thrust of 35 newton. The catalysts tested were; an heterogenous aluminum oxide supported ruthenium catalyst and a homogeneous catalyst, tungsten carbide. Applications of the ruthenium in monopropellant control thruster are described in the literature, Pitt⁵. Applications of aluminum oxide supported tungsten carbide and homogeneous tungsten carbide catalysts in monopropellant thrusters are reported by Chen⁶ and Rodrigues⁷, respectively. Scaling up for thrust levels of 200 newton and 400 newton is now under way.

II. The Catalyst

The catalyst is responsible for starting the decomposition of propellant in the chamber. It acts by decreasing the activation energy for the reaction of decomposition of the propellant, ensuring a smooth start even for a chamber bed temperature well below the temperature for thermal decomposition of the propellant. The decomposition of the propellant due to the action of the catalyst is referred to as an heterogenous reaction while the thermal decomposition is referred to as homogeneous reaction. A substance is said to have a catalytic effect on the decomposition reaction if it decreases the temperature for decomposition of the hydrazine below the thermal decomposition threshold. A catalyst that is capable of sustaining the decomposition of hydrazine at temperatures below 35°C is termed a spontaneous catalyst.

Two types of catalysts were produced and tested; aluminum oxide supported ruthenium, and a homogeneous catalyst, tungsten carbide.

A. The ruthenium catalyst

The production of the ruthenium catalyst comprises two phases; the aluminum oxide support preparation and the metallic impregnation. The main characteristics of the aluminum oxide support are shown in Table 1. The metallic impregnation is done in six phases. The weight fraction of the metallic component in the catalyst is 33%. Between each phase of the impregnation process the aluminum oxide support is first dried in an oven at 120 °C and then in a vacuum chamber at ambient temperature and 1 mbar pressure. After the drying phase the catalyst was reduced in H₂ medium at 400 °C during 4 hours.

Textural property	Aluminum support		Catalyst before firing		Catalyst after firing	
	Spheroid	Pelletized	Spheroid	Pelletized	Spheroid	Pelletized
Specific area	165 m ² /g	184 m ² /g	93 m ² /g	103 m ² /g	81 m ² /g	73 m ² /g
Volume of pores	0.38 cm ³ /g	0.38 cm ³ /g	0.15 cm ³ /g	0.16 cm ³ /g	0.15 cm ³ /g	0.16 cm ³ /g
Mean pore diameter			64 Å	59 Å	74 Å	80 Å

Table 1. Ruthenium catalyst characteristics

The following measuring techniques are used in the characterization process:

Gravimetry: is used to measure the metallic contents of the catalyst.

Nitrogen Fisisorption: is used to measure the specific area.

Nitrogen adsorption: the pore size and distribution measurement was carried out by nitrogen adsorption at its normal condensation temperature.

Transmission electronic microscopy: is used to measure the distribution and size of the metallic particles on the surface of the catalyst pores.

The evolution of the specific area and the pore size distribution and volume was measured after each phase of the metallic impregnation process.

After the fire test program the catalyst was collected and analyzed for loss of mass, quantity of fines generated, specific area and pore size, volume and distribution.

B. The tungsten carbide catalyst

The synthesis of the tungsten carbide is done in two phases. In the first phase a precursor to the carbide is obtained. In the second phase the tungsten carbide is obtained..

1. Synthesis of the carbide precursor

The synthesis of the carbide precursor starts from a mixture of powder of tungstic acid and aluminum hydroxide. The mixture is then subjected to a controlled dispersion process with a chemical agent, resulting in a moldable paste which is extruded forming pellet with diameter of 2.5 mm and length of 2.6 mm. The pellets are dried at 50°C and subsequently calcinated at 900°C during 1h .

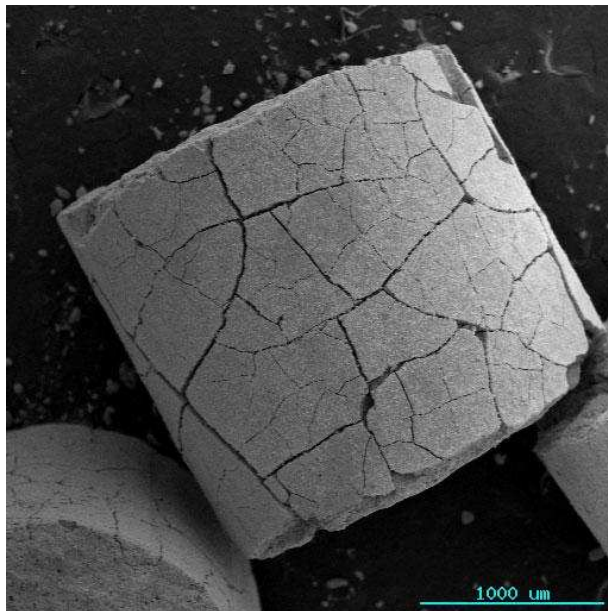
2. Synthesis of the tungsten carbide

The aluminum-tungsten oxide composite is carburized in a quartz reactor by an 80% methane 20% hydrogen mixture under a programmed temperature schedule. The carbide is then passivated in a mixture of helium with 1% dispersed oxygen.

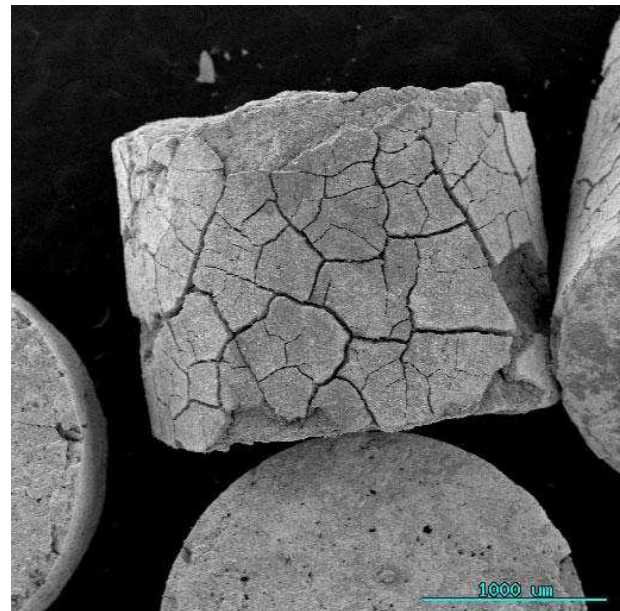
The main characteristics of the tungsten carbide are shown in Table 2. A picture of the tungsten carbide catalyst pellet magnified 35 times, before and after the fire test is shown in Fig. 1

Characteristic	Before firing	after firing
Specific area	70 m ² /g	22 m ² /g
Volume of pores	0.09 cm ³ /g	0.04 cm ³ /g
Mean pore diameter	51 Å	76 Å
Mechanical resistance	23 N/mm ²	12 N/mm ²

Table 2. Tungsten carbide characteristics



(a) Tungsten Carbide (35X) before fire test



(b) Tungsten Carbide (35X) after fire test

Figure 1. Tungsten carbide catalyst before and after the fire test

III. The test engine

The test engine geometry, shown in Figure 2, is composed of the injector head, the catalyst chamber and the expansion nozzle.

The engine was designed for operation in the feed pressure range of 2.2MPa to 0.55 MPa with nominal thrust of 35N at 2.2MPa feed pressure. The corresponding catalytic bed load is 2.75 to 0.9 g/cm² · s. The design values for the injector pressure drop and catalytic chamber pressure drop for a feed pressure of 2.2 MPa are 0.5 MPa and 0.2 MPa respectively.

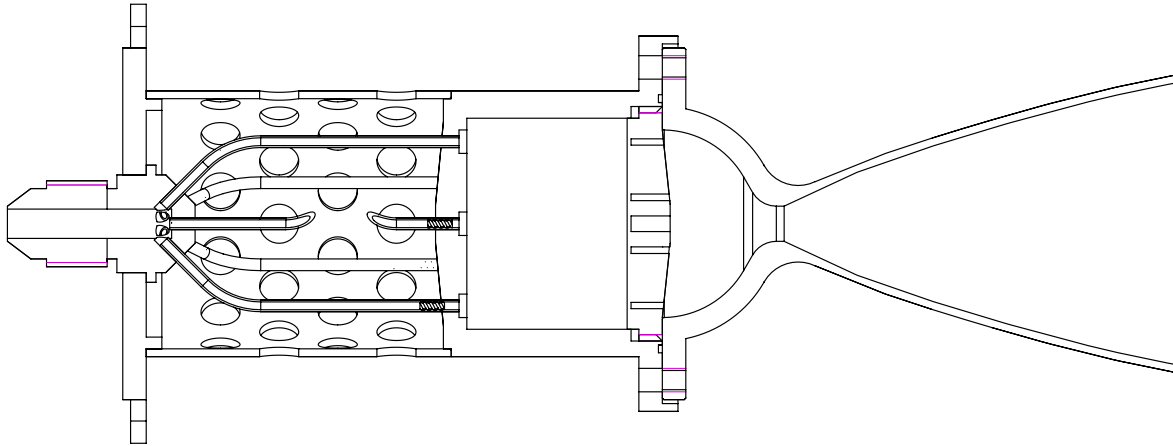


Figure 2. Thruster drawing

A. The injector head

The injector head comprises seven capillary tubes each one with an helical insert at the exit for atomization and metering of the propellant. The pattern distribution of the injector elements over the face plate is shown in Fig 3. One injector element is placed at the center and six elements are distributed in a ring. The wetted area of each injector element is approximately the same.

The helical insert with two entrances has a length of 2 mm and is placed 2.5 mm from the end of the capillary tube. The mass flow of each injector element is calibrated by adjusting the exit diameter of the tube. Each injector discharges into a small cylindrical chamber with a length of 1 mm and 3 mm diameter. Inside the chamber, the injected propellant forms a conical trunk sheet. The base of trunk is limited by the bottom screen and the top of the trunk is the exit diameter of the capillary injector. The main design parameters of the thruster are:

B. The catalytic chamber

The catalytic chamber is cylindrical with a length of 20 mm. Three mesh 60 platinum screens are used inside the chamber; one at the injector face plate, one to separate the fine catalyst layer from the coarse layer and one at the end of the coarse layer. A perforated disk with an outside thread is used to support the retaining screen and to apply a small load onto the catalytic bed for better packing. An insulated heating wire is wrapped around the catalytic chamber. The power dissipation of the heating wire is approximately 15 W. The catalytic chamber filled with the coarse catalytic layer is shown in Figure 3.

For loading the catalyst, the chamber was mounted onto a shaker. A vibration movement of 1.5 g acceleration and frequency of 250 Hz was applied.

C. The Expansion Nozzle

The nozzle is connected to the catalytic chamber by bolted flanges. Sealing between the chamber and the nozzle is provided by a metallic ring. The throat diameter of the nozzle is 4.5 mm and the expansion area ratio is 64. The divergent nozzle with total length of 50 mm is parabolic with an opening angle of 36° and an exit angle of 10°.

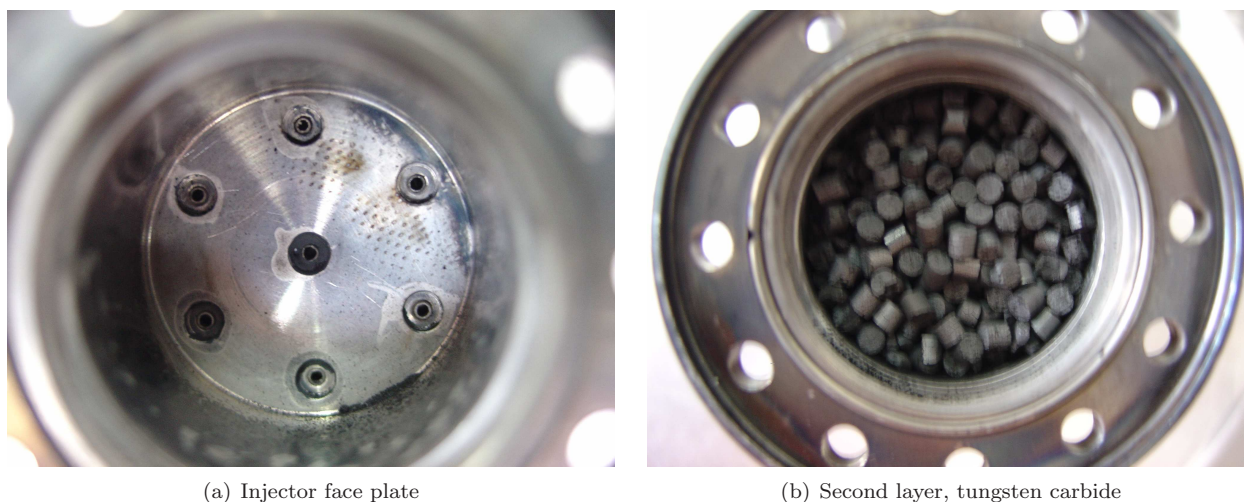


Figure 3. Catalyst chamber and catalyst layers

IV. The Test Facility

The test facility is located in Cachoeira Paulista and is operated by the local Division of Combustion and Propulsion of INPE. The test facility is equipped with an 10 m³ test chamber, a high pumping speed vacuum system, propellant conditioning feed system, a control room for the vacuum system, propellant conditioning and thruster operation and data acquisition and processing system. The vacuum pumping system comprises two series mounted vapor ejectors, one condenser unit, two liquid ring mechanical pumps, one gas-liquid separator and and mechanical pumps for non-condensable products.

The facility instrumentation consists of a thrust balance, propellant feed line pressure and temperature measurement, propellant mass flow rate and thermocouples and pressure transducers for measurement of the thruster wall temperature, propellant feed pressure and temperature and nozzle entrance chamber pressure.

Two computer controlled units are used for the operation of the facility; one unit commands the vacuum system, the propellant feed system and the thruster propellant valve, the other unit does the data acquisition and data processing functions.

The thruster is mounted in the vertical position with the exhaust jet directed downward.

V. The test program

Two catalyst loads were tested. In the first load both layers of the catalytic chamber were filled with the alumina supported ruthenim catalyst. In the second load the first layer was load with alumna supported iridium and the second layer was load with tungsten carbide pellets. Before the firing test the vacuum chamber was pumped down to a pressure below 1 mbar and the catalytic chamber was heated to a temperature of 120 °C for a period of at least 2 hours. An initial firing test of 5 seconds was carried out before the main test sequence. The purpose of this test was to verify the working condition of the thruster and to reduce any oxidation of the catalyst that might have occurred during the test preparation. The test program was designed to verify the operation of the thruster over the working feed pressure range and duty-cycle. Three levels of feed pressure

P_i	t	t_{on}/t_{off}	NP	T_{in}
MPa	s	ms/ms		°C
1.2	5	-	5	120
2.2	100	500/500	100	120
2.2	100	200/500	100	120
2.2	30	-	1	120
1.2	100	500/500	100	120
1.2	100	200/800	100	120
1.2	30	-	1	120
5.5	100	500/500	100	120
5.5	100	200/800	100	120
5.5	30	-	1	120
5.5	30	200/800	30	25

Table 3. Test program

were tested: 2.2 , 1.2 and 0.55 MPa. For each pressure level the thruster was fired in continuous mode, and pulsed mode. The complete sequence of test conditions for each catalyst load is presented in Table 3. A cold start test was performed as the last test in the sequence.

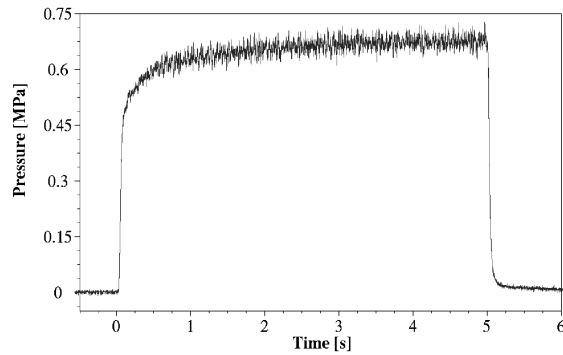
VI. Summary of test results

The steady state performance of the thruster is shown in Table 4 for three levels of feed pressure. P_i is the feed pressures at valve entrance, P_c is the chamber pressure at the beginning of the convergent section of the nozzle, T is the thrust, I_{sp} is the specific impulse, C^* is the characteristic velocity and C_f is the thrust coefficient. The thrust level is slightly higher than the design value (35 N for a feed pressure of 2.2 MPa). The reason for this is that the injector pressure drop and the catalytic bed pressure drop were lower than the reference design values.

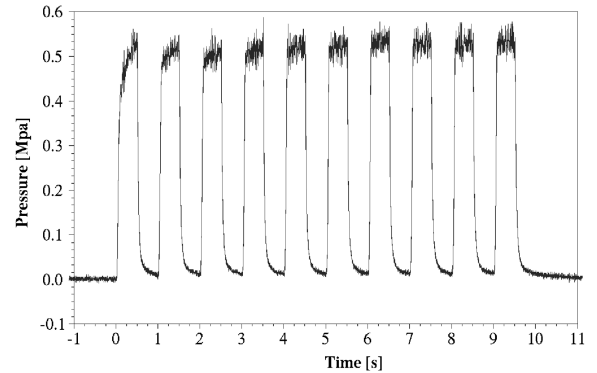
The “ignition” characteristics of the thruster are shown in Table 5. The table shows the characteristic times for the first pulse and last pulse in a pulse train with 100 pulses. The pulse frequency was 1 Hz and the duty-cycle 50%. P_i is the feed pressures at valve entrance. T_{in} is the temperature of the catalyst bed at the beginning of the pulse train. The response time, t_{resp} , is the time interval between the opening of the valve and the instant when the chamber pressures attains 10% of the steady state value. The ignition time, t_{ig} is the time interval between the valve opening and the instant when the chamber pressure attains the value of 75% of the steady state value. The last line of the table shows the results for a cold start.

P_i	P_c	F	C^*	I_{sp}	C_f
MPa	MPa	N	m/s	m/s	
2.17	1.46	40.9	1246	2184	1,75
1.20	0.88	24.3	1189	2047	1.72
0.57	0.44	11.8	1116	1856	1.66

Table 4. Steady state performance



(a) 5 s Continuous mode



(b) 10 pulse train

Figure 4. Pressure trace of continuous and pulsed modes

VII. Acknowledgment

The authors would like to thank FAPESP (PN 05/03605-4) for the support for the development of the catalyst. We also thank the LCP researcher David dos Santos Cunha for de production iridium aluminum catalyst and the BTSA staff for carrying out the fire test program, and Gilberto Marques da Cruz and Gerald Djéga-Mariadassou for the valuable comments and discussions on the catalyst properties and thruster test results.

VIII. Conclusion

Low cost catalysts (aluminum oxide supported ruthenium, and tungsten carbide) were produced and tested in a 35 newton catalytic engine. The energetic performance and characteristic response time are very close to those of the iridium catalyst. These catalysts may reduce significantly the production cost of high thrust, short operational time of thrusters for roll control of launch vehicles.

The test program covered the operational envelope of thrusters used for roll control of launch vehicles, regarding propellant feed pressure, duty-cycle and propellant throughput.

No significant degradation of the of the catalyst performance was observed during the tests. The loss of catalyst mass and generation of fines measured after the tests was negligible for the tungsten carbide catalyst. For the ruthenium catalyst a 20% loss of mass was observed. The mechanism responsible for this loss is being investigated.

Scaling up to thrusters with thrust level of 400 N is under way. Operational margins on propellant chamber load will be tested in order to determine possible reduction of catalytic chamber diameter and catalyst load.

P_i	T_{in}	first pulse		last pulse	
		t_{resp}	t_{ig}	t_{resp}	t_{ig}
MPa	°C	ms	ms	ms	ms
1.2	120	18	40	15	37
1.2	24	88	100	18	50

Table 5. Ignition characteristics

References

- ¹Schimtz, H. D., Tiedtke, P., and Steenborg, M., "Design, Development and Qualification of the OTS/MAROTS Mono-propellant Hydrazine Thrusters," No. AIAA-77-966, AIAA/SAE 13th Joint Propulsion Conference, Orlando, FL, July 11-13 1977.
- ²Hinckel, J. N., Trava-Airoldi, V., Corat, E., and Bressan, C., "Propulsion Subsystem Component Development for the MECB RSS Satellite," No. AIAA-91-1836, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference, Sacramento, CA, June 24-26 1991.
- ³Hinckel, J. N., "Development of a 115 Newton Thrust Hydrazine Catalytic Thruster," No. AIAA-93-1964, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, Monterey, CA, June 28-30 1993.
- ⁴Rath, M., Schimtz, H. D., and Steenborg, M., "Development of a 400 N Hydrazine Thruster for ESA's Atmospheric Reentry Demonstrator," No. AIAA-96-2866, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Lake Buena Vista, FL, July 1-3 1996.
- ⁵Pitt, R. and Rogall, H., "Design, Development and Evolution of the Ariane 5 Attitude Control System (SCA)," No. AIAA-95-2808, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, CA, July 10-12 1995.
- ⁶Chen, X., Zhang, T., Zheng, M., Xia, L., Li, T., Wu, W., Wang, X., and Li, C., "Catalytic Decomposition of Hydrazine over α -Mo₂C/ γ -Al₂O₃ Catalysts," *Industrial & Engineering Chemistry Research*, Vol. 43, No. 19, August 2004, pp. 6040-6047.
- ⁷Rodrigues, J. A. J., Cruz, G. M., Bugli, G., Boudart, M., and Djéga-Mariadassou, G., "Nitride and carbide of molybdenum and tungsten as substitutes of iridium for catalysts used for space communications," *Catalysis Letters*, Vol. 45, 1997.