Effects of Catalysts on Hydrazine Monopropellant Thruster Performances

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Keywords: Satellite Propulsion, Monopropellant Thruster, Catalyst, Shell405, KC12GA, S405

Abstract

Many monopropellant thrusters use a catalyst for decompose the propellant, hydrazine. The catalyst directly affects the thruster performances and lifetime. Therefore, it is important to confirm that the catalyst is suitable for our thrusters.

Until 2002, we used Shell405 catalyst, for satellite RCS thrusters, and H-IIA and M-V launch vehicle upper-stage RCS thrusters. In 2002, however, Shell Chemical Inc. ceased manufacturing Shell405 catalyst and transferred the product to AEROJET, where it was renamed S405.

We subsequently investigated the characteristics of AEROJET's S405 catalyst and SOLVAY's KC12GA catalyst, (SOLVAY is a Belgian chemical company, and KC12GA is used for ASTRIUM's thruster) and conducted thruster firing tests using the new catalysts.

After conducting, we confirm that the KC12GA catalyst was suitable for our thrusters, and decided to use KC12GA for two satellite programs.

Monopropellant thrusters and Catalyst

Monopropellant thrusters have been widely used for more than 30 years for spacecraft attitude control and orbit transfer. After Shell Chemical Inc. (US) developed the Shell405 catalyst, monopropellant thrusters achieved an Isp of 200 to 220 sec, a quick response, and long life[1].

The first monopropellant thrusters were developed in Japan in the 1970's. Currently, there are six types of monopropellant thrusters. These are used for satellites, H-IIA launch vehicles and M-V launch vehicles. All of them have used the Shell405 catalyst.

Shell405 is made of alumina granules, in which Ir metal is seeped. (Fig.2) On its surface, there are many micro-holes, In which, liquid hydrazine is quickly evaporated and decomposed into nitrogen, hydrogen, and ammonia gases. Through this reaction, gases are heated to about 1100K and expelled from the nozzle, producing thrust. Catalyst granules are very hard and breakable; they become small particles during firing, because of collisions or friction among granules, and destructive impulses in micro-holes[2]. Small catalyst particles are expelled from nozzles, and voids are produced in the thruster catalyst bed.

Figure. 3 presents an X-Ray photograph of a thruster catalyst bed with voids after firing tests. This large void affects thruster performances by decreasing thrust and increasing firing pressure roughness, etc..

Monopropellant thruster lifetime is determined only by catalyst lifetime, and which can be investigated by firing tests.

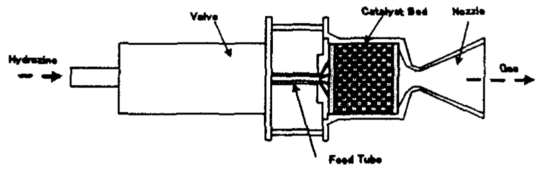


Fig.1 Schematics of a monopropellant thruster

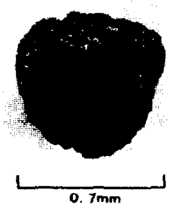


Fig.2 Shell405 granule

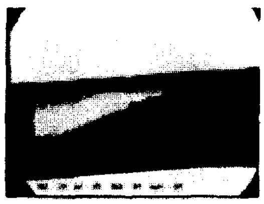


Fig.3 X-Ray Images of catalyst bed with voids

The Termination of Shell405 and "new" catalysts

In 2002, Shell Chemical Inc. ceased manufacturing Shell405 catalyst and transferred the product to AEROJET, where it was renamed S405. AEROJET stated that S405 characteristics S405 would be equal to Shell405, but we were anxious about the reliability of transfer programs (We believe catalysts to be very sensitive.). They also stated that the transfer programs would take more than six months to complete.

At that time, we lacked sufficient supplies of Shell405 for SELENE (lunar exploration satellite mission) and WINDS (wide-band communicating satellite mission). Therefore, we searched for another catalyst in the event of problems in the transfer program. There are several monopropellant thruster catalysts besides Shell405. We noticed KC12GA catalyst (SOLVAY S.A.), because it has been used for ASTRIUM's thrusters that is for Ariane programs. We subsequently procured both KC12GA and S405, and then conducted material tests of KC12GA, S405 and Shell405.

All catalysts came in two types, #14-18 and #25-30. This number indicates the sieve that is used to ensure diameters of catalyst granules.

Material tests

It is difficult to identify which properties are truly effective in thruster catalyst performances. We choose eight test, properties for tests referring to advises of a chemical specialist.

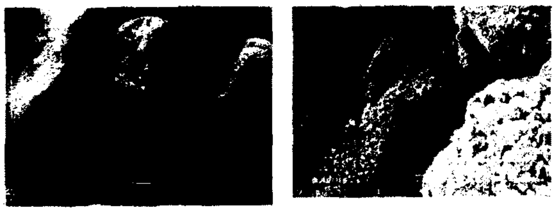
We purchased two sizes of catalyst.

1) Catalyst Granules Surface

We observed catalyst granules surface using SEM.

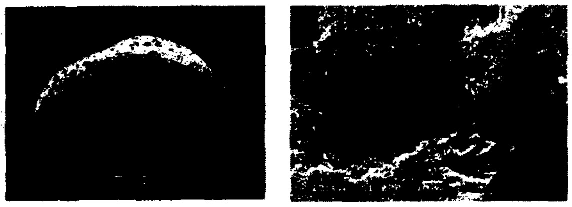
(a) ×65 (b) ×1000

Fig.4, SEM Images of Shell405(#14-18)



(a) ×35, (b) ×1000

Fig.5 SEM Images of KC12GA(#14-18)



(a) ×40,, (b) ×1000

Fig.6 SEM Images of S405(#14-18)

They all are similar porous alumina ceramics.. We can observe a crystal-like surface i in the photographs (magnified 1000x) of both Shell405 and S405, but cannot see in KC12GA. Of course, there may be some differences in each granules of the same catalyst, but we believe manufacturing methods of Shell405 and S405 to be equivalent.

2) Diameter of Ir

We measured the mean diameter of Ir using XRD. When the diameter is small, catalyst activation is high.

Shell406's Ir diameter is smallest, but the measurement precision is relatively poor, so we cannot make conclusions based solely on this data.

Table 1 Mean diameter of Ir metal [A]
Precision ±12 A

	Shell405	KC12GA	S405
#14-18	15.8	17.9	25.5
#25-30	16.5	17.7	22.2

3) Percentage of Ir

We measured mass percentages of Ir using ICP. With high Ir percentages, catalyst activation will be high.

All percentages were about 30%.

Table 2 Percentage of Ir mass [%]
Precision ±0.2 %

	Shell405	KC12GA	S405
#14-18	30.8	30.72	29.96
#25-30	30.73	30.76	30.02

4) Volume of micro-holes, Surface Area

Micro-holes and surface areas were measured for mean volume using the BET method. If the volume differs significantly from Shell405, activation will be low.

These are no large differences between the catalysts.

Table 3 Volume of micro-holes [ml/g]
Precision ±0.01 ml/g

	Shell405	KC12GA	S405
#14-18	0.147	0.141	0.160
#25-30	0.144	0.138	0.153

Table 4 Surface area [m2/g]
Precision ±6.2 m2/g

	Shell405	KC12GA	S405
#14-18	116	143	129
#25-30	111	149	125

5) Surface Area of Ir

We measured the surface area of Ir using a CO adsorption method. Activation will be high if surface area is large.

There are no large differences in the catalysts.

Table 5 Surface area of Ir [m2/g]
Precision ±4.3 m2/g

	Shell405	KC12GA	S405
#14-18	160	166	150
#25-30	154	181	147

6) Strength of catalyst granules

We measured the strength of catalyst granules using a piston-cylinder. Stronger granules mean a long catalyst lifetime.

Table 6 Strength of catalyst granules [%]
Precision ±4.8 %

	Shell405	KC12GA	S405
#14-18	78.6	75.2	91.6
#25-30	84.3	88.8	97.4

We loaded 451N per 2.5g of catalyst, and measured the percentages of undestroyed catalyst.

Because of its size,#25-30 is stronger than #14-18, and S405 is strongest.

7) Density of catalyst granules

We measured the densities of catalyst granules. Though we don't know whether this property is important, we can compare catalyst data.

Table 7 Density of catalyst granules [g/ml]
Precision ±0.05 g/ml

	Shell405	KC12GA	S405
#14-18	1.52	1.47	1.51
#25-30	1.56	1.5	1.56

There are no large differences among catalysts.

8) Diameter distribution of catalyst granules

Diameter distributions were measured with a sieve. Narrow distributions imply good manufactuirng quality of the catalysts.

Table 8 Diameter distribution of catalyst granules [%]

	Shell405	KC12GA	S405
#14-18	Over 5.8% Under 4.2%	Over 0.2% Under 4.1%	Over 2.6% Under 2.1%
#25-30	Over 1.9% Under 6.1%	Over 0.2% Under 5.2%	Over 2.0% Under 1.0%

KC12GA and S405 are narrower than Shell405.

This data didn't demonstrate which catalyst is best, but we concluded that all catalysts might be usable. Therefore, we could choose both KC12GA and S405 for thruster tests.

Because of S405 catalyst transfer program delays, we had to conduct KC12GA firing tests.

(In this proceeding, S405 and KC12GA material tests results are presented together. However, the KC12GA tests were conducted six months before S405 tests.)

Firing tests of 20N class thruster using KC12GA

We conducted a series of tests with two KC12GA thrusters.

Tests flow :
1. Valve and thruster function tests
2. Vibration tests
3. Firing tests
4. Valve and thruster function tests

Tests conditions were decided to satisfy SELENE and WINDS request, for example, thrust, Isp, vibration level, total impulse, total number of pulses and firing mode (On-Off time).

In this paper, we will mention only firing tests.

Fig.7 20N class Thrusters

Table 9 The targets of 20N firing tests

Thrust (Beginning of Life)		18.6~16.6N @2.07MPa
Isp (Beginning of Life)		> 225 @2.07MPa
Total Impulse [Ns]		> 300,000
Total number of pulses		> 100,000
Firing mode	On time	0.031sec ~ 2000sec
	Pulse width	0.1 sec ~ 2000sec

Fig.7 shows the tested thrusters. We always prepare at least two thrusters when firing test. That is for reducing uncertainty.

Table 9 shows the test target. The most important target is total impulse and total number of pulses. As mentioned, thruster lifetime is determined by catalyst lifetime. Catalyst lifetime is influenced by the these values and firing mode.

But we cannot demonstrate exactly the same firing mode on orbit.This is partly because no one could guess the disturbance of actual satellite, and partly because actual firing modes on orbit are too long off time to simulate on ground testing. So, we set mission duty cycle for ground test, which simulates typical firing modes of satellite, with enough margin on both cumulative impulse and cumulative pulses.

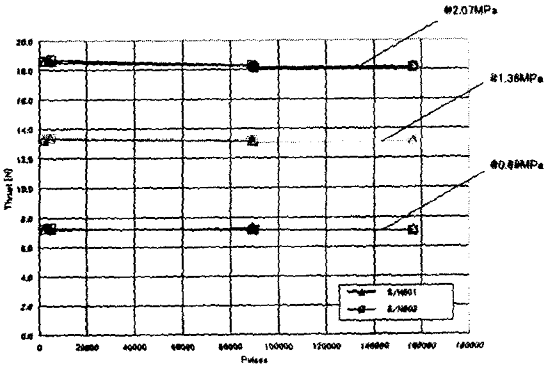


Fig.8 Thrust trend of 20N thrusters

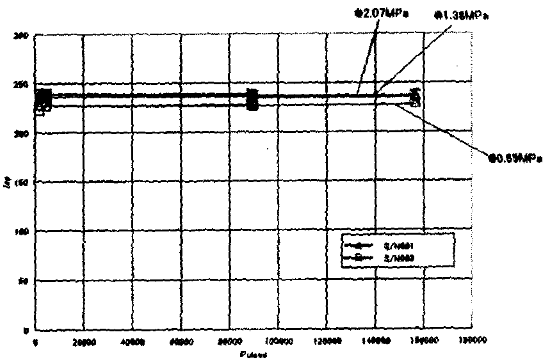


Fig.9 Isp trend of 20N thrusters

Table 10 The results of 20N firing tests

Thrust (Beginning of Life)		Demonstrated
Isp (Beginning of Life)		Demonstrated
Total Impulse [Ns]		263,036 S/N001 262,846 S/N003
Total number of pulses		157,352 S/N001 157,252 S/N003
Firing mode	On time	Demonstrated
	Pulse width	Demonstrated

Fig.8 and Fig.9 present the trends, and there are no drop of performances. We took X-Ray photographs of catalyst bed, no void was recognized.

Table 11 present the tests results. The total impulse was insufficiency, this is not for firing tests malfunction, but schedule delay.

Though there were some shortage from target, number of pulses are enough, because this targets had much margin. Therefore we could confirm that KC12GA is suitable for 20N thruster and our missions (SELENE and WINDS).

Firing tests of 4N class thruster using KC12GA and Shell405

We conducted a series of 4N thruster tests with two KC12GA and two Shell405.

Shell405 thrusters were made in 2002. A little firing tests were already conducted, and kept for one and half years. We used them for comparing data of two catalyst thruster firin smaller thrusters tend to have shorter life time. Though KC12GA catalyst were suitable for 20N thruster, we have to confirm using 4N thruster.

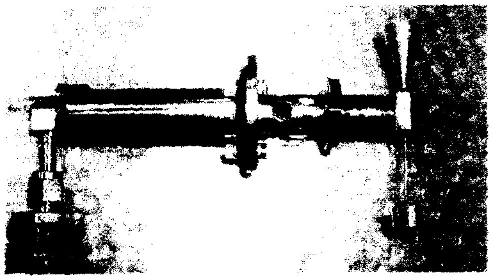


Fig.10 4N class Thruster

Table 11 The targets of 4N firing tests

Thrust (Beginning of Life)		5.7～4.32N @2.41MPa
Isp (Beginning of Life)		＞214 @2.41MPa
Total Impulse [Ns]		＞300,000
Total number of pulses		＞600,000
Firing mode	On time	0.015sec ～ 3600sec
	Pulse width	0.1 sec ～ 3600sec

At the beginning of the firing tests, KC12GA and Shell405 thruster indicated almost same performances, except thrust.

This thrust difference was due to the difference of pressure drop, which was controlled by orifice.. KC12GA thruster used larger size orifice, so KC12GA indicated larger thrust. We think that this thrust difference didn't affect catalyst lifetime too much. We recognized large thrust drop on one of Shell 405 thrusters, after completing 314,571 pulses. large thrust drop was measured in one of the Shell405 thrusters, and Isp was also dropped. (but it's not large.)

We took X-Ray Images of all thrusters. 4N thruster catalyst bed is separated upper and lower bed. X-Ray images showed that there were approximately 35% voids in the upper catalyst bed. (see Fig.13) This was caused by the catalyst granules break-up.

But at that time, there were no void in the other Shell405 thruster and KC12GA thrusters, and there were no differences in these thrusters performances.

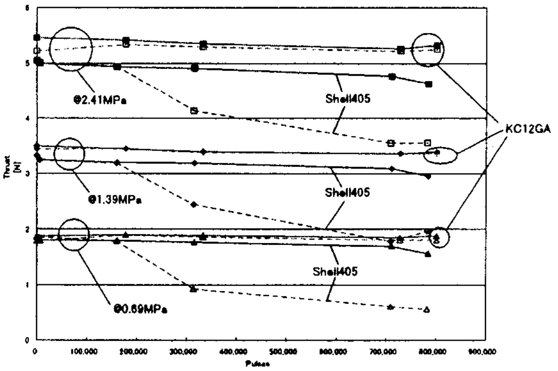


Fig.11 Thrust trend of 4N thrusters

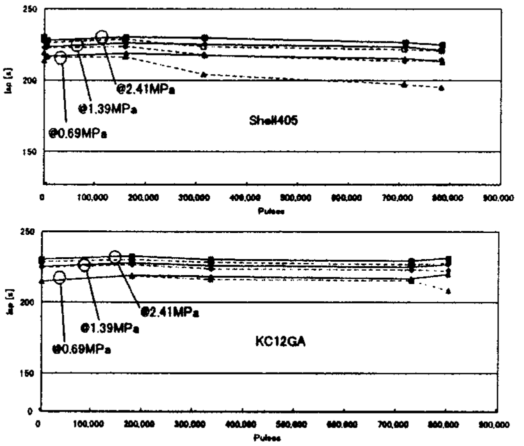


Fig.12 Isp trend of 4N thrusters

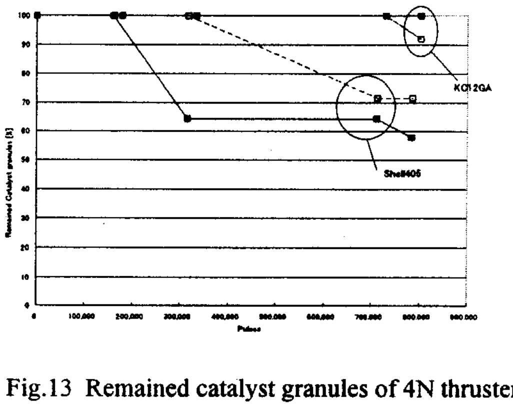


Fig.13 Remained catalyst granules of 4N thrusters

At 711,474 pulses, the second Shell405 thruster's thrust dropped, and then some voids was found out. But this drop was not large as first one.

At the end of these tests, 30 to 40% of Shell405 was lost from upper the catalyst bed. But on the other hand, KC12GA loss was only a few %.

In Table 12, tests results are shown. Shell-1 thruster achieved less than 300,000 Ns, and All KC12GA thruster achieved over 300,000 Ns. From this results, we knew that though BOL performances of KC12GA and Shell405 are almost same, KC12GA had longer lifetimes than Shell405.

We don't have clear idea of why KC12GA lifetime is longer. In material tests, there are no large differences between Shell405, S405 and KC12GA.

We estimate that a little differences of surface structure will affect hydrazine liquid vaporization, and it will lead to mild reaction.

On the other hand, there is a possibility that shell405 thrusters were damaged by the firing tests 2 years ago.

Anyway, we confirmed that KC12GA matched to 4N thruster and our missions.

Table 12 The results of 4N firing tests

Thrust (Beginning of Life)		Demonstrated
Isp (Beginning of Life)		Demonstrated
Total Impulse [Ns]		282,884 Shell-1 346,674 Shell-2 369,689 KC12GA-1 368,786 KC12GA-2
Total number of pulses		783,435 Shell-1 785,382 Shell-2 802,224 KC12GA-1 802,224 KC12GA-2
Firing mode	On time	Demonstrated
	Pulse width	Demonstrated

Conclusions

We conducted three tests.

1) catalyst material tests,
2)20N thruster firing tests using KC12GA,
3)4N thruster firing tests using KC12GA and Shell405.

From these results, we confirmed that KC12GA is suitable for 20N and 4N class thruster catalyst. And KC12GA lifetime is longer than Shell405 catalyst.

Now we are conducting S405 catalyst firing test with 1N class thruster.

References

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[2] H. C. Hern : Effect of Duty Cycle on Catalytic Thruster Degradation, AIAA81-4151