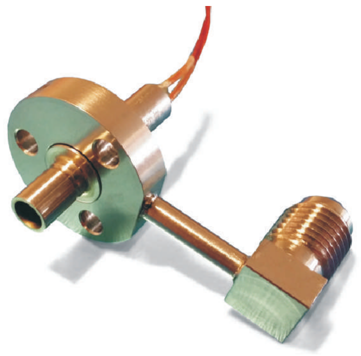
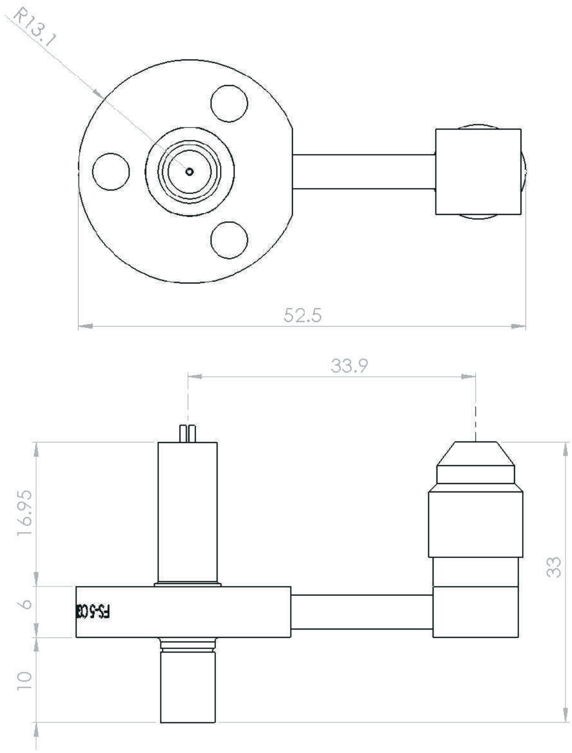
**AST Advanced Space Technologies GmbH**

# Cold Gas Thruster (CGT)






AST's miniaturized nitrogen cold gas thrusters provide a thrust of 42 mN at more than 69 s specific impulse. The fast switching thruster allows very small impulse bits of 110 µNs. Combined with its exceptional lifetime of more than 1 billion ($10^9$) actuations this opens up new operational modes of small satellite fine control.

The thrust level is linear with the inlet pressure. Together with our electronic pressure regulator it is possible to adjust the thrust level in flight.

The CGT has been fully qualified in the frame of the FORMOSAT 5 mission.

| Performance Characteristics | |
|---|---|
| Operating Media | $GN_2$ |
| Inlet Pressure (MEOP) | 1 … 6 bar |
| Proof Pressure | 2 x MEOP |
| Burst Pressure | 4 x MEOP |
| Internal Leakage | < $10^{-6}$ sccs GHe |
| External Leakage | < $10^{-8}$ sccs GHe |
| Thrust | 28 mN / bar<br>42 mN @ 1.5 bar $N_2$ nominal |
| Minimum Impulse Bit | 110 µNs @ 1 bar |
| Specific Impulse | > 69 s |
| Weight | 0.042 kg |
| Operating Voltage | 22 … 36 V pull in<br>50% hold |
| Coil Resistance | 140 Ohm |
| Operational Temperature Range | -30° … +80° C |
| Vibration | > 20g RMS |
| Lifetime | 1 million actuations qualified<br>1 billion actuations demonstrated |
| Other media | GXe |

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# Lifetime Test of a Cold Gas Thruster

By Hans-Peter HARMANN and Heiko DARTSCH

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AST Advanced Space Technologies GmbH developed a 47 mN cold gas thruster for fine point missions. A precise pointing control requires an agile actuator with short reaction time and small impulse bits. The developed thruster allows short pulses of 20 µNs with pulse rates of up to 100 Hz. At high repetition rates the total number of actuations over lifetime becomes a demanding requirement. AST already showed up the potential of the used valve technology during the development of a miniaturized xenon flow control unit. In the presented test campaign the lifetime actuations of the cold gas thruster (engineering model, EM) have been demonstrated for more than one billion ($10^9$) actuations before the test was suspended for a long term storage test. It is intended to continue the test after the storage test. After the EM development the flight models (FM) have been produced. The formal qualification of the cold gas thrusters for the FORMOSAT 5 mission was performed by SpaceTech GmbH. This mission requires "only" 1.5 million actuations. After end of the qualification, it has been decided to continue with an extended campaign to cover the billion actuations by a formal verification process.

**Key Words:** Cold Gas Propulsion, Thruster, Formosat 5, Qualification, Lifetime test

## 1. Introduction

Formosat 5 is a small LEO earth observation satellite of 525 kg mass. Designed and developed by the Taiwanese Space Organization NSPO, it will provide a panchromatic imaging from a sun synchronous orbit at 720-km altitude. The five years mission is planned to be launch on a Falcon 9 rocket in 2016.

The satellite is controlled by four cold gas thrusters (CGT) with 47 mN thrust each at 1.5 bar(abs). These thrusters have been designed, developed and manufactured by AST Advanced Space Technologies GmbH (AST). A special feature of this type of thruster is the high number of lifetime actuations. This had been demonstrated on valve component level during the development of a xenon flow control unit. For the CGT development a dedicated lifetime test campaign has been conducted to investigate the lifetime capability and the stability of relevant thruster parameter. A second campaign in the frame of an extended thruster qualification program is ongoing.

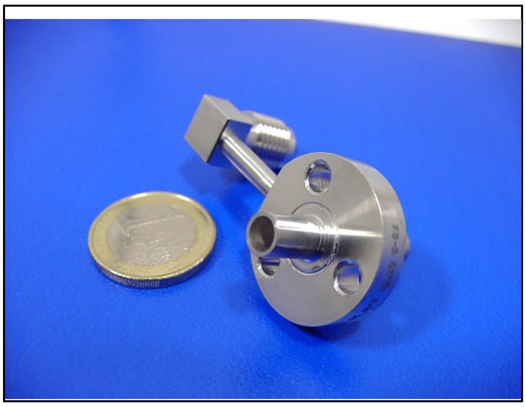

Fig. 1. AST's Nitrogen cold gas thruster

## 2. Cold gas thruster design

The CGT consists of the solenoid valve, a nozzle, a mechanical interface plate and the fluidic interface. The modular configuration allows the change of the nozzle diameter or the fluidic interface without modifications of the other parts

Table 1. CGT key figures

| | |
|---|---|
| mass | 43 gram |
| nom. thrust | 47 mN @ 1.5 bar $N_2$ |
| specific impulse | >69s |
| switch on time | <1ms |
| op. voltage range (pull-in) | 22 to 36 V |
| resistance | 140 Ohm |
| min. power (pull-in / hold) | 3.5 W / 0.1 W (typ. 0.25 W) |
| temperature range | -25°C to +60°C |

## 4 Development tests (accelerated lifetime test)

### 4.1. Test set-up

The accelerated lifetime test campaign has been conducted on an EM during thruster development. The tested EM was identical to the later FMs but taken from a first pre-series production batch (figure 3).

The purpose of the test was to improve our knowledge on mechanical lifetime limitations and wear effects.

For the test the CGT was connected to a pressurized Nitrogen gas supply and placed under ambient condition in the lab. A pressure sensor and a flow meter in the inlet line to the thruster monitored the propellant flow.

For an accelerated lifetime test the major stress and wear effect has to be applied in a representative way. For the CGT the switching transient of the valve introduces the major stress and wear on mechanics and seal elastomer. In a stable open or close position the remaining wear (gas dynamic wear on seal) can be neglected compared to the transient.

The AST CGT is able to open within less than a millisecond and close within 2 millisecond. The accelerated test operated the thruster at 100 Hz with 50% duty factor, so that the armature had three to four milliseconds to come to rest after a

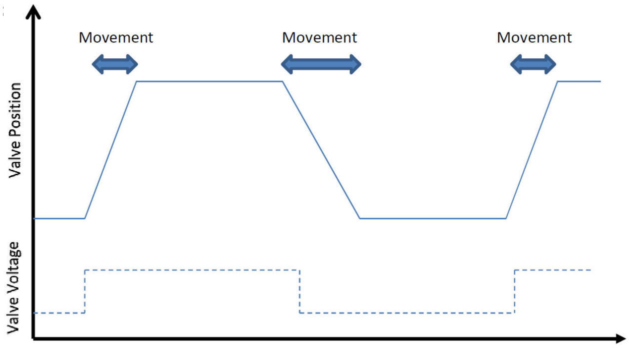


Fig. 2. Valve operation during accelerated lifetime test

With this operation scheme it is possible to perform more than eight million cycles a day. The total campaign operated the valve for one billion operations without applied gas flow and 100 million cycles with nominal gas flow. In total more than 30 kg Nitrogen has been consumed by the CGT.
Each working day of the half year test campaign the cycling was interrupted for measurement. For the measurement the gas flow was established at inlet pressure of 2.5 bar(abs). The capability to control the average flow by pulse width modulation has been investigated for different working points. A working point with duty factor of 0% was included to demonstrate the shut-off capability.

Fig. 3. Cold gas thrusters of pre-series production batch

### 4.2. Test results

During the first 250 million cycles a slight increase of the full flow by 3% has been determined. This is in correlation with former lifetime measurements on component level. The effect is related to a setting of the elastomer. For the following 500 million cycles the flow level stays pretty constant. After a total of 700 million actuations the flow a very slight tendency to decline. The same trend was detected for the throttled flow levels.

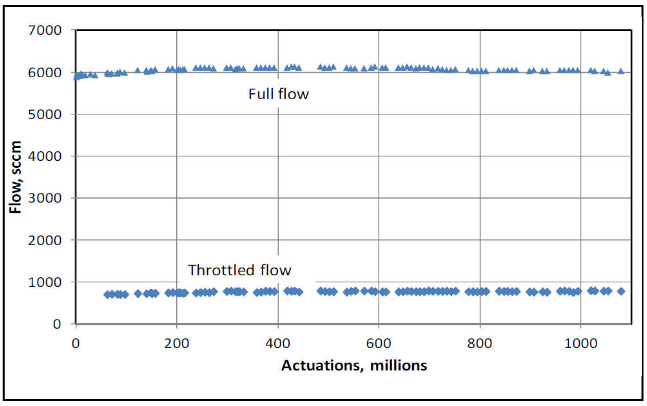


Fig. 4. Variation of the flow over lifetime

Over the full test time the variations in the mass flow for all working points remained within 3% of the starting conditions. The thruster was able to shut down below the sensitivity of the flow meter.
After the end of the test campaign the thruster was still functional. It has been removed from the set-up and put into a long storage test.

## 5. Qualification (QM)

### 5.1. Test set-up

The thruster qualification for Formosat 5 has been done in a combined acceptance and qualification test campaign. Six FM thrusters have been tested in parallel by SpaceTech GmbH Immenstaad (STI). One of the CGTs was applied to the extended qualification test levels. After all qualification tests (functional, pressure proof, vibration, thermal vacuum) the QM was sent to AST for lifetime testing.
The QM was placed in AST's vacuum test facility to provide representative operational conditions especially with respect to the gas flow dynamics.

Fig. 5. AST's vacuum facility

The inlet of the thruster was connected to a pressurized Nitrogen gas supply. The inlet pressure and gas flow was monitored by a pressure sensor and a Bronkhorst flow meter. The tests have been conducted with nominal inlet pressure of 1.5 bar (abs) to operate the thruster at the nominal working point.
During the qualification at STI the QM accumulated 340 thousand actuations. The total lifetime verification had to demonstrate 1.5 million cycles including a 50% margin.
The resulting 1.2 million cycles of the lifetime test had been split into 18 test blocks. At the beginning of the campaign each test block included 50K cycles, later after gaining confidence in the stable operation this has been increased to 100K cycles. The pulse frequency of the CGT was set to 15.4 Hz. Each day the thruster was shut down for about 16h simulating a non-operation phase.

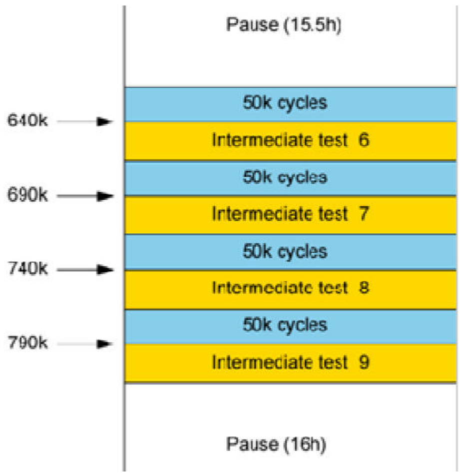


Fig. 6. Typical schedule of test blocks

Between each test block the

- coil resistance
- set-on time
- set-off time
- mass flow
- helium leakage rate at 1.5 bar GHe (integral)

have been measured to provide a monitoring of potential changes. The switch times and the electric parameters are sensitive probes for changes or failures in the internal mechanics of the valve or in its magnetic circuit. If the force of the spring, the magnetic force or dimensions between components change then the set-on/set-off voltages and with them the switch time will shift.

Before and after the test campaign

- HV insulation
- minimum open voltage,
- minimum hold voltage

have been checked.

### 5.2. Test results

**a) Coil resistance**

The coil resistance of 138 Ohm stayed constant over the full campaign.

**b) Set-on time / set-off time**

The set-on and set-off switch times have been measured for different voltage levels. Within the measurement accuracy the values did not change.
This is a clear indications that the internal conditions of the valve remained unchanged throughout the test.

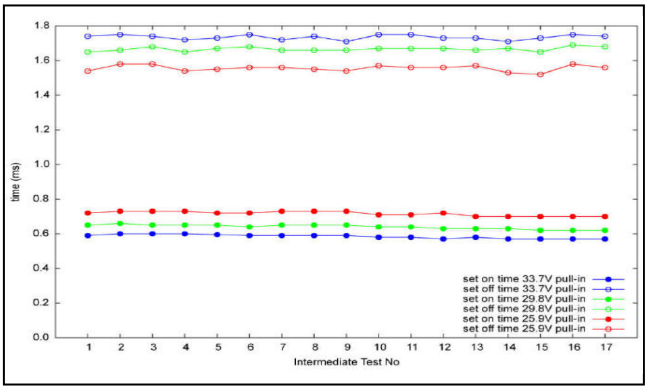


Fig. 7. Set-on time and set-off time stability

**c) Mass flow**

The measured mass flow at 1.5 bar(abs) and therefore the thrust level at nominal working point remained unchanged. The average value was 3320 sccm Nitrogen.

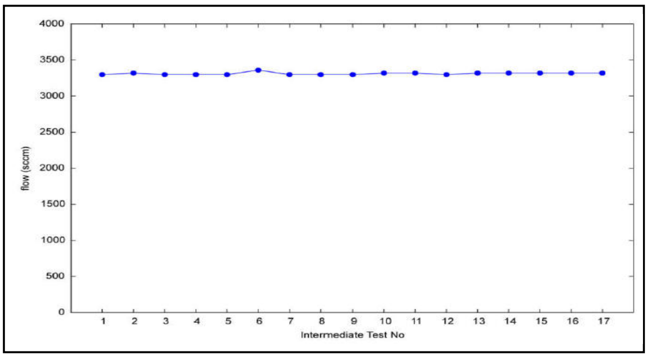


Fig. 8. Mass flow (thrust) stability

**d) Helium leakage**

The helium leakage test measured the integral leakage rate i.e. all leakages from seat leakage, welds, tubing and screw fittings inside the vacuum chamber. The rate has been determined at pressure of 1 bar(abs) and 1.5 bar(abs) GHe after elastomer saturation. Therefore the leakage includes also the Helium diffusion rate through FKM bulk material.
A slight trend to higher leakage rates can be determined over lifetime but far below the requirement of $2*10^{-5}$ mbar l/s. This is in correspondence with elastomer setting and run-in effects. An extended lifetime cycling campaign intended for 2016 will verify if the leakage stabilizes for higher lifecycles as expected or if the trend continues.

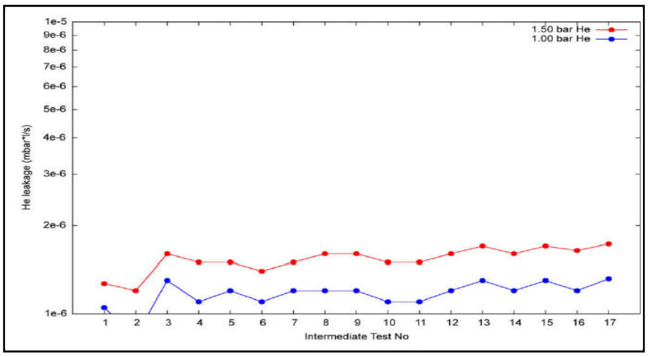


Fig. 9. Development of the leakage rate

**e) HV insulation test**

The high voltage insulation test at 500 V provided proof that the electric interface was still in good condition and without any non-conformances after the test.

**f) Minimum open voltage / minimum hold voltage**

The minimum open voltage and the minimum hold open voltage has been determined for nominal pressure before and after the cycling test. The values were 8V for the minimum open voltage and 2.2 V for the minimum hold voltage without changes.

## 5. Summary and conclusion

The AST CGT demonstrated an outstanding lifetime capability of more than one billion actuation cycles on an EM. In a formal space qualification program the thruster has been qualified for a 1.5 million cycles (incl. 50% margin) as it is state-of-the-art for today's mission scenarios.

## 6. Outlook

After the lifetime cycling test the QM has been put into a long term storage test. After one year of storage the thruster shall be remounted inside the vacuum chamber to continue the cycling in an extended lifetime campaign.

The huge number of lifetime cycles and the capability for short pulse times open the floor to pulse modulated cold gas propulsion. New mission scenarios with dynamic and precise attitude control become possible. A system concept exploiting these benefits is under investigation in cooperation with SpaceTech GmbH Immenstaad.

**Acknowledgments**

We would like to thank SpaceTech GmbH Immenstaad for the good cooperation during the thruster development and during the qualification test campaign.

## References

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2) Rothaus, S.. et. al.: *µFCU - Results of a Prequalification Test Campaign,* IEPC-2013-228, 33rd International Electric Propulsion Conference, Washington D.C., USA., Oct. 2013

3) Harmann, H.-P., Dartsch, H., Werner, E. *Low Drift Thrust Balance with High Resolution,* IEPC-2015-257, 34rd International Electric Propulsion Conference, Kobe, Japan, July 2015

# Cold Gas Thruster Qualification for FORMOSAT 5

By Hans-Peter HARMANN[1)], Tammo ROMBACH[2)] and Heiko DARTSCH[1)]

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[2)]*SpaceTech GmbH, Immenstaad, Germany*

Four cold gas thrusters will be used to control Taiwan's FORMOSAT 5 satellite. The thrusters have been developed and qualified by AST Advanced Space Technologies GmbH together with SpaceTech GmbH Immenstaad. The lightweight 43 gram thrusters provides a thrust of 46 mN at 1.5 bar(a) N2 with an ISP above 69 seconds. Low leakage of below $10^{-5}$ mbar l/s limits the gas loss during off times to a very low level. The thruster can be driven with a wide range of voltages from an unregulated bus and has design that allows an easy adaption to different mechanical interfaces. During the qualification program in 2014 the thrusters have been tested for the mission requirement of one million actuations. Based on the results of a parallel lifetime demonstration test (one billion actuations), it has been decided to extended the qualification program. The extended lifetime qualification is currently running.

**Key Words:** Cold Gas Propulsion, Formosat 5, Qualification

## 1. Introduction

Formosat 5 is a small LEO earth observation satellite of 525 kg mass. Designed and developed by the Taiwanese Space Organization NSPO, it will provide a panchromatic imaging from a sun synchronous orbit at 720 km altitude. The five years mission is planned to be launch on a Falcon 9 rocket in 2016.
NSPO was supported by SpaceTech GmbH Immenstaad (STI) in several fields including the propulsion system. The satellite is controlled by four cold gas thrusters. These thrusters have been design, developed and manufactured by AST Advanced Space Technologies GmbH (AST) especially for the Formosat 5 program. The qualification and acceptance testing has been mainly conducted by STI at their large vacuum test facility.

## 2. Cold gas thruster development

The cold gas thruster (CGT) bases on a miniaturized solenoid valve with low leakage and a unique lifetime capability. It has been converted and prequalified for space applications in a xenon flow control development program ("µFCU")[1), 2)] funded by the European Commission.
The development of the CGT has been initiated on the request of SpaceTech GmbH. As the satellite design was already frozen, the thruster design had to fit into the specified geometric envelope and electrical properties and operational schemes had to be met.
The development itself has been carried out in less than 2 years including an EM phase, FM production and qualification starting in February 2013.

### 2.1. Design

The CGT consists of the solenoid valve, a nozzle, a mechanical interface plate and the fluidic interface. The modular configuration allows the change of the nozzle diameter or the fluidic interface without modifications of the other parts.

Table 1. CGT key figures

| | |
|---|---|
| mass | 43 gram |
| nom. thrust | 46 mN @ 1.5 bar $N_2$ |
| specific impulse | >69s |
| switch on time | <1ms |
| op. voltage range (pull-in) | 22 to 36 V |
| resistance | 140 Ohm |
| min. power (pull-in / hold) | 3.5 W / 0.1 W (typ. 0.25 W) |
| temperature range | -25°C to +60°C |
| lifetime actuations | 1.5 million (qualification)<br>1.1 billion (demonstrated and under qualification) |

The nozzle design was supported by the Deutsches Zentrum für Luft-und Raumfahrt (DLR) at Göttingen. The DLR used their simulation tools to predict the flow characteristic and the performance of the CGT. EM tests to verify the simulations have been carried out at one of DLR's vacuum chambers. These tests included thrust measurements on a thrust balance[3)] to determine the specific impulse and the investigation of the "thrust on" delay using a Pitot probe. As best compromise a 15° cone nozzle with 0.6 mm throat diameter has been chosen.

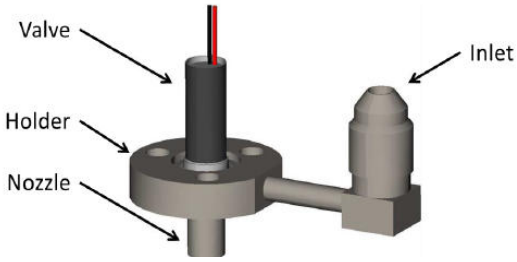


Fig. 1. AST's cold gas thruster design

## 2.2. Performance

The basic performance characterization has been done using EM thrusters that were identical to the FMs but produced in a first pre-series production step. The thruster was mounted on top of a thrust balance capable to measure thrusts between 0.1 mN and 1000 mN (figure 2). Then a set of firing demonstrated the good reproducibility of the thrust level. From the repeated measurements the specific impulse has been derived as 70.4 seconds at nominal inlet pressure of 1.5 bar.

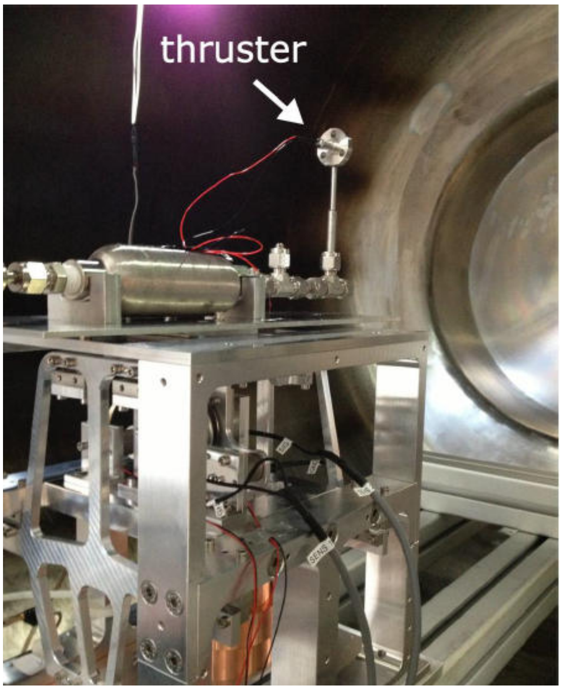


Fig. 2. CGT EM on top of thrust balance at DLR

Table 2. Thrust measurements for $I_{sp}$ determination

| Thrust mN | Mass Flow mg/s | $I_{SP}$ s |
|---|---|---|
| 42.6 | 61.6 | 70.4 |
| 42.3 | 61.6 | 69.9 |
| 42.6 | 61.6 | 70.4 |
| 42.3 | 61.6 | 69.9 |
| 42.5 | 61.6 | 70.3 |
| 43.1 | 61.6 | 71.2 |
| 42.8 | 61.6 | 70.7 |

$$\text{Average } I_{SP} = 70.4\,\text{s} \pm 0.5\,\text{s}$$

The thrust and the $I_{sp}$ for a given mass flow at constant temperature is defined by the nozzle geometry. As all nozzles are manufactured in a reproducible and precise way, the $I_{sp}$ is assumed to be valid for all thrusters of this configuration. For the further measurement campaigns only the mass flow has been monitored to determine the equivalent thrust level.

## 3. Operation

The thruster operational profile for Formosat 5 was already defined as AST started the development. The thruster is operated in pull-in / hold mode with a fixed pull-in time of 50 ms. The minimum pull-in time is defined as 2.5 ms.

The CGT is designed for a pull-in voltage between 22V and 36V and a hold voltage above 6 V to allow the supply from an unregulated bus.

## 5. Manufacturing

A batch of ten thrusters has been manufactured for the Formosat 5 project. One was used for production process monitoring. Four flight models (FM), one flight spare and one qualification model have been delivered to STI for acceptance and qualification testing. These thrusters have been selected from the batch for best matching of the mass flow. By the selection process the variation between any FM is less than 1.3% while the maximum allowed variation is 5%.

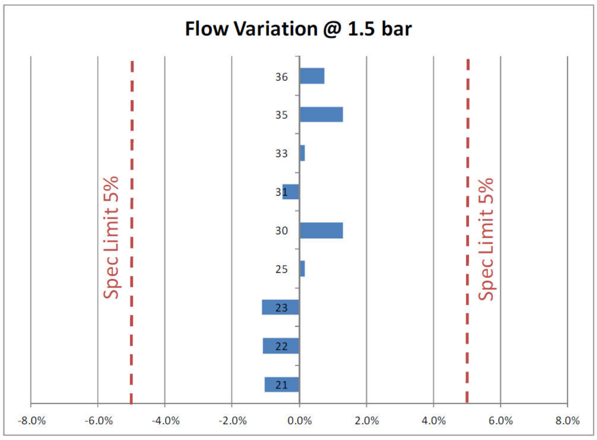


Fig. 3. Mass flow variations within the series production batch

The CGTs have been fully welded with electron beam welding and laser welding processes. The electrical interface has been vacuum potted. In a final step before delivery each thrusters has been precision cleaned and dried.

After delivery, STI added a diode clamping circuit to the CGT harness.

## 4. Qualification and acceptance testing

### 4.1. Test philosophy

A valve similar to the one used for the CGT had already demonstrated its capabilities and quality within the flow control development program. These tests included a lot of margin compared to the requirements of Formosat 5.

It has been decided to do the acceptance test and the qualification test in one shared test. The FMs are tested to acceptance level while the QM is tested with additional margins.

Core parameters of the CGT have been verified twice. Once at AST in the frame of a factory acceptance test and the second time within the official acceptance and qualification test performed by STI.

The acceptance and qualification program includes

- function performance tests including electric parameters and insulation test
- leakage test (repeated between individual tests)

- proof pressure test
- thermal balance and thermal cycling test (TV)
- vibration test

After the qualification tests the QM has been sent to AST for lifetime test. The lifetime test has been carried out in AST's vacuum facility for a total of 1.5 million actuation cycles (incl. 50% qualification margin).

### 4.2. Functional and performance tests

The mass flow depends linearly on the inlet pressure. During the acceptance tests the pressure has been varied between 0.8 bar and 5 bar covering an equivalent thrust range between 25 mN and 160 mN.

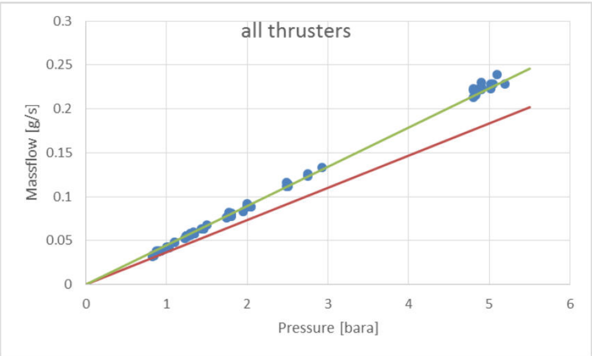


Fig. 4. Linear flow response to inlet pressure for all tested thrusters. The green and the red lines showing the thrust requirement range.

The functional and performance test also includes the electric insulation test and the determination of characteristic parameters as set-on voltage, hold voltage and switch times.
The switch times have been measured electrically. The acceleration of the valve armature as it hits the rest induces a voltage that drives a current. In the current time diagram the impact is visual as small dip.

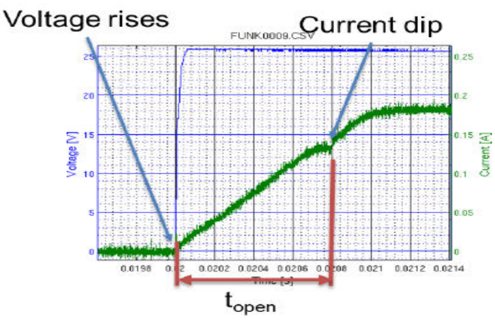


Fig. 5. Determination of the switch on time

The switch time and the electric parameters are sensitive probes for changes or failures in the internal mechanics of the valve or in its magnetic circuit. If the force of the spring, the magnetic force or dimension between components change then the set-on/set-off voltages and the switch time will shift.
Therefore the switch times have been measured for each thruster after each intermediate test.
Figure 5 shows the switch times for different pressures and voltages exemplarily for one valve (S/N 30 QM) throughout the full acceptance and qualification test campaign. The small number at each entry give the voltage level. The switch time depends slightly on pressure and voltage but stays unchanged after all stress tests.

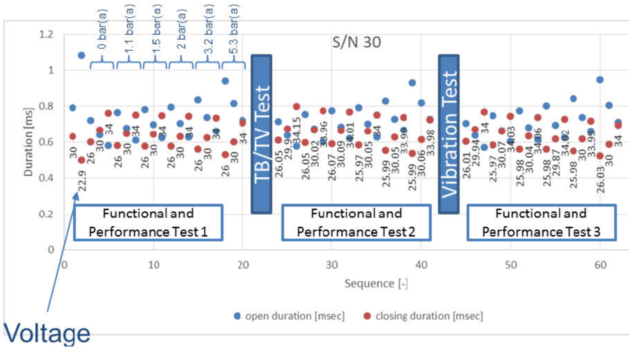


Fig. 5. Switch time stability of CGT S/N 30 (QM) during qualification test

A further parameter monitored through the test campaign is the mass flow and respectively the thrust of the CGT. This parameter remained very constant over the full test campaign. All requirements have been met.

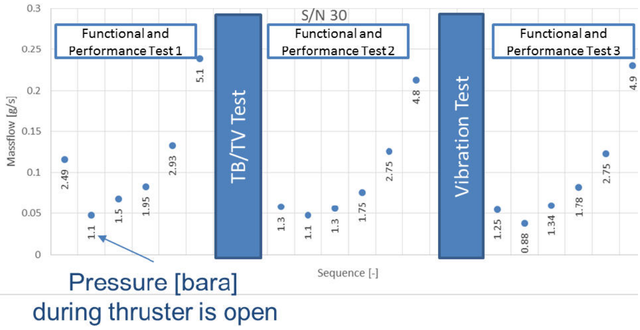


Fig. 6. Mass flow stability of CGT S/N 30 (QM)

### 4.3. Leakage test

The leakage requirement defines a limit of $2*10^{-5}$ mbar l/s GHe. The measured leakage values (helium leak tester) were measured as being below $10^{-6}$ mbar l/s. This very low leakage was not influenced by any stress test. Figure 7 shows the measure leakage levels (small numbers give the serial number of the CGT). The variation are resulting from measurement uncertainty in the $10^{-7}$ mbar l/s range.

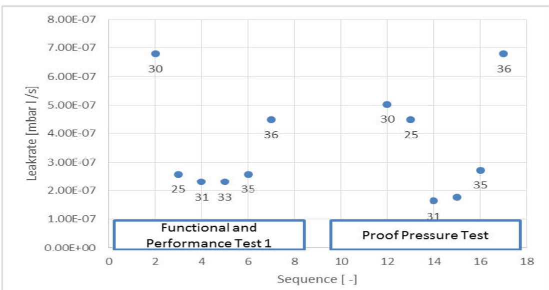


Fig. 7. Leakage stability of all thruster

### 4.4. Proof pressure test

For the proof pressure test an inlet pressure of 6.5 bar(abs) was applied. Before and after the test the electric parameters, the switch time and the leakage has been measured.

### 4.5. Vibration test

While the EM flow control unit had been tested to levels of up to 21.5 gRMS the Formosat 5 requirements for the CGT were much more relaxed. It has been considered as no risk to test all thrusters in parallel to qualification level. The six thrusters have been mounted on a representative support structure including a flight similar pipework.

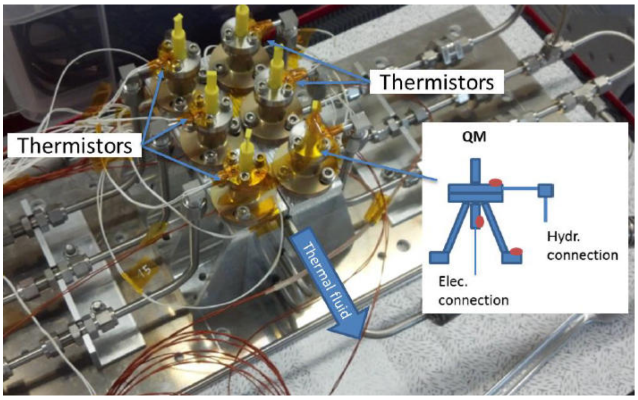


Fig. 8. Test set-up for thermal vacuum test and vibration test at STI

Table 3. Vibration levels of random vibration test (top: in plane, bottom: out of plane)

| sensor position | model | g-rms value test | g-rms value qualification | g-rms value acceptance |
|---|---|---|---|---|
| 1y | QM | 13.1 | 12.2 | 8.7 |
| 2y | FM | 14.4 | 12.2 | 8.7 |
| 3y | FM | 13.4 | 12.2 | 8.7 |
| 4y | FM | 12.7 | 12.2 | 8.7 |
| 5y | FM | 12.4 | 12.2 | 8.7 |
| 6y | FM | 12.3 | 12.2 | 8.7 |

| sensor position | model | g-rms value Test | g-rms value qualification | g-rms value acceptance |
|---|---|---|---|---|
| 1x | QM | 17.1 | 17.3 | 12.2 |
| 2x | FM | 15.4 | 17.3 | 12.2 |
| 3x | FM | 17.7 | 17.3 | 12.2 |
| 5x | FM | 17.4 | 17.3 | 12.2 |
| 6x | FM | 18.1 | 17.3 | 12.2 |

During vibration the leakage has been measured by monitoring the pressure decay in the pressurized system. All thrusters survived the test without pressure loss and without any changes in the electric parameters or switch times.
The alignment of the thrusters has been determined with a mirror and an autocollimator before and after the vibration test. The potential variation stayed within the measurement error of 0.2°.

### 4.6. Thermal vacuum test

During thermal vacuum test the CGT performance for the operational and non-operational temperature range has been determined. For thermal stress investigation eight temperature cycles have been performed under vacuum.
The FM acceptance test applied operation temperatures between -20°C and +50°C and non-operational temperatures between -30°C and +60°C. The QM was operated at the elevated range to cover the required test margins. During the former EM flow control development program the valves showed their viability for operational temperatures between -40°C and +80°C.

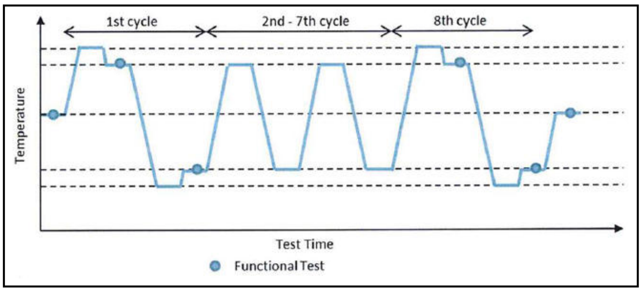


Fig. 9. Temperature cycle profile

### 4.7. Lifetime test

During the former EM test campaign the CGT demonstrated a total of 1.1 billion actuation cycles without failing. For the Formosat 5 project "only" 1.5 million cycles are required including 50% qualification margin.
The lifetime test has been performed within AST's vacuum facility (50 cm diameter). The thruster has been fired under representative conditions with nominal nitrogen mass flow and nominal pull-in / hold operation.
Each 50K cycles (later 100K) the pulsing has been stopped for leakage, switch time, electric parameter and mass flow tests. After the test the pulse operation continued.

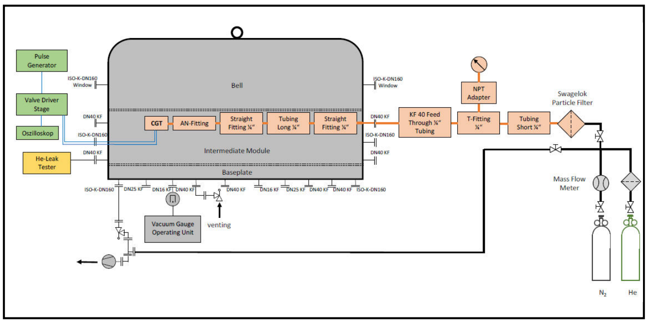

Fig. 10. Test set-up of lifetime test at AST

For the tested 1.5 million actuation cycles no variation or drift of the measured parameters beyond the measurement noise have been found.[4)]
After the lifetime test the QM has been put to storage for a long term storage test (not part of the qualification) of about one year. Then the QM shall be reinstalled into the vacuum chamber to continue the lifetime test in an extended qualification.

### 5. Summary and conclusion

Five FM thrusters and one QM have been successfully tested. All requirements have been verified and met. The operation of the AST CGT has been proven to be very stable and reproducible. The FMs have been delivered and integrated into the Formosat 5 satellite waiting for the launch expected in 2016.

## 6. Outlook

After the qualification according the Formosat 5 specification an extended qualification program using the QM is planned. This program shall qualify the CGT for higher lifetime cycles that already have be demonstrated on EM level[4].

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