

# Subscale Lifecycle Test of Thermal Arcjet Thruster TALOS for the Lunar Mission BW1

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The performance of the thermal arcjet thruster TALOS for the lunar mission BW1 has been investigated during 30 hours of operation. The operation cycles of this investigation were one hour on / one hour off cycles as planned during operation on-board the satellite. The aim of this investigation is the determination of performance changes due to nozzle throat closure or expansion as well as ignition reliability and thruster operation during the ignition phase. During the test campaign, the thruster is operated in current regulated mode with an initial electrical power of 700 W. The mass flow rate for ignition is set to 28 mg/s, for the phase from ignition to stable operation to 35 mg/s and for stable operation to 25 mg/s. This results in an average of 26 mg/s during the one hour operation for all conducted tests. This is well within the mission requirement of a mass flow rate between 20 and 30 mg/s. The so-called burn-in period of the thruster, where the voltage of the thruster and thus the electrical power continuously increases, is identified to end after 15 hours of operation. Optical inspection and determination of the nozzle throat diameter is conducted prior to thruster operation and after 1, 5, 10, 20 and 30 hours of operation. The result of this investigation shows an overall increase in nozzle throat diameter from 0.6 mm prior to experiment to 0.66 mm after 30 hours of operation. However, it is found that this increase in the nozzle throat diameter has no major effect on thruster performance. During thruster operation, fluctuations of voltage and therefore feed line pressure occurred up to a maximum of seven times during one test. This fluctuations have been found to be non-critical for thruster operation, but further investigations on this phenomenon are going to be conducted. Although the ignition reliability is very high, sparks occurred at ignition occasionally. This is identified to be one of the major reasons for anode erosion. It is supposed that a change of propellant injection into the discharge chamber may minimize these effects.

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## Nomenclature

$c_e$	= effective exhaust velocity
$d$	= nozzle throat diameter
$p$	= feed line pressure
$\dot{m}$	= mass flow
$A$	= area
$F$	= thrust
$I$	= current
$I_s$	= specific impulse
$M_e$	= effective molecular weight
$U$	= voltage
$P$	= electric power
$T_0$	= combustion chamber temperature
$\eta_F$	= thrust efficiency

## I. Introduction

The Lunar Mission BW1 is one of the four small satellite missions within the small satellite program of the Institut für Raumfahrtssysteme (IRS), Universität Stuttgart.<sup>1</sup> For this all-electrical satellite mission two different electric propulsion systems are used. One propulsion system consists of a cluster of stationary pulsed plasma thrusters, SIMP-LEX,<sup>2</sup> and the other propulsion system is a thermal arcjet thruster system. It consists of the thruster – TALOS –, the propellant feed system, and the power supply and control unit for thruster and feed system.<sup>3</sup> The propellant of the thermal arcjet thruster is gaseous ammonia.

The flight to the moon is divided into four distinct phases: Phase one starts after separation from the launcher in GTO and lasts until the spacecraft perigee is raised above the outer van-Allen-belt. The second mission phase stretches from there to the Moon's sphere of influence, whereas phase three extends to the stable elliptical lunar capture orbit at an altitude of about 1400 km above the lunar surface. During the final mission phase the satellite is inserted into a circular polar mission orbit at an altitude of 100 km around the Moon. For mission phases one and four, the thermal arcjet thruster is used. Development and qualification of the two thruster systems is completely accomplished at IRS in cooperation with industrial partners. The present paper will focus on the thermal arcjet thruster system.

After first optimization investigations of the thermal arcjet thruster had been conducted with respect to the requirements of the lunar mission BW1 (thrust 100 mN, maximum electrical input power for thruster system 1 kW, mass flow rate between 20 and 30 mg/s and assumed lifetime of 700 hours) and after one possible operating point had been defined in earlier work, investigations of the thruster performance for operating cycles as foreseen at the lunar mission BW1 – 1 hour on / 1 hour off – are being conducted at the moment.

During this multi-hour test campaign the thermal arcjet thruster is disassembled and optical investigation and measurement of the nozzle throat diameter is done after 1 hour, 5 hours, 10 hours, 20 hours and 30 hours of operation. Thus, possible changes in the constrictor area are monitored. They could be caused on one hand by the thermal load at the nozzle throat during an experiment, which can come close to the melting temperature of the material. On the other hand the ignition procedure is found to be one of the critical points concerning anode erosion. Furthermore, the temperature cycles may cause material problems concerning material viscosity.

Considering the work of Kinefuchi et. al., a 30 hour test period is chosen as the constrictor closure phenomenon and crack generation are observed mainly in the first 30 hours of operation for thermal arcjets in the low power class.<sup>4</sup> As during previous projects constrictor closure phenomenon appeared and was one of the lifetime limiting factors, special focus is laid on the investigation of anode erosion effects in this study.<sup>5,6</sup>

The cathode gap is adjusted to 0.8 mm prior to the first experiment and is not corrected during the 30 hour test period. This is done to get a realistic impact of cathode erosion effects on thruster performance in comparison to the operation on board the satellite, where no cathode adjustment is foreseen.

The operating point investigated in the presented study is 25 mg/s ammonia mass flow rate during stationary operation with 10 A current at an initial electric input power of 700 W. The experiments are conducted in



layer at its edge. The cold gas layer, which is also present in the nozzle throat, has the important effect of cooling the nozzle material during operation and thus limiting anode erosion effects.

## B. Test Facility

The facility used for the test campaign is a stainless steel vacuum chamber of 1.2 m in diameter and 2 m in length. The 3-stage pumping system of this test facility is capable of providing a background pressure of  $5 \times 10^{-2}$  hPa during thruster operation at a mass flow rate of 25 mg/s ammonia. A pendulum type thrust stand with a non-contact displacement sensor is integrated into the vacuum chamber. In-situ calibration of the thrust stand is conducted prior to every experiment. All thrust measurement data is corrected for thermal related zero shift.

During each test, current, voltage, mass flow rate, thrust, feed line pressure and nozzle surface temperature are monitored. Current and mass flow rate are regulated. The operating point is defined at 10 A current and a mass flow rate of 25 mg/s ammonia. The propellant delivery system consists of an ammonia gas cylinder, where the ammonia is stored under  $6 \times 10^3$  hPa, a thermal mass flow regulator and stainless steel piping system. The thermal mass flow regulator has been calibrated prior to the test campaign by use of a so-called 'Sartorius' balance with an accuracy of 10 mg. Pressure measurement of the propellant is done by use of a pressure transducer inside the vacuum chamber. The power supply of the thruster provides a breakdown voltage of about 2000 V, up to 140 V during operation of the arcjet and a direct current of up to 25 A.

## III. Thruster Performance

Thruster operation can be divided into different operation phases – ignition phase and stationary operation phase. Figure 3 exemplarily shows the recorded data of voltage, current, thrust, mass flow and feed line pressure of the twentieth hour of operation. During ignition phase the mass flow rate is higher than during stationary operation. The ignition phase is characterized by fluctuations in the plasma plume, i. e. fluctuations in intensity and direction of the plasma plume or even a minor number of sparks occur. Fluctuations of the plasma plume are also observed during stationary operation up to a maximum of seven times during one test. During each of these fluctuations the voltage decreases and as a consequence of this the feed line pressure, the thrust and slightly the outer nozzle temperature decrease. The current as well as the mass flow rate remain constant. Figure 4, which is the highlighted region of fig. 3 shows the recorded data during one of the fluctuation phases. One can clearly see the voltage drop and the resulting drop in

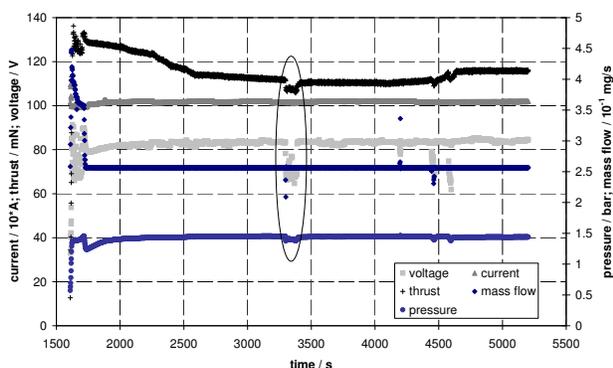


Figure 3. Performance data of one hour operation

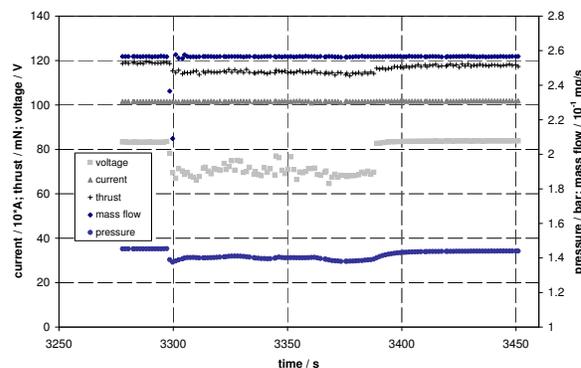


Figure 4. Fluctuations during thruster operation

thrust and the pressure, whereas mass flow and current remain constant.

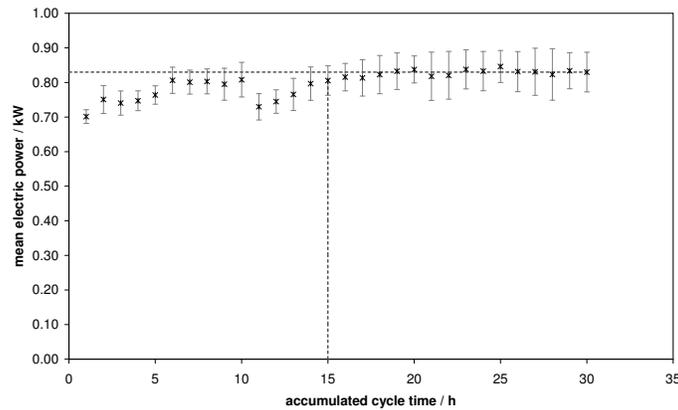
The performance data of the thruster, of which a selection is shown in table 1, show an increase in voltage and thus electrical power over the first hours of the test campaign. This is the burn-in period and caused by the degradation of the cathode leading to a slightly increased cathode gap and anode erosion effects.

Figure 5, where the mean electric power for each one hour operation period of the test campaign is shown,

**Table 1. Performance data of thruster**

hour of operation	$I$ A	$U$ V	$P$ kW	$\dot{m}$ mg/s	$F$ mN	$I_s$ s	$\eta_F$ %	$P/\dot{m}$ J/kg	$F/P$ $10^{-4}$ N/W
1	10	66.4	0.7	26.3	110.2	427	32.9	26.7	1.57
2	10	69.7	0.75	25.8	104.8	415	28.4	29.2	1.40
5	10	75.7	0.76	25.8	112.4	444	32.1	29.6	1.47
6	10	78.9	0.81	25.6	105.8	422	27.1	31.5	1.31
10	10	79.3	0.81	25.9	111.1	438	29.5	31.2	1.37
11	10	71.6	0.73	26.2	85.2	332	19.0	27.9	1.17
20	10	82.3	0.84	26.0	122.7	481	34.6	32.2	1.46
21	10	81.2	0.82	26.3	104.1	404	25.2	31.2	1.27
30	10	82.3	0.83	26.3	110.2	426	27.8	31.5	1.32

illustrates that after 15 hours of operation the voltage and thus current increase stops and the burn-in period is terminated.



**Figure 5. Characteristics of mean electric power over accumulated cycle time**

#### IV. Anode Erosion Effects

According to Lichon et. al. the approximate value of constrictor area is defined by the parameter  $p_c/\sqrt{\dot{m}}$ . A plot of this parameter gives information about the status of the nozzle throat according to<sup>6</sup>

$$p_c/\sqrt{\dot{m}} \propto 1/A. \quad (1)$$

Using this correlation, changes in constrictor diameter for different thrusters can be easily compared. Figure 6 gives the evolution of the normalized constrictor closure parameter  $p_c/\sqrt{\dot{m}}$  over the accumulated time of thruster operation. An increase of  $p_c/\sqrt{\dot{m}}$  corresponds to increasing pressure and thus constrictor closure, whereas a value lower than one corresponds to an increase in constrictor diameter. One can see that for this test campaign  $p_c/\sqrt{\dot{m}}$  varies between 0.8 and 1.2. What is noticeable is the value of the thirteenth hour of operation. During this test a pressure leap occurred, for which no reason could be identified yet. As the other recorded data stayed in the nominal range it is assumed that an abnormality in pressure data reading occurred. During the next test the pressure was normal again. The decrease of  $p_c/\sqrt{\dot{m}}$  after 13 hours of operation indicates an increase in constrictor diameter. This indication is verified by optical investigation of the constrictor.

For monitoring the anode erosion of the thermal arcjet thruster, the nozzle is disassembled after a defined interval of operation and photographs are taken. These photographs are taken by use of a microscope with an accuracy of  $0.1 \mu\text{m}$  and a maximum resolution of  $0.01 \mu\text{m}$ . Determination of the nozzle throat diameter is

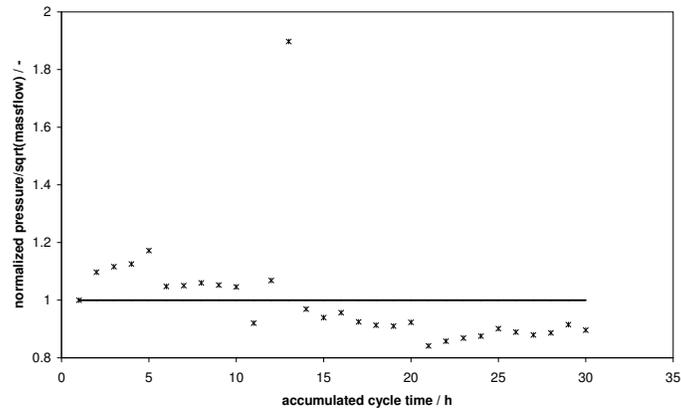


Figure 6. Anode characteristics

conducted by fitting a circle to the contour of the nozzle. The best fit of the circle is obtained by a one pixel fit. This allows the software to put nozzle material one pixel out of the circle fit. The diameter of the circle is then measured and set equal to the nozzle throat diameter. For contours that differ very strongly from the circle shape, this method of determining the diameter is not very accurate. The evolution of changes in the nozzle throat diameter is shown in fig. 7.

It can be seen that after one and five hours of operation nearly no changes in the nozzle throat occur. The

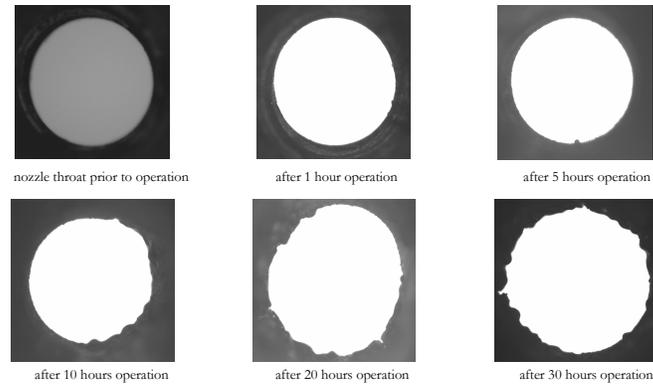


Figure 7. Comparison of nozzle throat diameter conditions

nozzle throat is still circular and the changes in diameter as listed in table 2 together with the corresponding feed line pressure data are minimal. After ten hours of operation the shape of the nozzle throat starts to deform. The cyclic form is still visible, whereas after 20 hours of operation the nozzle throat shape has significantly changed, which made the determination of the diameter difficult. Therefore two circles had to be fit into the nozzle throat. This caused a relatively high uncertainty in diameter determination. After 30 hours of operation the nozzle is nearly circular again. Furthermore, one can clearly depict crack formation at some places. At the beginning of the test campaign a slight decrease in the nozzle throat diameter is visible.

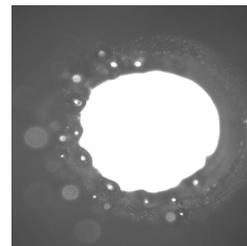
Table 2. Evolution of nozzle throat diameter

hour of operation	nozzle throat diameter / mm	feed line pressure / bar
0	0.6033	
1	0.6002	1.55
5	0.6044	1.81
10	0.6080	1.61
20	0.63	1.43
30	0.66	1.40

After five hours of operation the nozzle throat continuously increases. This measurement corresponds well to the pressure data inside the feed line recorded during experiment. The constrictor closure phenomenon as reported in other work<sup>4-6</sup> was not observed during this work.

Figure 8 shows a photograph of the diverging part of the nozzle after 20 hours of operation. One can clearly identify spherical material. This indicates melted material of the nozzle throat that solidified at the relatively cold diverging part of the nozzle. The downstream position of the material in the region where the nozzle throat is deformed corroborates this theory. This phenomenon has also been observed by Curran et. al.<sup>8</sup> Overall the performance data of the thruster in correlation with the investigation of the nozzle throat diameter show that the change in the nozzle throat diameter has no major effect on thruster performance. This corresponds well to the results Curran et. al. found in their work.<sup>8</sup>

However, the evolution of the thruster performance for a longer time of operation, i. e. up to 100 hours of operation, has to be investigated. It is imaginable that if further increase of the nozzle throat diameter occurs this could lead to stability problems during thruster operation or even thruster operation in the so-called low-voltage mode. The low-voltage mode is characterized by thruster operation at very low voltage usually about 20 V under regular operation voltage. This is caused by arc attachment in the converging part of the nozzle, which requires adjustment of a new operating point. If the thruster is operated for a longer time in the low-voltage mode, thruster destruction could possibly occur, caused by the immense heat load at the attaching point of the arc.



**Figure 8. Photograph of diverging part of nozzle**

## V. Conclusion and Outlook

A 30 hour test campaign with one hour on / one hour off cycles of the thermal arcjet thruster TALOS has been accomplished successfully. The thruster is operated at repeatable operating conditions – current 10 A, electrical power 0.83 kW and mass flow 25 mg/s – after the burn-in period, which is identified to last 15 hours. The nozzle throat diameter is inspected by optical means during the test campaign and an increase in nozzle throat diameter is determined from an initial diameter of 0.6 mm to 0.66 mm at the end of the test campaign. This corresponds well to the change in the parameter  $p_c/\sqrt{\dot{m}}$  defined by Lichon et. al.<sup>6</sup> The increase in nozzle throat diameter has no major effect on thruster performance so far, although further investigation for prediction of total thruster lifetime is found to be necessary since crack formation at the constrictor occurred after 30 hours of operation. In the diverging part of the nozzle, solidified material is found, which argues for material melting inside the constrictor during operation and being taken away by the propellant stream. Solidification then takes place at the relatively cold diverging part of the nozzle. During ignition of the thruster and stable operation of the thruster, fluctuations in voltage and thus feed line pressure with a voltage drop of up to 20 V occurred. It is assumed that these fluctuations may be caused by the central ignition of the propellant and further investigations on change of the ignition angle to get a swirl stabilized arc are going to be conducted. Doing so, it is presumed that the occurrence of sparks at ignition should also decrease.

In the near future, investigations of two other nozzle materials using the same test campaign will be conducted. Doing so, the best nozzle material concerning thruster performance as well as lifetime issues will be identified. The other materials are tungsten with 1% lanthanum-oxide and tungsten with 5% rhenium. The different additives have different influence on material behaviour during thermal cycles or thermal shocks as well as the melting temperature. Furthermore, a comparison of the different test results should give information about whether the additives have a noticeable influence on thruster performance.

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