7500-hour Life Test of the QM LIPS-200 Ion Thruster

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Abstract: The life test of the QM-2 LIPS-200 ion thruster has reached 7500 hours and 3750 cycles. This paper describes the test systems, test procedures, and test progress, and discussions about the test results.

I. Introduction

LIPS-200 Ion Thruster developed by Lanzhou Institute of Physics (LIP), will be applied onto DFH-3B Satellite Platform for satellite's NSSK mission [1, 2]. The first satellite will be launched in 2016. In order to confirm the Ion Thruster's capability of fulfilling in-orbit task for 15 years, the life test, which aims for the target of 12000h and 6000 cycles, has begun since December 25th, 2013. By May 1st, 2015, 7500h and 3500 cycles of operation were achieved. At present the thruster is still operating normally, and will reach the target in January 2016.The test progress is described in this paper.

II. Test System

A. QM-2 Ion Thruster

LIP developed two QM thrusters, i.e. QM-1 and QM-2. After the completion of the acceptance test, the QM-1 carried out a complete qualification test and QM-2 carried out the life test. The situation of QM thruster was described in detail in [2]. Figure 1 shows QM-2 ion thruster photo after the acceptance test.

Fig. 1 QM-2 Ion Thruster

B. TS-7 Vacuum Facility

The Ion Thruster Life Test was conducted in the TS-7 facility with a vacuum chamber of 3. 8m diameter, 10m length, and pumped by six cryopumps [3, 4]. Figure 2 shows the device photo and test site. This pumping system provides pressure less than 5×10^{-4}Pa at the full power operating.

Fig. 2 TS-7 Facility

C. Support Equipment

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High purity xenon is supplied to the thruster by a ground propellant feed system based on three flowmeters. The specially developed power system used to provides power supplies to the thruster. The test control system consists of a thruster operation control subsystem and a vacuum facility control subsystem. The former controls thruster operating cycles and the latter controls the vacuum facility.

To detect thruster performance and corrosion, the beam divergence angle measuring device, the grid corrosion measurement equipment, and camera and so on were equipped in the vacuum tank.

III. Test process and Progress

A. Test Process

The Thruster Life Test applies the time accelerated simulation process: the Thruster works for 2 hours and then pauses for half an hour. Each cumulation of 250 cycles and 500 hours signed as a test section, and about 24 test sections will be needed to reach the test target, otherwise, the thruster will be ineffective permanently before 12000 hours and 6000 cycles [3].

All parameters, including flow rates, currents, voltages, temperatures, vacuum pressure and so on, were recorded for every second while the thruster is working. After each test section, a set of diagnostics will be conducted in order to characterize the status change of the thruster. These diagnostics include divergence angle of beam, electron backstreaming (EBS) limit, plume model threshold value of the cathode and the neutralizer, characteristics resistance, the the characteristic magnetic field in outside, and acceleration grid corrosion. Figure 3 shows the thruster working and characteristics resistance measurement.

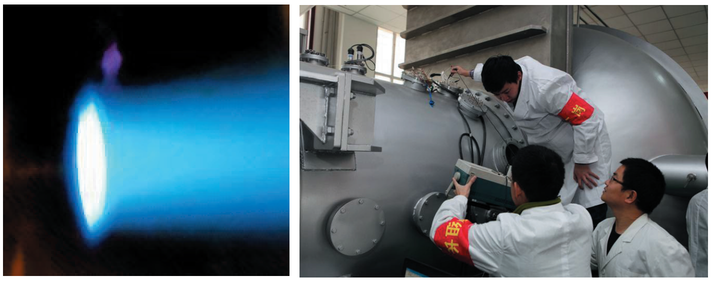


Fig. 3 Thruster Working and Resistance Measurement

A standard processing program is executed to eliminate the influence of atmosphere whenever the thruster is exposed to the atmosphere, due to equipment malfunction or non-online acceleration grid corrosion measurement.

B. Test Process Control Philosophy

Three flow rates of the discharge chamber, the cathode, and the neutralizer remains constant. Both the screen grid power and the accel grid power are voltage regulars, and their current may be changed with the thruster performance. The discharge power, the cathode keeper power and the neutralizer keeper power, are current regulars, and their voltage be changed with the thruster performance.

Because the thrust of LIPS-200 ion thruster is not closed-loop controlled by monitoring the beam current, the beam current current will be gradually reduced in the Life Test with performance degradation or corrosion of units, such as the discharge chamber, the grids and the cathode. So the test control strategy is that: if the beam current is reduced to less than 0.74A, discharge current should be increased to enable the beam current to reach 0.8A. However, if the discharge current was increased to the upper limit, discharge current would not be increased, and the rest life test would continue under the natural degradation.

If the test was broken by the fault of the vacuum facility, the ground power system and the ground propellant feed system, the test would continue after the fault was repaired.

C. Test Progress and Status

The life test was officially launched on December 25, 2013, and it has been conducted successfully for 7500 hours and 3750 cycles by May 1, 2015. The results of 15 sections are shown in Table 1. Due to diagnostics, the actual cumulative time and cycles have reached 7635 hours and 3810 cycles, respectively.

Table 1 The Time and Cycles of 15 Sections

Section No	Time(h)	Cycles	Diagnostic Time(h)	Diagnostic Cycles	Completion Time
1st	500	250	9	4	2014-01-24
2nd	500	250	9	4	2014-03-04
3rd	500	250	9	4	2014-04-03
4th	500	250	9	4	2014-05-04
5th	500	250	9	4	2014-06-05
6th	500	250	9	4	2014-07-04
7th	500	250	9	4	2014-08-04
8th	500	250	9	4	2014-09-04
9th	500	250	9	4	2014-10-04
10th	500	250	9	4	2014-11-04
11th	500	250	9	4	2014-12-04
12th	500	250	9	4	2015-01-04
13th	500	250	9	4	2015-02-10
14th	500	250	9	4	2015-04-08
15th	500	250	9	4	2015-05-01
SUM	7500	3750	135	60	---
Total	7635 hours、3810 cycles				

There are several important events in the tests are presented as follows:

1) From the 2nd section, the thruster temperature was measured with six thermocouple sensors installed on the outside surface of the thruster body;

2) After the 6th test section（i.e after 3000 hours）, the discharge current was increased according Control Philosophy ;

3) During the first 12 sections, the accel grid corrosion was measured in off-line mode and the thruster exposure atmosphere. From the 13th sections, the accel grid corrosion was measured with on-line mode;

4) By now, three times of arc diminishing occurred and it is resulted from carbon fibers fall between the grids.

IV. Test Results and Discussion

During the 7500 hours and 3750 cycles life test, these regular parameter ranges of flow rates, voltages and currents are as follows: the flow rates of the cathode and the neutralizer are (1.00±0.02) sccm, the flow rate of the discharge is (8.00±0.02) sccm; the screen grid voltage is (1000±5) V, the accel grid voltage is (185±2) V, the cathode keeper current is (0.60±0.02) A, the neutralizer keeper current is (1.60±0.02) A, the discharge current is (4.00±0.02)A, the heater current of the cathode and neutralizer are (7.50±0.04)A.

Due to the lagging of the data processing, this paper only shows the results of 7000 hours test. The ignition time, the main characteristic parameters, the rated performance, thermal, degradation diagnosis and corrosion measurement are discussed, respectively.

A. Ignition Time

The thruster ignition time mainly depends on the ignition time of the cathode and the neutralizer. Figure 4 shows the ignition time of the cathode and Figure 5 shows the ignition time of the neutralizer. The cathode ignition time value are maximum 359s, minimum 163s, average 259.1s and the neutralizer ignition time value are maximum 366s, minimum 169s, average 264.5s. Both ignition time statistics are fairly consistent, because they are the same design and operating conditions for firing. By now, the ignition time remains stable and changes periodically because of the thrust exposure to atmosphere after each test section.

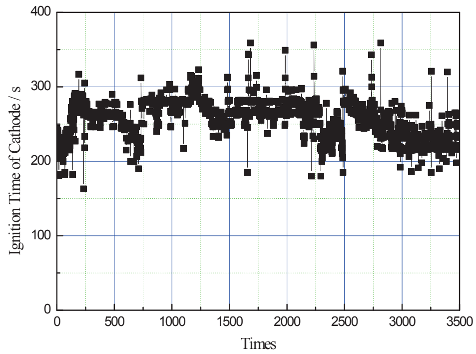


Fig. 4 Ignition time of cathode

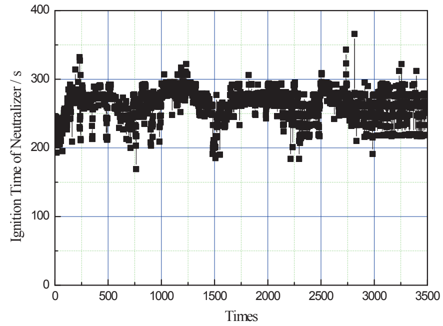


Fig. 5 Ignition time of neutralizer

B. Main Characteristic Parameters

Several characteristic parameters can reflect performance of the thruster, including the beam current, the discharge voltage, the cathode keeper voltage, the neutralizer keeper voltage and so on. The changes in these characteristic parameters can be related to the change of the thruster, the discharge, the cathode and the neutralizer respectively. Figures 6, 7 and 8 show these variations of the discharge voltage, the cathode keeper voltage and the neutralizer keeper voltage respectively. The discharge voltage value is maximum 40.10V, minimum 34.97V, and average 37.27V; The cathode keeper voltage value is maximum 20.60V, minimum 15.70V, and average 17.58V; The neutralizer keeper voltage value is maximum 24.70V, minimum 21.60V, and average 22.96V. The stable of the discharge voltage indicates that the discharge chamber is in good performance. The slowly decreasing of the cathode keeper voltage indicates that the cathode is becoming better gradually. The slowly increasing of the neutralizer's voltage is shows a slight degradation in the neutralizer. Figure 9 shows variation of the beam current.

The beam current value is maximum 0.821A, minimum 0.730A, and average 0.794A. In the first 3000h, the beam current continues to decrease. When the discharge current was increased, the beam current has a step increases and remained its stability after that.

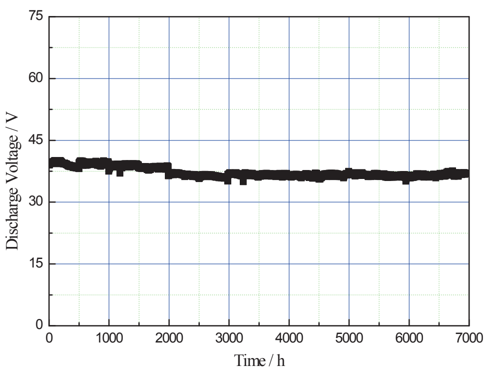


Fig. 6 Variation of discharge voltage

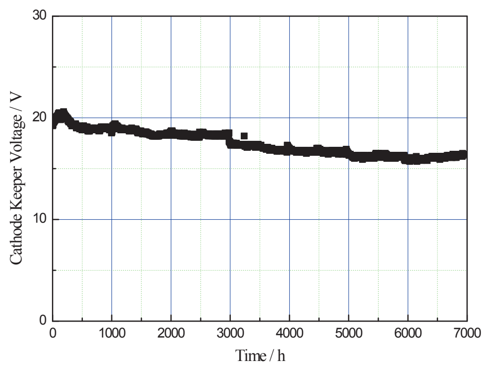


Fig. 7 Variation of cathode keeper voltage

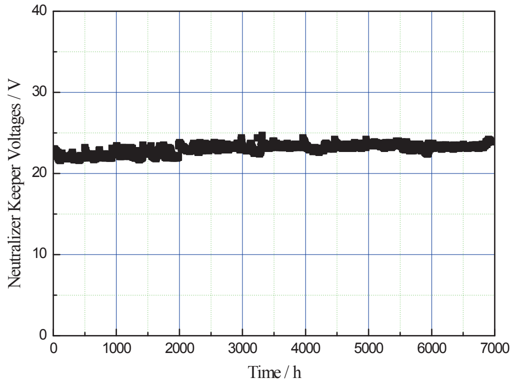


Fig.8 Variation of neutralizer keeper voltage

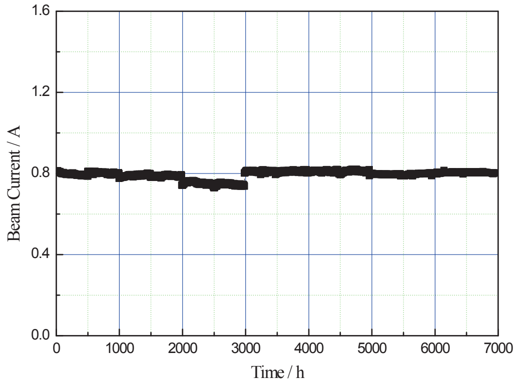


Fig. 9 Variation of beam current

C. Rated Performance

Thruster performance under rated conditions consist of the thrust, specific impulse, and total power. Among them, the thrust is calculated by the screen grid voltage and the beam current, the total power is the sum of the individual power supply of the thruster, the specific impulse is calculated with the thrust and the flow rates. Figure 10 shows variation of the thrust. The thrust value is maximum 40.87mN, minimum 36.34mN, and taverage 39.52mN. After 3000 hour, the thrust increases because the discharge current is increased. Figure 11 and Figure 12 shows variation of the specific impulse and the total power, respectively. The specific impulse value is maximum 3026s, minimum 2683s, and average 2926s. The specific impulse and the thrust is fully consistent because the flow rate is constant. The total power value is maximum 1027.5W, minimum 920.9W, and average 996.2W.

D. Surface Temperature

The change in the thruster surface temperature was normal in the test. Figure 13 shows the change trend of the temperature which were selected only for seven cycles. The temperature of the TR12 for neutralizer is below 120℃. When the thruster was turned down, the temperature was cooled down to a minimum of about 83℃. The temperature of each measurement point is repeated and changes periodically as the thruster is turned on and off.

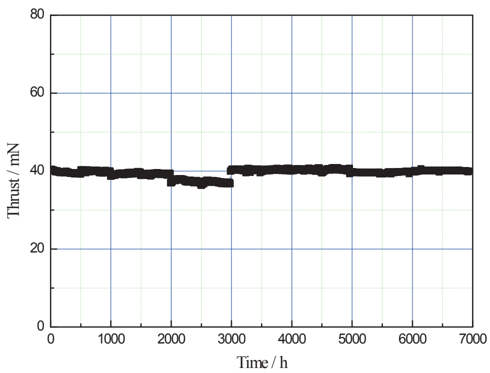


Fig. 10 Variation of calculated thrust

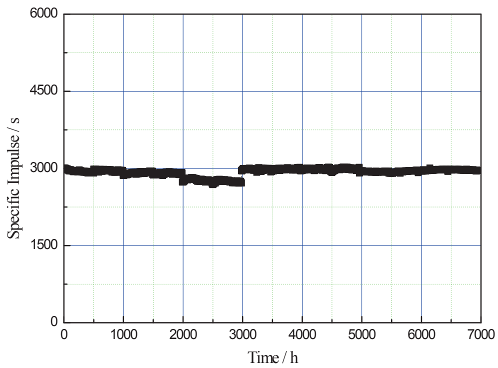
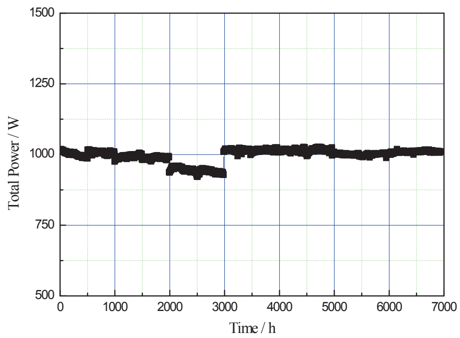


Fig. 11 Variation of specific impulse



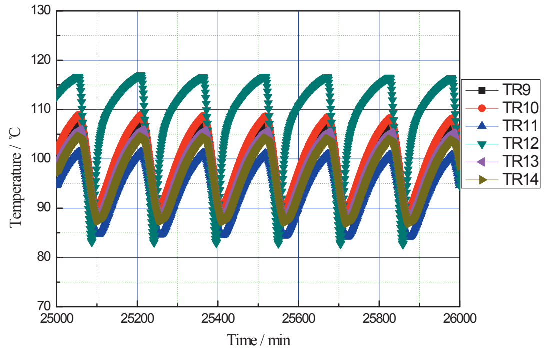


Fig. 12 Variation of total power

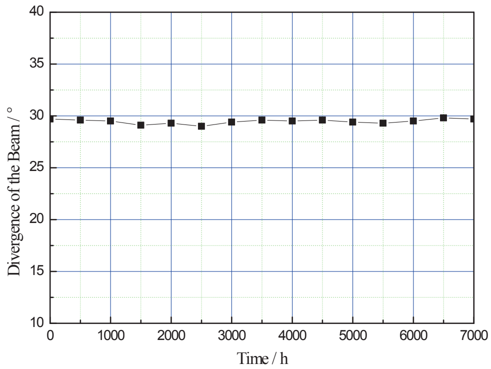
Fig. 13 Variation of temperature

E. Degradation Diagnostics

After each test section of 500 hour, diagnostics of the thruster will be conducted in order to diagnose the degradation of the grids, the cathode, the neutralization, and the magnetic property, including divergence angle of beam, EBS limit, threshold values of cathode and neutralizer plume model, characteristics resistance, the characteristic magnetic field strength and accel grid corrosion.

Divergence angle of the beam, which contains 90% of the beam, was measured by calculating the distribution of beam with the Faraday array. Figure 14 shows the variation of the divergence angle. The results were in the range of 29.5◦ ±0.5◦ , and deviated within the measurement error. It did not display any obvious change and suggesting that no significant change in grids geometry.

EBS limit was measured by decreasing the accel grid voltage and monitoring the 1mA increment of the beam current. The thruster had been turn off for 4 hours and fired again, then EBS limit is measured after the beam is extracted for 15 minutes. Figure 15 shows the variation of EBS limit, which is gradually increased and the magnitude of change in 30V. The change trend indicated that the acceleration aperture became larger, which was consistent with the result of the accel grid corrosion as presented later. The EBS failure would take place after more than 21000 hours by a linear corrosion speculating.



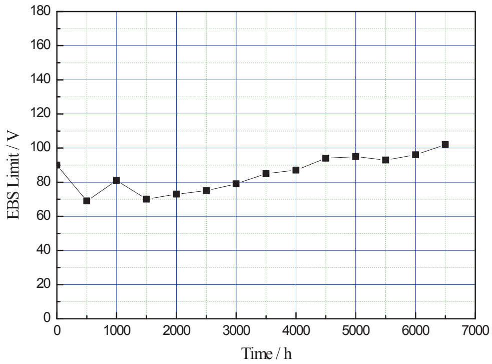


Fig. 14 Variation of divergence angle

Fig. 15 Variation of EBS limit

The threshold values of the cathode and neutralizer plume model was measured by step reducing flow rate and monitoring the DC and AC component amplitude of the keeper voltage. The criterion is the DC amplitude ≥30V, peak to peak AC voltage≥20V. The results show that the cathode and the neutralizer still did not work in the plume mode when the flow rates of them decrease to 0.2sccm, which shows performance of the cathode and neutralizer is stable and no obvious aperture erosion occurred.

Both resistances, that between the neutralizer keeper and the power ground, and between the cathode keeper and screen grid, were measured by a mutimeter and always displayed “OL”. These resistance, between the other electrodes, and between electrodes and the thrust body, was measured by the insulation tester at 500V and always displayed “>100G”. All the results indicate that characteristic resistances remain good so far.

The external characteristic magnetic field strength was measured directly by a gaussmeter. These results of six characteristic points on the thruster surface showed no measureable change, and indicated that there was no degradation of magnetic material caused by thermal cycling.

F. Accel Grid Corrosion

The accel grid corrosion was measured by a specially configured optical method and device. The pit and groove depth and the accel grid aperture diameter were measured by this device and the 3D surface data were processed by a computer software. As shown in Figure 16, the red means aperture, the green means pit, and the blue means groove. Because of the accel grid’s centrosymmetric structure, in the data processing, three regions are selected along the grid diameter, which are the middle region, the middle-edge region and the edge region, respectively.

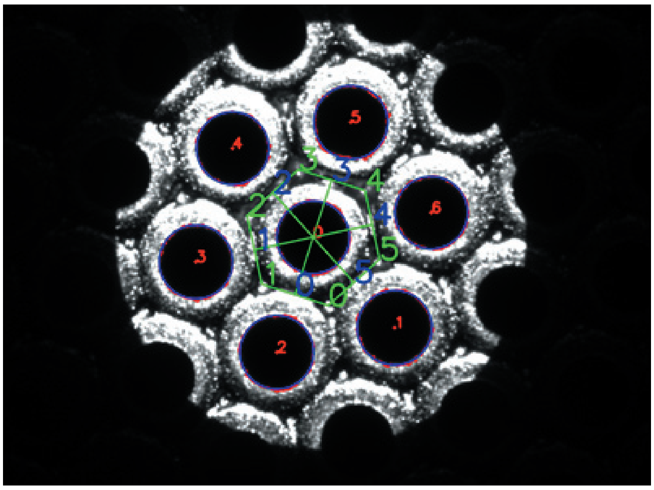


Fig. 16 Schematic diagram of accel grid

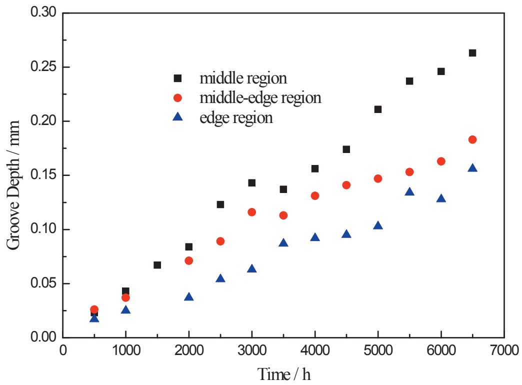


Fig. 17 Variation of the groove erosion

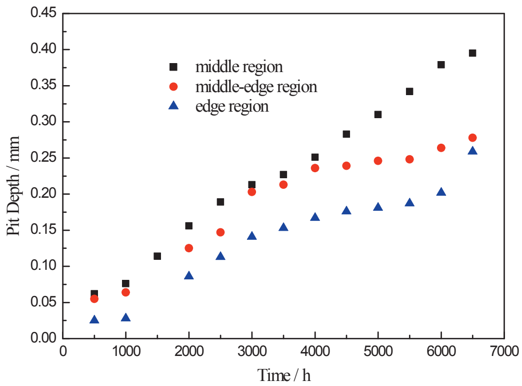


Fig. 18 Variation of the pit depth

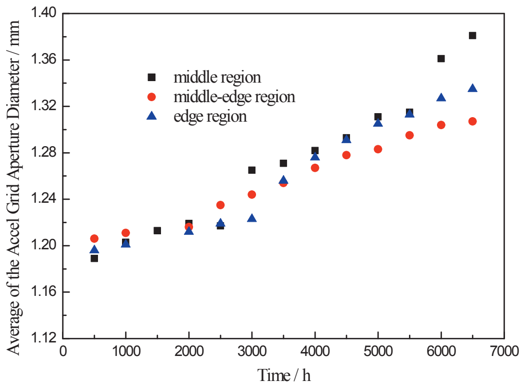


Fig. 19 Variation of aperture diameter

Figure 17, 18 and 19 are the measured results of the groove, the pit and the accel grid aperture diameter respectively. It is noticed that the method of data processing was optimized after 3000h in order for more accurate. These results show that the grid corrosion was a continuous progress. The corrosion is most serious in middle region and is weakened along the diameter to outward, which corresponds directly to the beam current density distribution. After 6500h test, the deepest pit has been reached 0.381mm, which is more than half of the thickness of the accel grid; the deepest groove has reached 0.253mm which reaches half the thickness of the accel grid; the maximum aperture has reached 1.38mm and increased by 0.18mm with respect to the original size. If the structural failure criterion is penetration of the groove, The structural failure would take place after more than 2113000 hours by a linear groove corrosion speculating.

V. Subsequent Test Program and Conclusions

A. Subsequent Test Program

The 18th test section has begun. Because the device for the accel grid corrosion measurement is on-line, the diagnostics after each section will cost less time than before. In our program, the life test will reach 12000 hours and 6000 cycles by the end of January 30, 2016.

B. Conclusion

The life test for the QM-2 LIPS-200 ion thruster has been reached 7500 hours and 3750 cycles. The result of the degradation diagnosis shows that the performance of the discharge chamber, the cathode, the neutralizer, and the grids is still well. The thruster performance can be revised by adjusting the discharge current. The overall performance of the thruster was better than expected. Corrosion measurement results show that the life of 12,000 hours and 6000 cycles would be optimistic.The accel grid' structural failure is the critical failure mode of the LIPS-200 thruster because it determines the life of the thruster.

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