Typical transient phenomena of Hall Effect thrusters

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The long standing relationship between Maxar (formerly SSL) and Fakel allowed to develop and operate 148 Hall Effect Thrusters (HET) in orbit in the last 14 years, including both 1.35 kW SPT-100 and the higher power system based on the 4.5 kW SPT-140. The HETs operated by Maxar cumulated more than 100,000 hrs in orbit and accomplished partial Electric Orbit Raising which included the continuous operation for about 39 days. Some specific phenomena are experienced during testing and in-orbit operation of the HET, which Maxar and Fakel assessed to better understand the impact of the unit and assess its health. The outgassing of contaminants from the ceramics and other elements is typically experienced during the first fires after the thruster is exposed to ambient environment; this is mainly due to the absorption of moisture and other elements. The outgassing of the discharge chamber of the anode presents higher discharge current oscillations (AC components) which can be potentially on the same order of magnitude of the DC component of the discharge current (DC is measured after filtering out the oscillation). When contaminants are present in the cathode, the noisy behavior is mainly reflected on the cathode-to-ground voltage, and eventually affecting the other thruster parameters. These phenomena are constrained to the first fires of the thrusters, the higher the power the higher the thermal load, thus the outgassing is accelerated. Similar noisy behavior can also be associated to superficial accumulation of sputtered material. Indeed, particulates could deposit on grounded surfaces (or at a different potential), such as a thruster that has not been in operation while a secondary thruster nearby has been operating for an extended period of time. Finally, over the lifetime the thruster consumes the ceramics of the discharge chamber, and depending on the power level this process can be more or less noticeable. At a higher power it is typical to experience single events which are related to ceramic sputtering. This phenomenon manifests itself as spikes in discharge current that can be as high as 10% of the discharge current and persists less than 1 s. This paper will present data from ground testing and in-orbit operation that better explain such phenomena. The effect on the thruster health and performance will be here assessed to show that such events are indeed harmless.

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Nomenclature

ΔU	– *voltage of losses*
e	– *electron charge*
Eff	– *efficiency*
F	– *thrust*
Id	– *discharge current*
Ii	– *Ion current*
K	– *propellant utilization coefficient*
$\dot{m}$	– *Xe flow rate*
Mxe	– *Xe atomic mass*
P	– *discharge power*
U	– *discharge voltage*
V	– *effective ions velocity*
CRP	– *cathode reference potential*

I. Introduction

The start of a stationary plasma thruster is accompanied by transient processes, which duration depends on the design, dimension, operation mode and can last for minutes to hours during the first fire during the first fire. During this period of time a lower value of thrust and flow rate, CRP instability and a higher level of discharge current oscillations are observed. The magnitude of thrust and flow rate change during these processes is 5 – 10 % from the stabilized value. Discharge current oscillations (RMS) can reach as many as 50 % of the discharge current value, while this level is typically several percentage These processes may have a significant impact on the mission with short-time thrusters firings. Besides, studying these processes allows one to better understand the principle of thruster operation and causes of parameters degradation.

This paper studies an impact of start conditions on transient processes and gives the results of on-ground acceptance test of 25 SPT-140 thrusters, life test results of the qualification model and results of in-orbit operation of the first SPT-140s used on Maxar spacecraft.

II. SPT-140 Hall thruster

The SPT-140 is a classical stationary plasma thruster with a nominal power of 3.0…4.5 kW. This thruster was qualified and passed life test with the duration of 9300 h in 2015 /1/. In 2017 the thruster lifetime was extended to 10500 h, where 500 h were accumulated in the mode of 0.9 kW for a potential mission to the Psyche /2/. In 2018 the first SPT-140s were used on board of Maxar satellites. Currently there are 16 thrusters successfully operated in orbit. The maximum accumulated operation time of one of the thrusters is 2000 h. Fig. 1shows an external appearance of the thruster.

III. Efficiency loss mechanisms

In a stationary plasma thruster thrust is generated by accelerating ionized propellant in intersected electrical and magnetic fields and is proportional to the plume outflowing speed and mass accelerated at a unit of time.

$$F = \dot{m}\Delta V \qquad (1)$$

The incremental velocity is defined by electric forces and is proportional to the square root of an accelerating voltage. The accelerating voltage can be defined as a difference between the discharge voltage and voltage of losses.

$$\Delta V = \sqrt{\frac{2e(U-\Delta U)}{Mxe}} \qquad (2)$$

The propellant mass, which is accelerated at a unit of time, is proportional to ion current.

$$\dot{m} = \frac{Mxe}{e} Ii \qquad (3)$$

Namely, thruster operation efficiency is proportional to ion current and accelerating voltage.

$$\mathrm{Eff} = \frac{F*V}{2P} = \frac{Ii}{Id}\frac{U-\Delta U}{U}K_m \quad (4)$$

Therefore, we have 4 mechanisms which degrade the parameters:
the increase of electron component of discharge current;
the decrease of propellant utilization efficiency;
the increase of voltage of losses;
the presence of double charged ions.
All these mechanisms may affect the thruster output parameters.

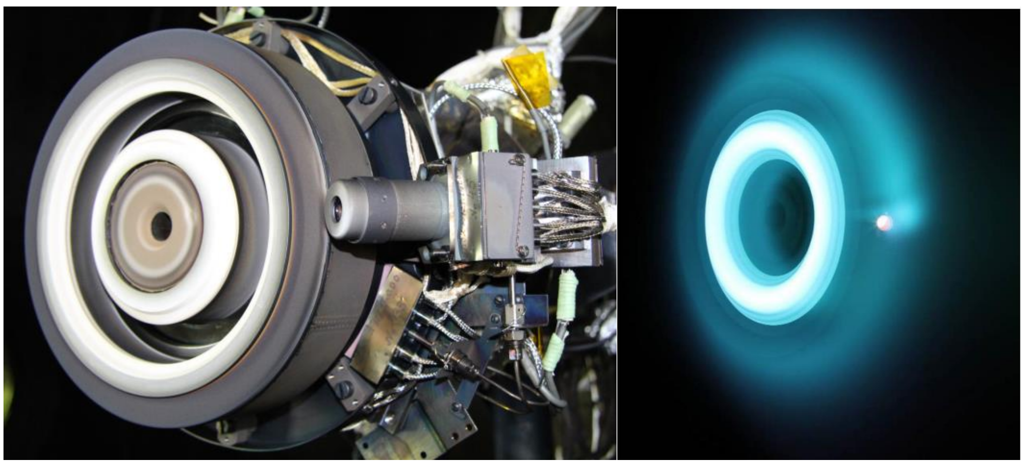


Figure 1. An SPT-140 mounted on a thrust balance and an operating SPT-140

IV. Test and on-orbit operation results

Currently there are only few papers about outgassing processes and other transient processes that accompany the thruster start. The following possible factors, which determine the transient processes, are emphasized in the papers /3/ and /4/: the discharge chamber outgassing, outgassing of other design elements, a change of the magnet system size due to heating, a change of the coefficient of secondary electron emission.

In order to distinguish one or another factor, the thruster is started from various conditions (heated and unheated, outgassed and non-outgassed state). In the paper 3 the following contributions of each of the parameters is considered: ~5 % is an impact of outgassing and ~3 % is a change of the thermal state. In the article 4 a contribution of an increased secondary electron emission is also studied.

Both in 3 and 4 we studied transient processes when starting from various states. Here we propose the evidence that results from the data that was collected during development and manufacturing years of the SPT-140.

Acceptance test results of 25 thrusters were studied. During the acceptance test the thruster is started several times after a contact with atmosphere, one of which after it is manufactured thruster. In the course of the acceptance test there are starts at extreme cold temperatures.

Transient processes were also studied during the thruster start in the course of life test.

The starts after the cryogenic pumps regeneration were of a special interest; this is a condition when the thruster was in Xenon atmosphere for about 24 h.

Transient processes, which are observed during the thruster start on a S/C, were also studied.

In order to distinguish between an impact of cathode, discharge chamber and magnet system heating, we used the results of the thermal analysis, with typical heating dynamics of those components shown in Fig. 2. By the time of the start the cathode is heated up to the temperature that is close to the operation temperature. Therefore, transient processes in the thruster cannot be referred to the result of the cathode thermal state change.

The outgassing ability of the magnet system elements, as well as the moisture absorption ability of the discharge chamber insulator were identified previously. These results are given in Fig. 3. As seen from Fig. 3, the magnet system coils can lose about 0.3 % from the wire mass during outgassing.

The discharge chamber insulator can absorb water vapors which are about 0.3 % from the total mass. It should be noted that unlike water vapors, which influence only the current operation parameters of the thruster, the magnet coils outgassing products can deposit on the thruster design elements and can lead to the deterioration of the thruster operation in the future. The magnet coils outgassing products are vapors of varnish and paint compositions used for wire impregnation. Airborne water vapors and gases are the discharge chamber outgassing products.

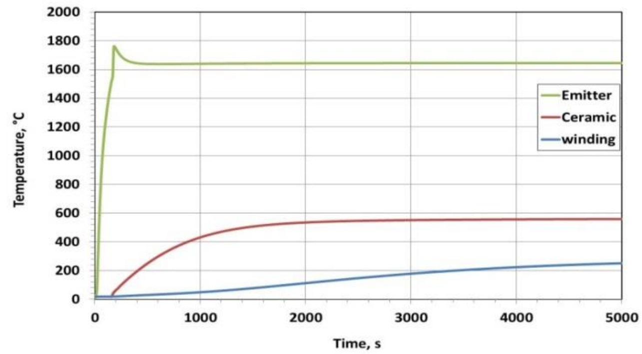


Figure 2. Temperature dynamics of the SPT-140 elements

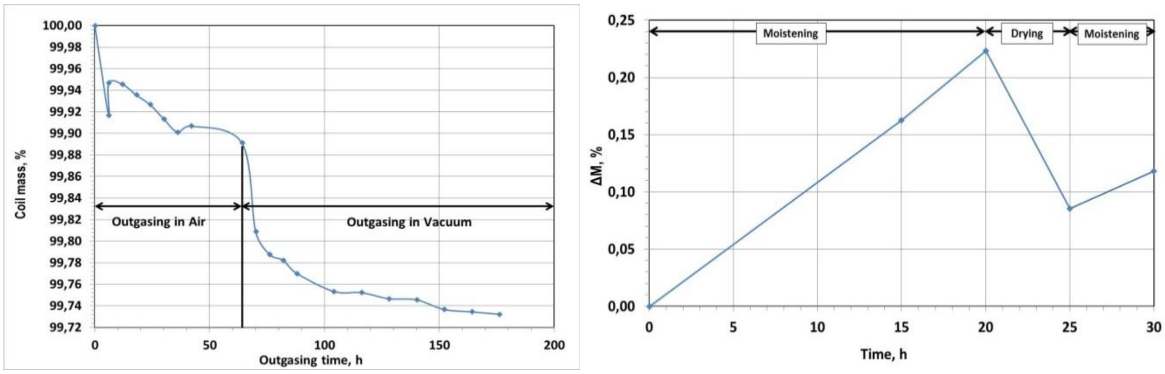


Figure 3. The magnet coils mass change during outgassing and the discharge chamber mass change during moisture absorption.

A. The first start after manufacturing

Firstly, we have gathered the available information on the first start after manufacturing. The plots in Fig. 4 show the change of thrust, mass flow rate, discharge current oscillations and CRP. Test results are given for 25 SPT-140 thrusters. These starts present an interest, because during the first start the most intensive outgassing of the magnet system coils takes place. In other respects these starts are similar to any other start after a contact with atmosphere. The following transient processes can be emphasized in the course of these starts:

The heating and increase of the discharge chamber outgassing intensity. This process lasts for about 15 min and is accompanied by the discharge current oscillations increase from 2…3 A up to 5…6 A. At this time the thrust and flow rate decrease by 5 %, see Fig. 4. It can be concluded that the parameters decrease is caused by the increase of the electron component of the discharge current. CRP average value is stable at this time, however, at this time the biggest amount of instant spikes from 19 up to 30 V is observed.

The outgassing intensity decreases within the next 15 min. It is accompanied by the decrease of oscillations level, thrust rise and proportional flow rate increase. CRP spikes frequency decreases. It can be assumed that CRP spikes are linked with the discharge chamber outgassing. It also should be noted that during operation at a lower discharge power about 1 kW we observed the CRP instability even on the outgassed thrusters. The instability is manifested during new cathodes operation and decreases in the course of lifetime accumulation. During the life test after 10000 h all the thruster parameters were stable.

The technological firing (burn-in) procedure stipulates operation in low power mode for several tens of minutes followed by a transition to high power. A switch to the higher power mode is accompanied by an instant decrease of the discharge current oscillations. Then the discharge chamber temperature rises by 200 °C, at which point the remaining impurities are evacuated. After 15 min the oscillations become stabilized at the level of 2 – 3 A. As in the mode of 3 kW / 300 V thrust and flow rate decrease when oscillations increase and there are no CRP spikes.

After parameters stabilization a rapid increase of the discharge current oscillations up to 5…6 A is observed. The change occurs within 30 sec. The oscillations increase is accompanied by thrust and mass flow rate decrease. The moment when the rapid increase of oscillations starts (70 – 80 min of operation) corresponds to the magnet system heating time. Moreover, it can be noted that such a behavior is observed only on the thrusters which design is “leak proof" and does not allow the outgassing products to be released through the lateral walls. Therefore, such a behavior is most probably linked with the magnet system outgassing.

The 2nd start is performed after a 20-min pause. Fig. 5shows the parameters change during the 2nd start. It is seen that the thruster operation parameters are stable during this start. A higher level of oscillations is observed in the first minutes of operation on the thrusters for which the oscillations had not stabilized in the course of the 1st firing.

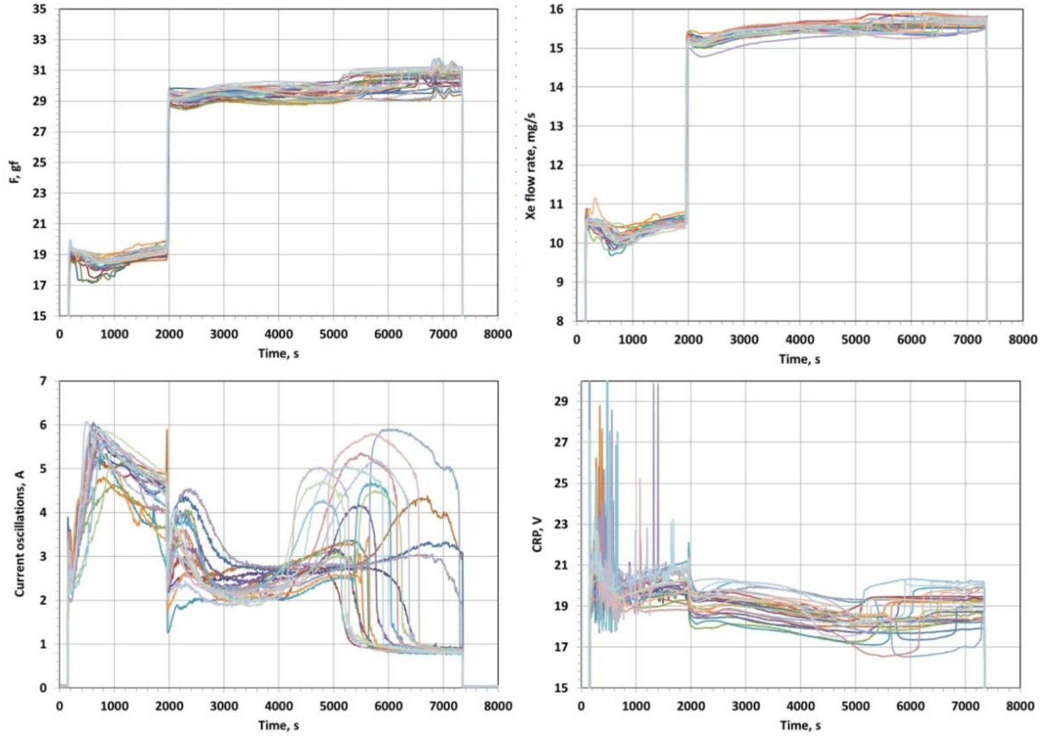


Figure 4. The first start after manufacturing

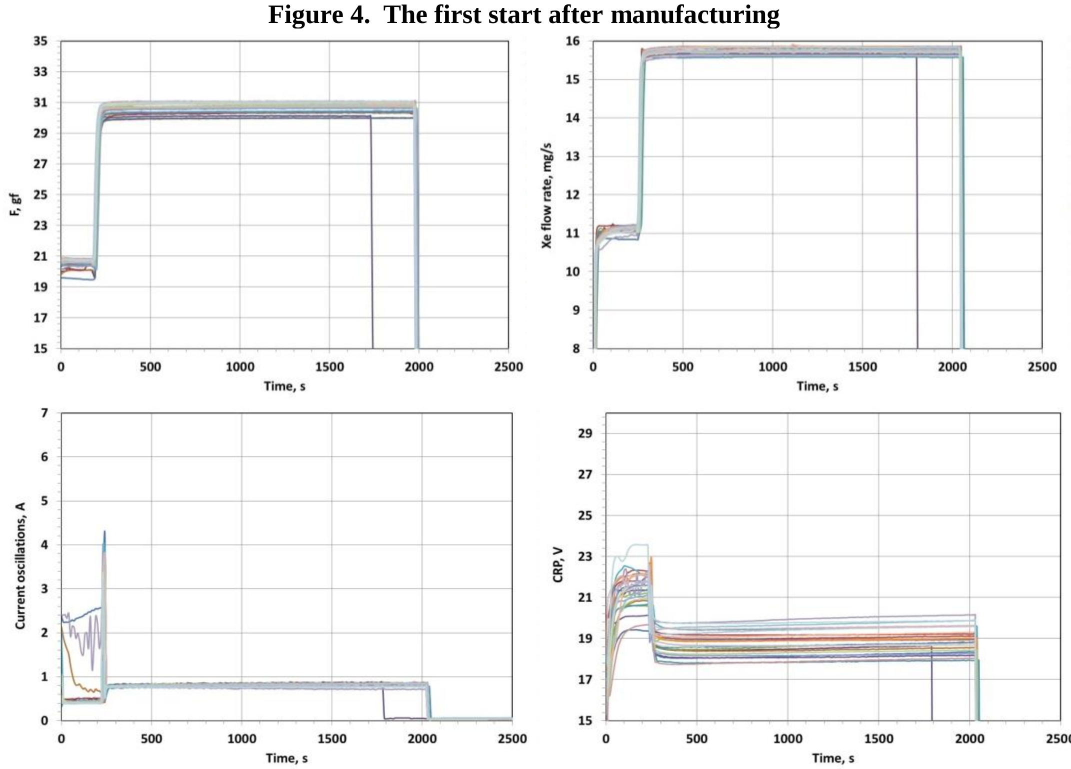


Figure 5. The second start after manufacturing

B. The first start after a contact with atmosphere and a cold start

It is interesting to compare between the first start after manufacturing and consequent starts after a contact with atmosphere. For comparison we chose the SPT-140 #022. For this thruster we observed the most rapid increase of oscillations. Fig. 6 shows the parameters change for this particular thruster during the first starts after a contact with atmosphere. Fig. 6 also shows the parameters change for this thruster at a cold start with the initial temperature equal to -60 °C. The thruster thrust during the burn-in 2 and cold start was not measured.

The comparison between Fig. 4, 5, 6 shows that a start of a newly manufactured thruster differs significantly from the consequent starts. It can be noted that the transient process, which is caused by a contact with atmosphere, is manifested only during first 30 – 40 min of operation. If the thruster has some accumulated time, then the oscillations increase within the first 15 min is not observed. The oscillations level after a switch to 4.5 kW/300 V is set at a nominal level and is not changed afterwards. A rapid increase of oscillations is absent.

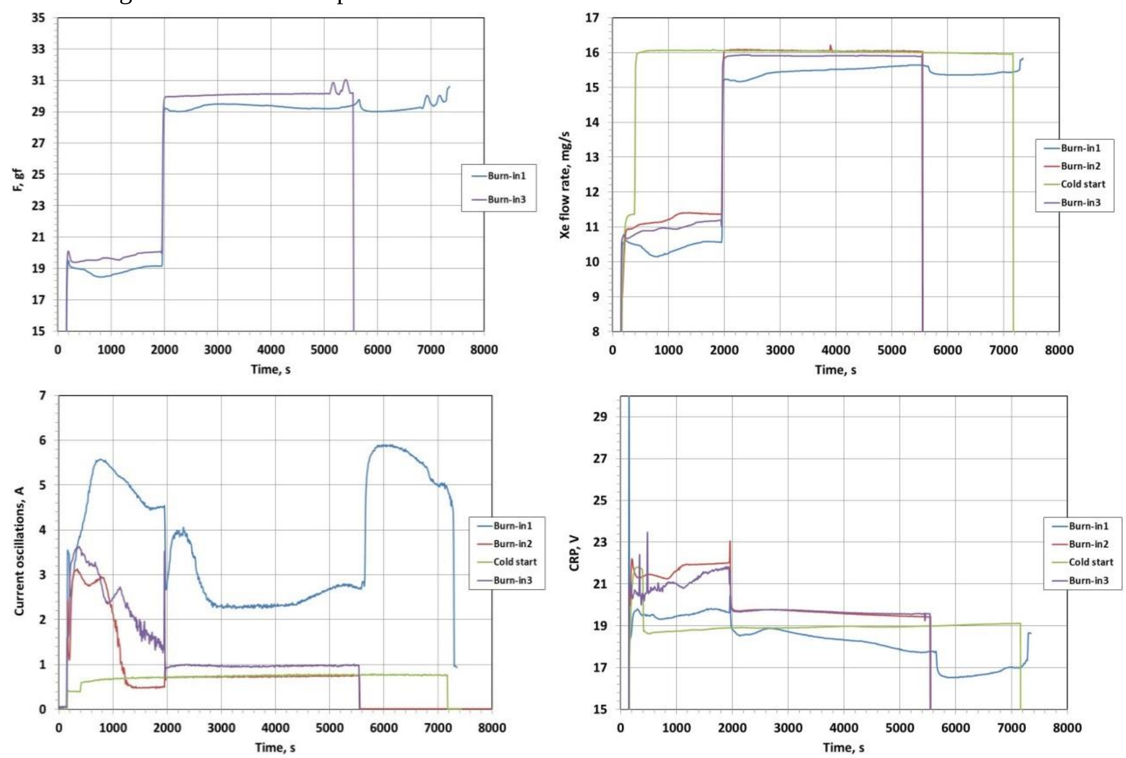


Figure 6. The first start after a contact with atmosphere and a cold start

C. The first start after regeneration of cryopumps

The first starts after a contact with atmosphere are characterized by a higher level of oscillations and lower level of thrust during the first operation minutes. As a rule, it is linked with the fact that in the discharge chamber pores there are such impurities accumulating as N_2, O_2 and water vapors. A contribution of these impurities to the operation process has an impact on the thruster operation parameters, because their properties differ much from Xenon properties. It is interesting to consider the thruster start after the cryopumps regeneration. This procedure is done during long-time life test and consists of the cryopumps panels defrosting, where the accumulated Xenon evaporates and removed from the vacuum chamber. During this procedure the thruster is in Xenon atmosphere at the pressure of ~10^{-2} Torr for 20 h.

In the course of the SPT-140 life test it was noted that after regeneration the thruster starts are accompanied by transient processes, which are similar to the processes observed during a start after a contact with atmosphere. At that, when accumulating lifetime the impact of regeneration decreases. It is shown in Fig. **7** (dots during the first 1000 h). It is interesting that thrust is stable throughout all the life test during start after regeneration. The causes of the parameters decrease, which are linked with the lifetime accumulated, might have something in common. In 3 and 4 it is noted that the parameters decrease at transient processes might be caused by the magnetic field change as a result of the magnet system dimensions change during a thermal expansion. Fig. **7** shows how the magnetic field change affects thrust at 4.5 kW/300 V during life test. For this mode the nominal magnet current is 5.5 A.

Fig. **7** shows that in the process of the lifetime accumulation the impact of magnetic field and cryopumps regeneration decreases. At the same time, it is seen that the magnet current decrease by 20 % leads to only 5 % thrust decrease, while a start after regeneration is accompanied by a 10 % thrust decrease. Such a change of parameters cannot be caused by the magnetic field changes due to the thruster thermal state change. Besides, the parameters stability at a cold start, see Fig. 6, shows that a change of the thruster thermal state has no impact on the operation parameters.

A strong impact of the magnetic field on the thruster parameters at the beginning of life is explained by the fact that at this time the plume interacts more with the discharge chamber wall. The fact, that the regeneration impact is also manifested only at the beginning of life, justifies that the parameters decrease is caused by the near-wall processes. An increase of propellant share in the near-wall area might lead to the result that the electrons, which are generated here, reach the anode in an easier way thanks to the near-wall conductivity mechanism. It should lead to the increase of the discharge current electron component and to the thrust decrease. In the process of the lifetime accumulation the plume interaction with the wall decreases and the transient processes intensity also decreases. After reaching 5000 hrs the transient processes do not practically appear, see Fig. 8.

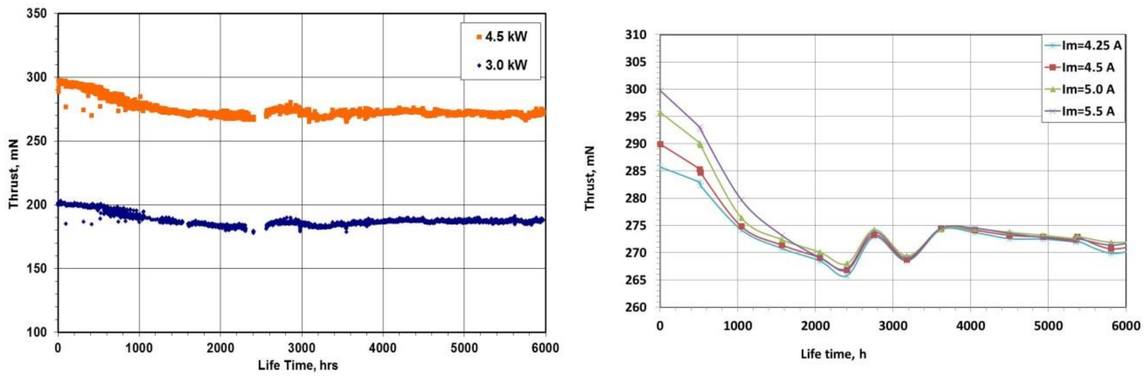
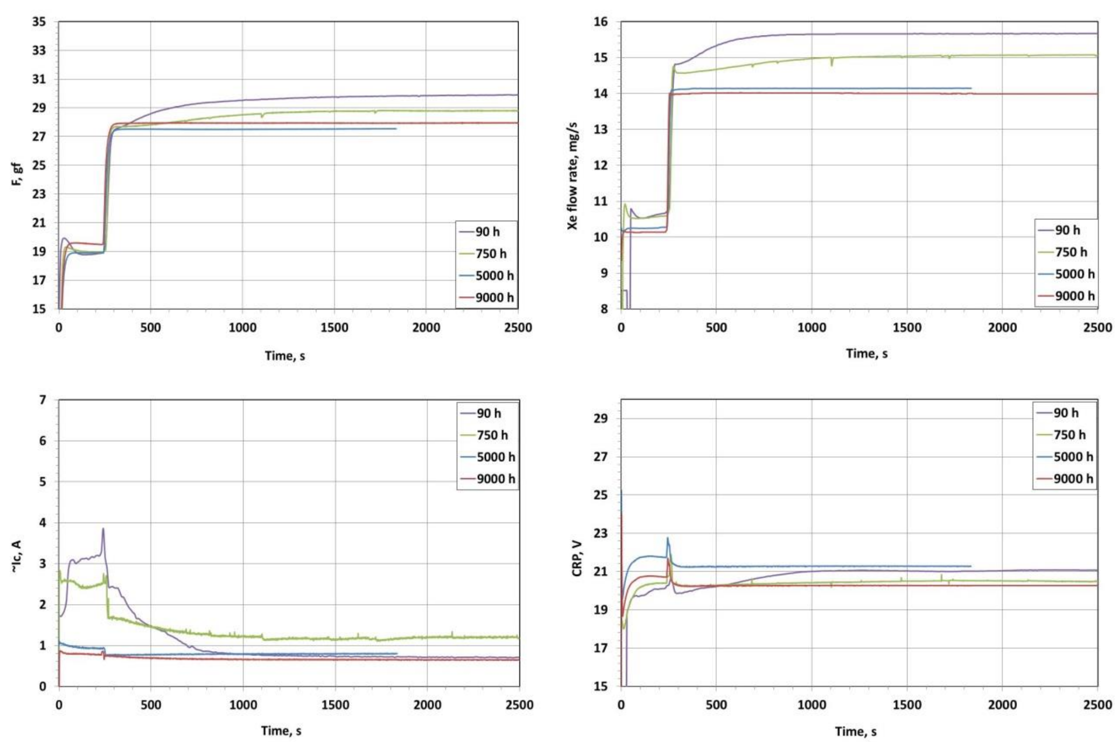


Figure 7. Thrust behavior in life test



8. The first start after regeneration of cryopumps

D. Cold start

Fig.9 shows the thruster parameters change when starting from a cold state at the initial temperature of -60 °C. The cold starts results are given. These starts were done at various stages of the thruster lifetime. As said above, a start from a cold state is not accompanied by transient processes for a newly manufactured thruster. However, for a thruster with 2500 h accumulated lifetime the temperature impact turned out to be more significant. At this accumulated operation time there is a very weak dependence observed between the parameters and magnetic field, see Fig. **7**. However, the speed of the transient processes indicates that the cause of the parameters change lies in the thruster thermal state.

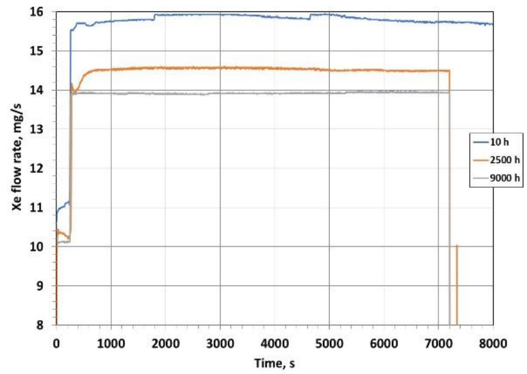


Figure 9. A cold start at various life phases

E. First start in space

Fig. 10 shows a typical first start up in space after launch, which can happen as early as 6 hours after launch to as long as several weeks depending on the mission plan. It is noticeable that the discharge current oscillations can increase to as much as the same amplitude of the DC component of the discharge current. However this event only last about 5 minutes, most likely linked to first outburst of contaminates, as explained above, present on the first layer of the ceramic of the discharge channel. The oscillation that persist at higher values on the order of 2-3A for as long as 30-45minutes before damping down to nominal values of 1A or less. These persistence is related to the continuous outgassing of the contaminates escaping from the lower layer of the ceramic block.

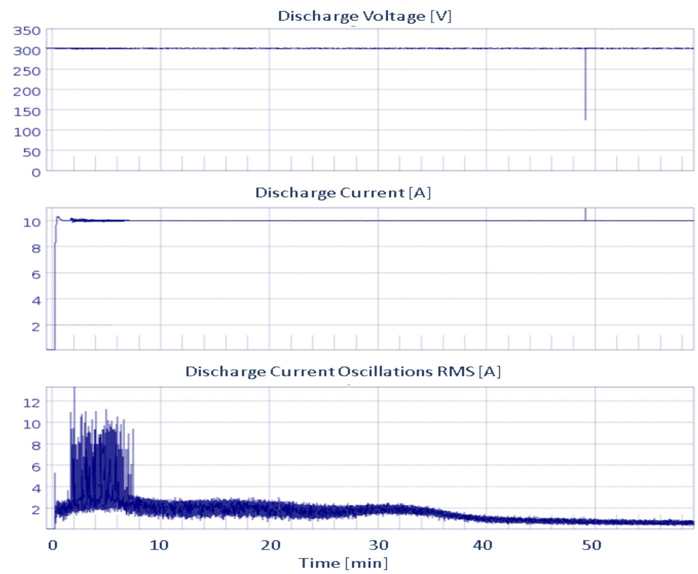
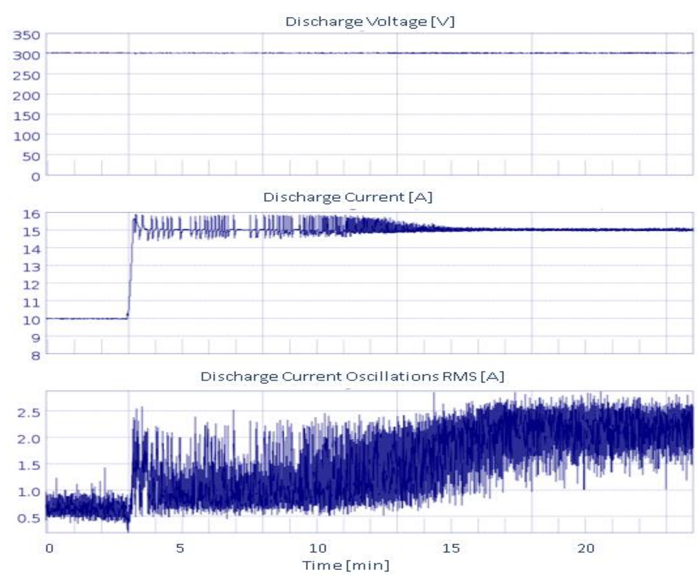


Figure 10. First start-up in space at 3.0kW

To complete the outgassing the thermal load is increased by bringing the discharge power from 3.0kW to 4.5kW after at least one hour operation at the lower power. Fig. 11 shows the completion of the outgassing with the remaining contaminates to be expelled from both anode and cathode. Within 15minutes the outgassing it is completed and it manifests as a series of perturbations before turning into white noise as in the previous case. This perturbations have an amplitude of ~1A, persist for about 0.5 to 2 seconds, and repeat at frequency from 0.1Hz to 1Hz, see Fig. 12. In this case it is clearer the outgassing that is ongoing in the cathode, as it respond with step functions in the cathode float voltage that is measured between the cathode and the S/C chassis isolated by a resistance on the order of hundreds of kΩ



11. First operation at 4.5kW in space

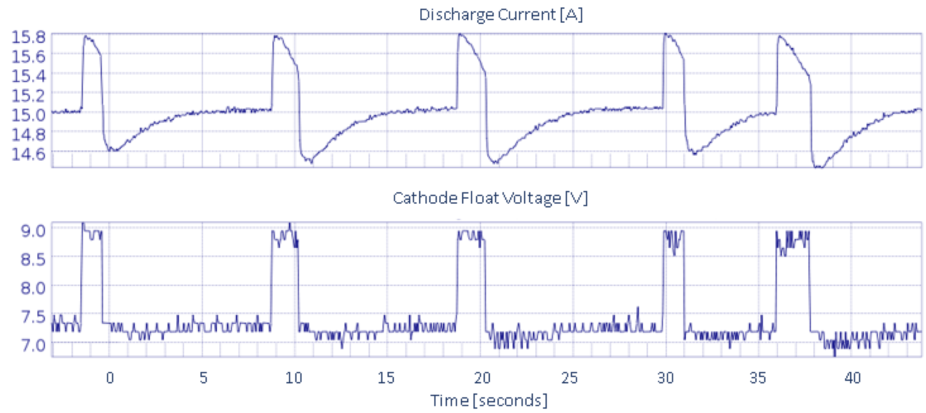


Figure 12. Periodic perturbations at 4.5 kW

In conclusion of this article we would like to pay attention to the processes named Single Events (SE). SE were revealed for the SPT-140 during a flight operation. SE is a rapid change of thruster parameters (discharge current and discharge voltage, CRP). This process is very fast. That is why the registered amplitude of spikes depends much on the sampling rate. During the SPT-140 life test the thruster parameters were registered with the frequency of 1 time per sec. The review of the life test data showed that this frequency is not enough to register the single events. When registering the parameters with the frequency of 10 times per second the SE is manifested as the discharge current spike as high as 1 – 3 A and a 10 – 150 V discharge voltage drop. The registered SE showed the true disturbance amplitude and its duration. Fig. 13 shows an SE registered with the frequency of 10 measurements per second using an oscilloscope.

As seen from Fig. 13, SE duration is about 2 ms. The average value of discharge current is 30 A. The peak value of discharge current is 80 A. Attempts to explain the nature of SE lead to the result that these events are linked to a constant change of electron conductivity. A visual observation of the thruster operation demonstrated that at the moment of SE occurrence there are sparks escaping the discharge chamber. The sparks escape is linked to contaminations emissions (discharge chamber sputtering products). These contaminations deposit as films in the discharge chamber areas which are not exposed to erosion. As the film thickness increases the film starts to delaminate and escape the acceleration channel changing the thruster operation process.

In the process of the lifetime accumulation the speed of the insulator sputtering slows down. The frequency of SE occurrence decreases. Closer to the end of the lifetime SE stop to occur. When developing the next modifications of SPTs it is planned to reduce the amount of the sputtered material and reduce SE occurrence frequency, respectively.

These events have been recording also in space during the extended operation of the thruster for orbit raising, when sampling at a rate of ~5Hz. Fig. 14 shows a typical single event that was recorded only sporadically (less than once every 24hrs) at beginning of life, with the frequency increasing to about once every 4 hours after 1,000 hours of operation. As mentioned above, this are more energetic event that show a higher spike in discharge current,

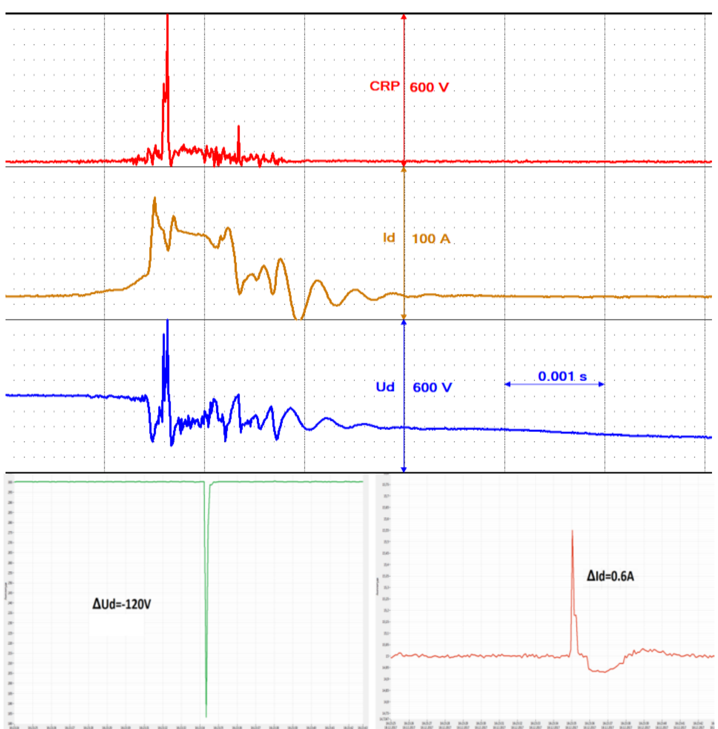


Figure 13. A Single event registered by oscilloscope (from above) and by registration system (from below)

and consequent drop in discharge voltage, due to expulsion of larger particles, produced during the erosion process of the ceramic.

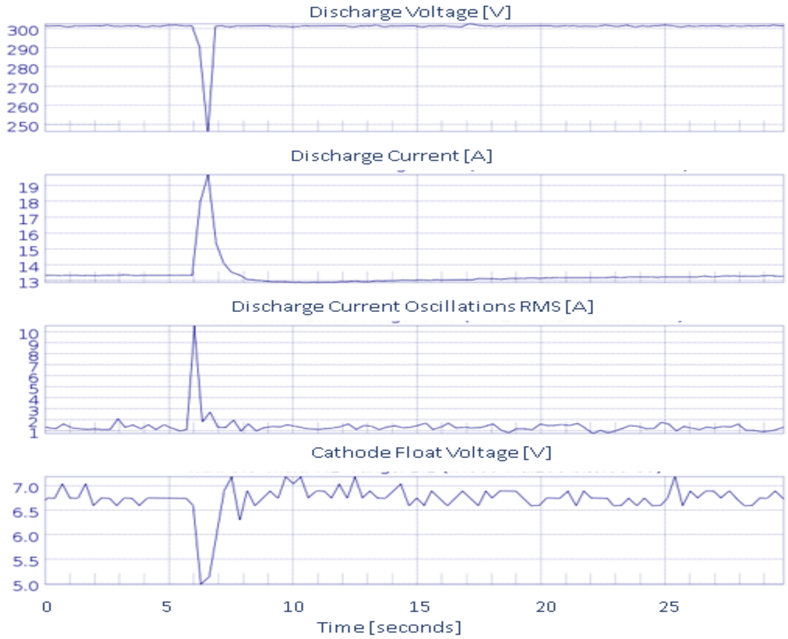


Figure 14. Single event recorded in space

V. Conclusion

The transient processes, linked with the thruster thermal state change and its outgassing, have been studied. It can be concluded that the transient processes, which are linked with the discharge chamber outgassing, do not depend on the chemical composition of the impurities.

It has been identified that a start from a cold state can be accompanied by transient processes. The level of impact depends on the accumulated lifetime. An impact from the cold state start does not correlate with the results of the magnet stability determination. That is why, we should not consider the magnetic field change as a cause of the transient processes when starting from a cold state.

The character of the transient processes and their change in the course of lifetime make it possible to assume that the transient processes are caused by a change of the interaction intensity with the discharge chamber wall. When the accumulated lifetime increases the plume interaction intensity with the discharge chamber wall decreases.

In the course of the lifetime accumulation the transient processes stop.

The discharge chamber walls contamination with sputtering products leads to periodical emissions of macroscopic particles. These emissions are accompanied by the discharge current spikes (Single Events).

When developing the next SPT models the volume of the sputtered material should be reduced, what will allow one to have more stable parameters during transient processes (as a result of the lower intensity of near-wall processes) and it will also allow one to reduce the occurrence frequency of Single Events.

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