

IEPC 2003-0336
TAL RELATIVE EROSION RATE REAL-TIME MEASUREMENTS
THROUGH ANALYSIS OF ITS EMISSION SPECTRA

O.S. Tverdokhlebov,

TsNIIMASH, Pionerskaya 4, Korolev, Moscow region, Russia 141070,
Phone: (095) 513-44-46, Fax: (095) 516-59-10, E-mail: olekos@pisem.net

G.F. Karabadzhak,

TsNIIMASH, Pionerskaya 4, Korolev, Moscow region, Russia 141070,
Phone: (095) 513-44-68, Fax: (095) 513-41-91, E-mail: karabadzhak@mtu.net

Abstract

Implementation of a simple non-intrusive optical diagnostic method to determine local erosion rates within Hall thrusters has been shown to be an extremely sound approach for thrusters of anode layer type. The development of probabilistic failure analysis tools to estimate thruster lifetime is critical in the space program today with highly cost and time constrained missions. These tools with experimental data are required to optimize the configuration of the thrusters, thruster materials, and operating conditions to maximize lifetime and optimize performance. These tools also improve our understanding of the accelerating capabilities of these thrusters so that we can better model their performance. Possibility of the anode layer thruster erosion rate evaluation through analysis its optical emissions and methods is demonstrated in present paper. The ability to quantify and identify erosion rates using a relatively inexpensive diagnostic method could lead to a very significant reduction in the development and flight validation cost of these thrusters. To date these methods after careful consideration are improved at TsNIIMASH. Based on these new methods of investigation data processing equipment was improved, several experiments with TAL D-80 were conducted and described. New experimental data which verify the method were obtained in various condition of the TALs operation and discussed. Erosion rate of the anode layer thruster was monitored through measuring of emissions of chrome and iron atoms sputtered from the thruster body. Despite the difference between excitation functions of these atoms, time dependence of the erosion rate appeared to be almost identical in both cases indicating the method reliability. The new diagnostic method could be widely implemented at many different laboratories where optical diagnostics is used.. Results discussed in the paper, will definitely contribute to the successful development of a Hall thruster erosion properties diagnostics.

Introduction

Hall thrusters with closed electron drift, such as the anode layer thrusters (TAL) developed at TsNIIMASH, are increasingly being considered for different spacecraft propulsion requirements. The mission and integration requirements for these various applications are varied. In order to confirm the utility of the anode layer thrusters to meet these requirements various experimental and analytic tools are available. This investigation is a next step in consideration of the suitability of emission spectra analysis as a diagnostic method for evaluation mission and integration requirements of anode layer thrusters. It is well known that operation lifetime of TAL suffers mostly from degradation of the guard rings protecting its magnetic pole pieces [1]. Assuredly, the thruster channel materials relative erosion rate changes during operation and with variation of the thruster operating parameters. Previous investigations of TAL emission spectra at TsNIIMASH have been done on three different TALs, D-38, D-55, and D-110. All of them used xenon as the propellant. General characteristics of the TALs as well as detailed information about their design and performance characteristics may be found in literature [2-5]. A simple and robust optical diagnostic method was suggested recently for evaluation of the TAL erosion rate in a close to real time condition. Final stage of this method development goes on at TSNIIMASH at this time. . Concurrently with independent D-80 lifetime erosion test was conducted an on-line erosion rate measurements for the future method verification. In addition, method sensitivity for the external influence was investigated. This paper present experimental relative erosion rate dependence of variation of the thruster operating parameters, such as voltage, current, magnetic field, mass flow rate, background pressure. In addition to the thruster guard rings erosion rate measurements test specimen spectra analyses of a different material were conducted. Obtained experimental data also discussed below.

Experimental apparatus

All of the optical measurements described in this paper were carried out concurrently with the performance and lifetime tests of different TALs. The vacuum chamber where the D-80 thruster was installed had a quartz window, giving an opportunity to work in the UV region of spectra. An illustrative sketch and photo of the experimental set up is present in Figure (1).

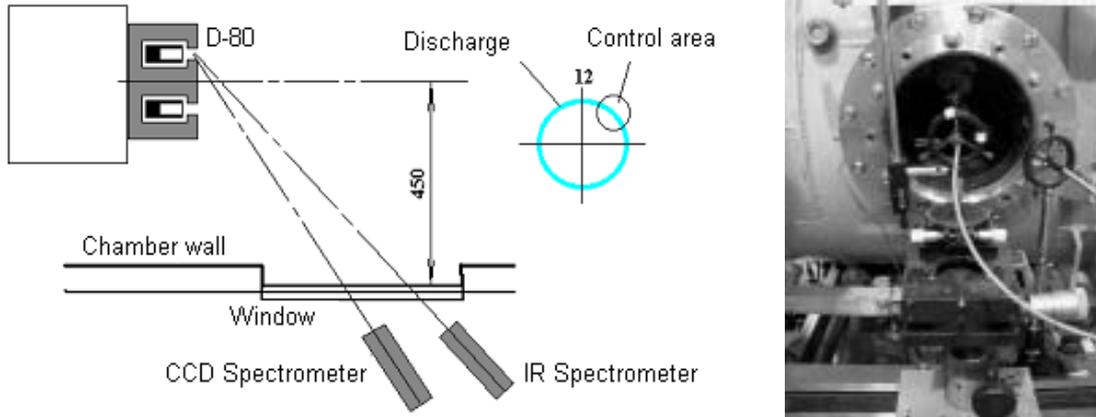


Figure1. Sketch and photo of the experimental set up

A set of spectral instruments was used for the spectra acquisition in different tests. In fact the instruments, hardware and procedure for the optical setup respond calibration were the same in different tests excluding the optical scheme. All data discussed in present paper were acquired with the use of a CCD based UV-spectrometer. The hardware was capable to acquire discharge and plume spectra with spectral resolution of 0.45 nm and relatively high signal to noise ratio. The spectrometer covered the wavelength region from 230 to 380 nm. Typically, it took about 1 sec for a spectra acquisition. So that most of weak lines could be detected and reliably resolved.

For the wide spread investigations of erosion characteristics of eroded materials the test specimen of titanium, tantalum, brass and permendure were installed in chamber. All of specimens were located at 1 meter from thruster in thruster plume. To avoid a first quartz window coating by the sputtering materials a special window screen was installed. In addition, for the specimen observation a second quartz window was installed. Second window had no a screen and it completely become dusty over several hours.

Method description

Presented method is dedicated to determination of sputtering properties and erosion rate of a Hall effect thruster operated with xenon propellant. The method is based on comparison of optical spectra measured at any operating regime with the spectra measured at some nominal operating mode. Result of this comparison is relative variation of the thruster sputtering properties. Once the absolute value of the sputtering rate is known in the nominal regime, the method provides the absolute sputtering rates as well.

Basic statements of the method were discussed earlier [6]. According to the model discussed in ref.[6] erosion rate (material sputtering rate) R of any particular material in TAL may be expressed as:

$$\frac{R}{R_n} = \frac{N^+}{N_n^+} \cdot \frac{I_s}{I_{sn}} \cdot \frac{I_{xn}}{I_x} \quad (1)$$

where R – erosion rate, I_x and I_s are the radiation intensities of the reference xenon line and sputtered atom line, N^+ is the xenon ion number density, subscript n is attributed to the same values in nominal condition.

In previous work [6] appropriate emissions were found in the TAL spectrum that satisfied to the condition (1). For this purpose, emission spectra from the thruster discharge at various operating voltages were analysed. Tested version of the thruster with stainless steel guard rings and well-studied erosion characteristics was utilized for this test. In particular, erosion rate of the guard rings was known to be directly proportional to the operating voltage in that thruster. Given the proportionality of the material-sputtering yield to the energy of bombarding xenon ions [8], this makes a simple physical sense.

In present work, to determinate a relative erosion rate of chrome (Cr) and iron (Fe), as a main guard ring material components, we have used a relation between integral spectra line intensities of chrome and iron and same reference xenon lines as in Ref [6].

Spectra and Erosion test data and discussion

Current work present experimental relative erosion rate dependence on variation of the thruster operating parameters, such as voltage, current, magnetic field, mass flow rate, background pressure. Besides, of thrusters, guard rings erosion rate measurements; test specimen spectra analyses of a different material were conducted. Each test specimen was located at 1 meter from thruster in thruster plume. Obtained experimental data also discussed below. One of the first phase tasks was the adjustment of procedure and spectral data acquisition. Second task was the comparison with results of independent erosion tests.

All erosion data were obtained during D-80 lifetime tests. One-stage and two-stage thruster operating modes had been investigated and analyzed. General lifetime tests characteristics of the D-80 as well as information about their design and performance characteristics may be found in literature [9]. Spectra taken from the thruster discharge were processed and relative erosion rates were recovered in accordance with relation (1). The data are presented on the following figures.

Figure (2) shows the thruster operating time dependence of the erosion rate during first life-time test in high-voltage one-stage mode. The figure illustrates that in first 20 hours of thruster operation the Fe and Cr erosion rate constantly grow. After 20 hours the value of the erosion rate came to the mean value with some oscillation. As it was later proved, such kind of oscillations corresponds to external influences. The range between 15 and 20 hours illustrate the brake in data acquisition.

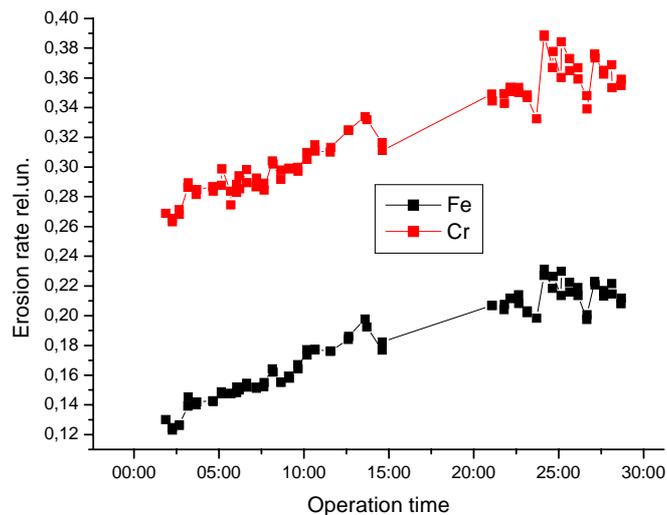


Figure 2. Cr and Fe erosion rate during TAL D-80 lifetime test (one-stage mode).

Figure (3) shows the discharge voltage dependence of the Fe and Cr erosion rate of the same thruster. There are three characteristic curve zones. First zone with double measurement on 300V illustrate thruster heating. Second zone between 300V and 600V describe a proportional growth of the erosion rate of each element and applied power. In the third zone from 600 volts and higher, significant is that observing erosion rate growth almost stopped. It should be noted that variation of the thruster operation voltage accompanied by variation of some other parameters, such as current, magnetic field etc. The letter might explain the non-linear erosion rate growth at higher voltages.

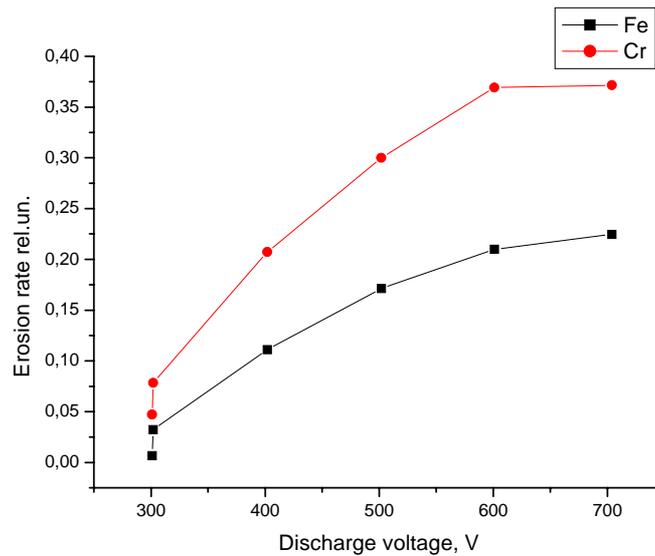


Figure 3. Cr and Fe erosion rate dependent on discharge voltage (one-stage mode).

Figure (4) shows the thruster operating time dependence of the erosion rate during second D-80 lifetime test in two-stage mode. The figure illustrates that curves consist of several characteristic zones. Thus, zone 1, which look like drop, describe a magnetic field improvement. Zone 2 corresponds to the thruster operating interruption. In spite of first and second zone presents it is evident that Fe and Cr erosion rate decreased in general during first hours of operating. As it turned out, it is correspond with inaccuracy of guard rings manufacturing, presence of burr, etc. It is significant that in two-stage mode similarly to the one-stage mode erosion rate comes to some constant value obtaining. The average mean value oscillations (zone 3) correspond with external influences, in particular with feed system pressure variation.

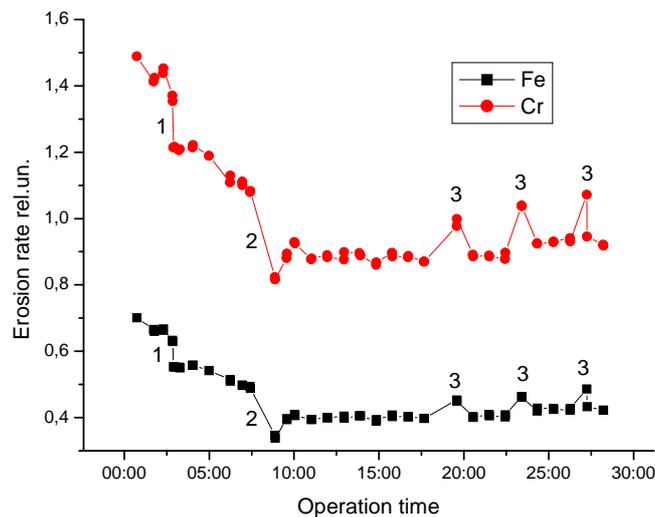


Figure 4. Cr and Fe erosion rate during TAL D-80 lifetime test (two-stage mode).

Figure (5) shows the discharge voltage dependence of the Fe and Cr erosion rate in tow-stage mode. There are also three characteristic curve zones. First zone up to 200V is abnormal operating mode with unstable value of erosion rate. Second zone between 200V and 450V describe a proportional growth of the erosion rate of each element and applied power. Third, zone from 450 volts and higher. Just us in one-stage mode it is significant that erosion rate growth stopped at mean value.

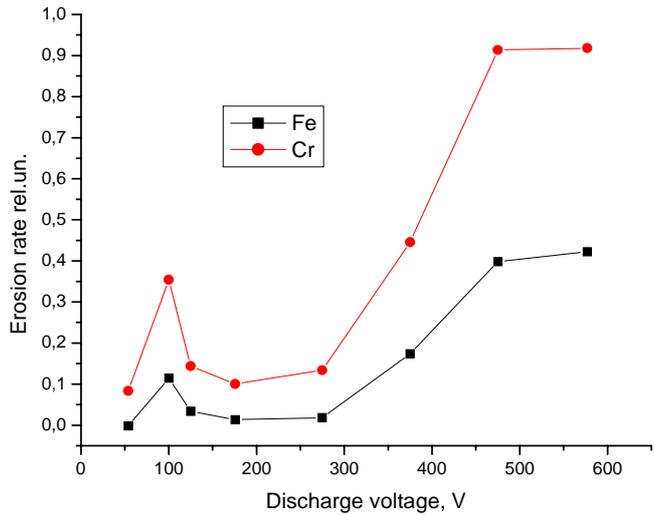


Figure 5. Cr and Fe erosion rate dependent on accelerating voltage (two-stage mode).

In the course of method verification the sensitivity of spectra measuring to operating parameters variation was investigated. The sensitivity of UV discharge spectra to background pressure variation was investigated. At nominal thruster operation point a background pressure were changing from 1.75×10^{-4} torr to 3.25×10^{-4} torr. by closing a high-vacuum gate. No pressure dependence was found. Intensity of every line of UV spectra region was the same. Since this erosion rate measuring method can be use with a different TALs in different vacuum chambers it is significant that background pressure had non an influence on it.

Besides, of thrusters, guard rings erosion rate measurements, test specimen spectra analyses of a different material were conducted. Tantalum, titanium, brass and permendure samples were placed in the TAL plume at about 1 meter downstream from the thruster. The spectra were obtained with the same UV-spectrometer. Samples of the spectra were presented in figure 6.

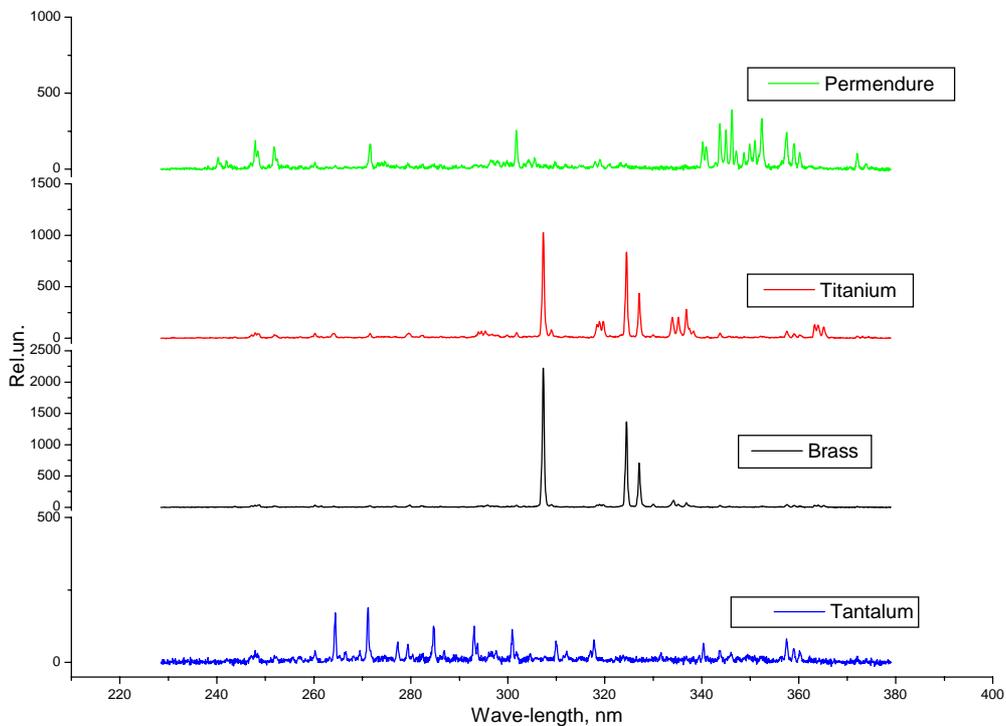


Figure 6. UV spectra of the tests specimens in the thruster plume

Calibration of the optical diagnostic method for the erosion rate evaluation became possible through comparison of the optical method predictions with results of independent erosion tests [9]. In the course of these erosion tests integral erosion of the guard rings was measured. At the current stage of the study the integral erosion measurements are being compared with relative optical measurements. Results of this comparison will be published in future.

Conclusion

The new optical method for the real time monitoring of the erosion processes in a Hall effect thrusters has been further tested. The method demonstrated excellent capabilities. How the experiments showed, the stability of spectral characteristics and method independence of variation of background pressure making it useful for the designers of the electric propulsion thrusters operating with xenon propellant.

Future improvement of the method assumes its detailed verification through comparison with results of independent erosion tests.

References

1. Morozov. A.I. Physical Basics of Space Electric Propulsion Thrusters. Volume 1. Atomizdat. Moscow. 1978. (in Russian).
2. Domonkos, M.T., Marrese, C.M., Haas, J.M., Gallimore, A.D., "Very Near-Field Plume Investigation of the D-55", AIAA-97-3062, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conf., July 1997, Seattle, WA.
3. Semenkin, A.V., et al., "Development Program and Preliminary Test Results of the TAL-110 Thruster" AIAA-99-2279, 35th Joint Propulsion Conference, June 1999, Los Angeles, CA.
4. Manzella, D.H., Oleson, S., Sankovic, J., Haag, T., Semenkin, A., Kim, V., "Evaluation of Low Power Hall Thruster Propulsion", AIAA-96-2736, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conf., July, 1996, FL.
5. Garner, C.E. at al, "Experimental Evaluation of Russian Anode Layer Thrusters", AIAA-94-3010, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conf., June, 1994, IN.
6. Karabadzhak G.F., Semenkin A.V., Tverdokhlebov S.O., "Semi-empirical method for evaluation of a xenon operating Hall thruster erosion rate through analysis of its emission spectra", Proc. 3rd International Conference on Spacecraft Propulsion, Oct.2000, Cannes, France, p. 909.
7. Karabadzhak G.F., Chiu Y.-H., Williams S., Dressler R., "Hall thruster optical emission analysis based on single collision luminescence spectra", AAIA 2001-3880.
8. Pleshivtsev N.V., "Sputtering processes", Moscow, 1968 (in Russian).
9. Solodukhin A.E., Semenkin A.V., "Study of discharge channel erosion in multi mode anode layer thruster", This conference paper IEPC 2003-0204.