Advancements in Reservoir-Type and Scandate Hollow Cathode Technology
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Abstract: Current and future missions employing electric propulsion involving functions such as orbit raising, orbital maneuvering, long-term station keeping, and deep space exploration demand higher performance, higher power, and higher propellant throughput (lifetime) relative to past requirements. These needs translate directly into enhanced demands for substantial improvements in hollow cathode performance. While there are competing technologies, ongoing development of dispenser cathode technology, based in principle on the well-proven and successfully applied traditional barium calcium aluminate impregnated insert, is yielding remarkable performance improvements. Both, reservoir-type and impregnated scandate cathodes are being developed and their performance characterized. This paper emphasizes the performance characterization, which has advanced substantially in the recent past.

Introduction

TWO approaches are being pursued in development of thermionic dispenser-type hollow cathodes providing enhanced performance. Both approaches utilize dispenser cathode technologies developed for use in vacuum devices and clearly demonstrated to provide performance, both current density capability for a given operating temperature as well as lifetime, superior to the impregnated cathode technology now applied in traditional electric propulsion applications of hollow cathodes.

The first is application of reservoir-type hollow cathode designs in lieu of traditional impregnated dispenser cathode insert technology. This approach was first addressed under the auspices of the NEXIS ion thruster development project as part of the JIMO program in the 2004-2005 timeframe. Although mechanical problems were encountered with the designs of that era, the limited performance testing results obtained were extremely promising. Reservoir-type dispenser cathodes predate the ubiquitous impregnated type, but, since the introduction of the impregnated dispenser cathode, reservoir cathodes have typically been employed only in applications that were uniquely suited to their capabilities. Recently, in extensive testing in vacuum devices simulating the environment of microwave tubes, the superior long life, high current density capabilities of the reservoir-type cathode have been clearly demonstrated. These test results provide a sound basis for pursuit of groundbreaking technology in hollow cathodes.

The other technology, which also comes from recent developments in vacuum device applications, is scandate cathodes, which can simplistically be described as traditional barium calcium aluminate impregnated cathodes with an addition of a small amount of scandium oxide. Although numerous manifestations of scandate cathodes have

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been devised, tested, and found wanting since the 1970's, over the last decade scandate cathode technology has been substantially advanced largely through efforts of a group working under Y. Wang at the Beijing University of Technology (BJUT). In the U.S. e-beam, inc. has developed proprietary technology based in part on the Chinese work, including efforts related to both vacuum devices and hollow cathodes intended for EP applications.

All of the cathodes tested used emitters with the nominal dimensions of the NSTAR insert, 0.160” inside diameter, 0.210” outside diameter, and 1.00” in length.

Discussion

Reservoir-type Hollow Cathodes

The work reported here has involved development and testing of reservoir-type hollow cathodes using iridium-tungsten and osmium-tungsten emitters with standard barium calcium aluminate utilized as emissive materials in the reservoirs. This effort has extended earlier development of reservoir -type hollow cathodes using tungsten emitters and the same emissive materials.

Schematically the reservoir-type hollow cathode is shown in Figure 1. It differs from the traditional impregnated type insert in that the emitter matrix does not contain the barium calcium aluminate impregnant, but the emissive material is contained in an annular cavity surrounding the outside diameter of the emitter. This cavity is closed by an outer body and end plates.

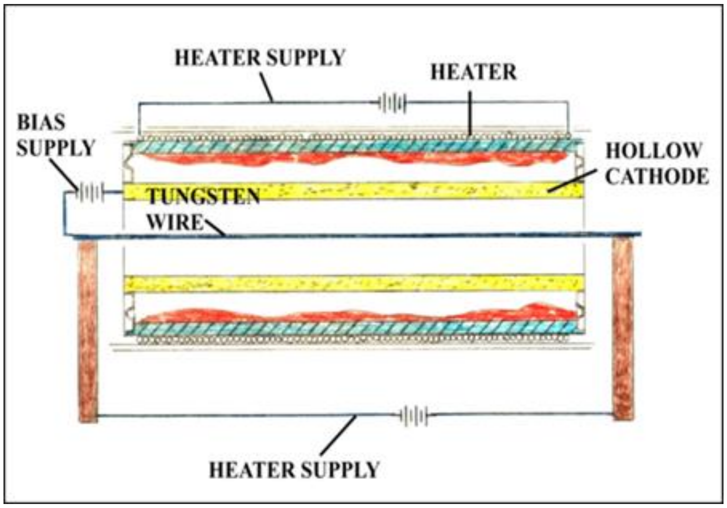

Figure 1. Schematic of reservoir-type hollow cathode.
The test configuration used at e-beam is also shown.

Hollow Cathodes with Impregnated Scandate Inserts

Hollow cathodes using impregnated tungsten matrix inserts in which the impregnant material has been modified by addition of scandium oxide have also been addressed in the e-beam development program. This type of cathode has been the subject of intense development for application in vacuum devices, but there has been limited success in achieving consistent performance, although the promise shown has been extremely attractive. The most important results from the current work have been significant progress in understanding the fabrication processes applied and optimization of material compositions and processing parameters. For example, it it has been claimed by numerous investigators that a 5-10 weight percent addition of scandium oxide to the standard barium calcium aluminate impregnant was appropriate. Recent results, however, have shown that this level of scandium oxide content is substantially greater than optimum, and it is now believed that 2-4 weight percent is more nearly optimum.

Xenon Discharge Testing of Hollow Cathodes

Unique, economical discharge testing methods have been devised to support rapid characterization of emission performance of both types of hollow cathodes under development. The configuration used in this testing is depicted schematically in Figure 1. As shown, a tungsten wire, used as the anode, is deployed on the centerline of the inside diameter of the emitter. The anode wire is tensioned by a spring arrangement to maintain its position compensating for thermal expansion upon heating. Due to thermal limitations associated with the anode wire, testing is performed in pulse mode operation.

Testing of the hollow cathode in the configuration shown in Figure 1 is performed using a test vehicle comprised of a glass envelope glass envelope closed by a stem with appropriate feedthroughs for necessary electrical connections. A typical test vehicle is shown in Figure 2.

Figure 2. Test vehicle for xenon discharge testing of hollow cathodes.

The test vehicle is initially evacuated to a pressure typically less than 1 x 10^{-7} Torr. Cathode activation and initial testing to verify satisfactory emission performance is performed in vacuum. Maintenance of the vacuum and subsequently the cleanliness of the xenon atmosphere used in discharge testing is assured by the use of a barium getter.

Once the vacuum emission characteristics have been characterized, a glass capsule containing the necessary quantity of xenon to establish a pressure of approximately 1 Torr in the test vehicle is broken. The emission testing in vacuum is also performed in pulse mode due to the thermal limitations of the wire anode.

Results

Baseline Reservoir-type Hollow Cathodes with Tungsten Emitters

In previous efforts e-beam has tested reservoir-type hollow cathodes with tungsten emitters, and those test results have now proven invaluable by providing a baseline for comparison of performance improvements obtained in the current work. Typical results of xenon discharge testing of a reservoir-type hollow cathode with a tungsten emitter are shown in Figures 3 and 4.

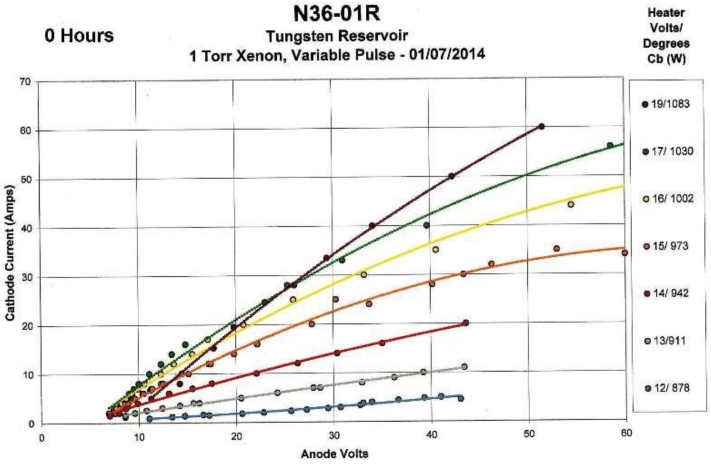

Figure 3. Xenon discharge I-V curves for reservoir-type hollow cathode with tungsten emitter at zero hours.

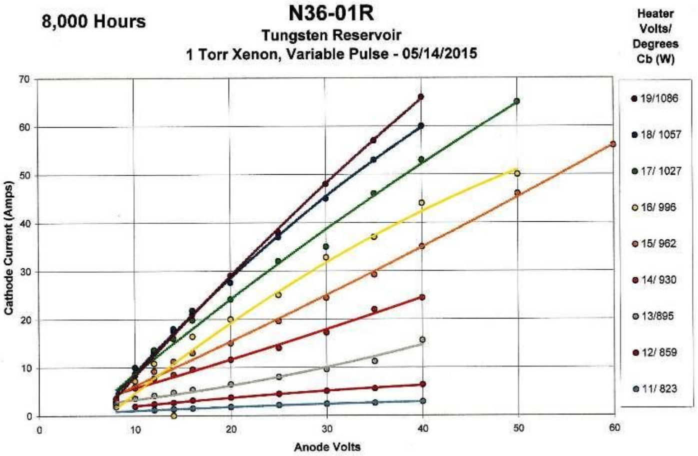

Figure 4. Xenon discharge I-V curves for reservoir-type hollow cathode with tungsten emitter after 8000 hours.

Comparison of the two sets of data reveals that over the 8000 hour duration of testing the performance of this cathode significantly improved. Initially the cathode delivered a discharge current of 50 A at an anode voltage of 50 V while operating at approximately 1030° C. After 8000 hours of operation the same discharge current was achieved at an anode voltage of 50 V operating at approximately 996° C. This test was terminated after 8000 hours, so it is unknown whether the trend shown here would have continued and how many hours of operation could have been achieved before degradation of the discharge current was observed. However, this data reveals one of the advantages of the reservoir-type cathode, which has been universally observed in vacuum testing; namely, that even at operating temperatures of 1030° C, where impregnated cathodes would undoubtedly have displayed degradation of performance over the test., the reservoir-type cathode has actually improved. Consideration of the results of testing reservoir-type cathodes in vacuum makes these results somewhat less surprising. Reservoir cathodes operating at 1030°-1050° C have been reported to display no degradation of space charge limited current for test periods in excess of 100,000 hours.

Reservoir-Type Hollow Cathodes with Iridium-Tungsten Emitters

Iridium-tungsten emitter matrices have been used in vacuum devices for both impregnated and reservoir-type cathodes. However, in the vacuum applications a less than optimum iridium-tungsten composition has been used. The same composition was evaluated in hollow cathode usage in the form of an impregnated insert.[1]

It was reported that there was no evidence of iridium deposition where tungsten deposits were observed, as they typically are in hollow cathodes employing impregnated inserts with tungsten matrices.

These results infer that iridium-tungsten alloys of appropriate composition are resistant to material transport in impure propellants, specifically those containing low levels of oxygen or oxygen bearing compounds. It is also known that iridium-tungsten alloys with higher iridium content than those used in the impregnated cathode applications provide lower work function values. None of the limitations on composition iridium-tungsten alloys used in the impregnated cathode applications apply to their use in reservoir-type cathodes. This advantage has been exploited in development work at e-beam.

Figures 5 and 6 show the results of xenon discharge testing of reservoir-type hollow cathodes employing iridium-tungsten alloy emitters. In the testing performed at e-beam it is impossible to assess the issue of material transport. Those issues can only be assessed in testing comparable to that reported in Reference 1, which is beyond the scope of e-beam capabilities.

At the initiation of testing a discharge current of 50 A was obtained with an anode voltage of approximately 42 V at 938° C. When testing was concluded after 12000 hours the same discharge current was observed at approximately 39 V on the anode at 964° C.

The cause of the increase in the required temperature to sustain 50 A discharge current is not known, but the reduction in operating temperature and anode voltage for equivalent discharge current is significant. The expected reduction in operating temperature due to a lower work function appears to have been realized. Such a reduction in temperature would be expected to pay a substantial dividend in lifetime.

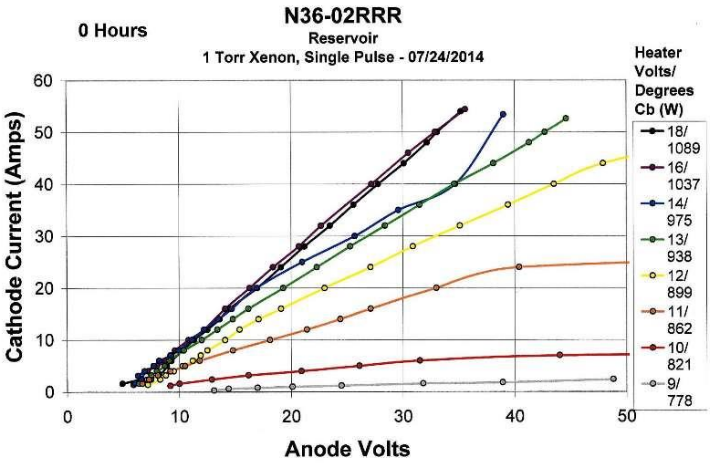

Figure 5. Xenon discharge I-V curves for reservoir-type hollow cathode with iridium-tungsten emitter at zero hours.

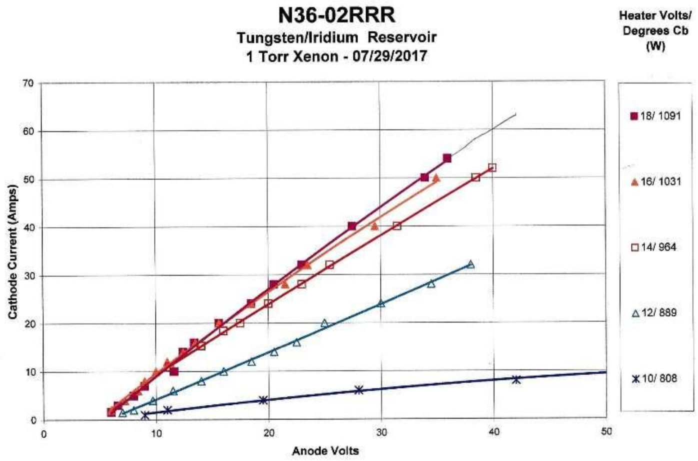

Figure 6. Xenon discharge I-V curves for reservoir-type hollow cathode with iridium-tungsten emitter after 12000 hours.

Reservoir-Type Hollow Cathodes with Osmium-Tungsten Emitters

Osmium-tungsten alloys have been employed as cathode emitting surfaces in the form of surface coatings as well as cathode matrices. Notably, there have been reports of prior efforts to apply impregnated osmium-tungsten alloy emitters in hollow cathodes.[2,3]

Although the performance reported for these cathodes was superior to that to be expected from cathodes employing tungsten emitters, the use of a less than optimum alloy composition for the emitter probably limited the extent of the advantage gained.

In development of reservoir-type hollow cathodes using osmium-tungsten emitters a more nearly optimum composition can be and has been employed by e-beam. This has resulted in achievement of extremely worthwhile results.

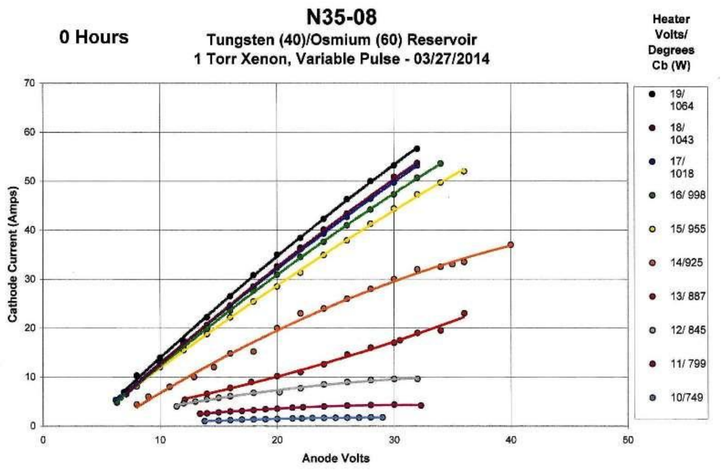

Figure 7. Xenon discharge I-V curves for reservoir-type hollow cathode with osmium-tungsten emitter at zero hours.

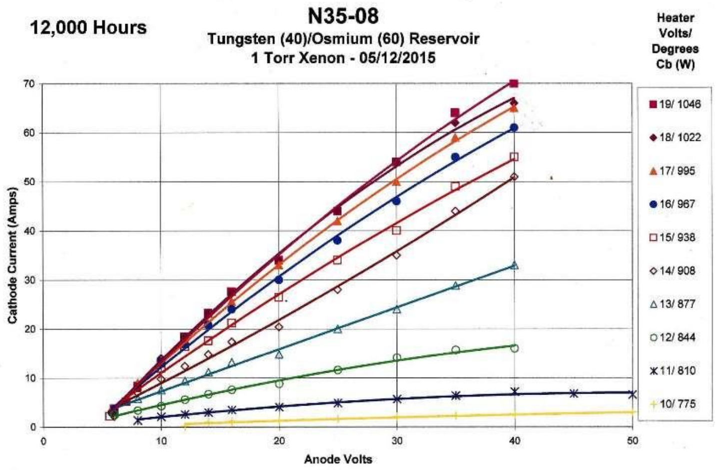

Figure 8. Xenon discharge I-V curves for reservoir-type hollow cathode with osmium-tungsten emitter at 12000 hours.

At the initiation of testing 50 A of discharge current was obtained at an anode voltage of approximately 35 V and 955° C. After 12000 hours of operation an equivalent current was realized at 40 V on the anode and an operating temperature of 908° C. The ability to produce 50 A of discharge current at a temperature of only 908° C represents potential for substantially increased lifetime.

Hollow Cathode with Barium Calcium Aluminate Impregnated Sc_2O_3-W Insert

Scandate cathodes have been under development since the 1970s, and have demonstrated great promise; but that promise has been impossible to realize with an adequate level of reproducibility, rendering them unsuitable for commercialization. Wang's group at the Beijing University of Technology has reported consistent progress in development of reproducible processing and realization of the performance potential of scandate cathodes since the early 2000's. Investigators at e-beam have followed this work closely and have extended the performance capabilities of scandate cathodes based on ongoing development of proprietary processing technology. While this work has focused primarily on development of cathodes for application in vacuum devices, recent efforts have extended the applications of interest to hollow cathodes for use in electric propulsion.

The scandate cathode technology developed by e-beam is based on fabrication of a scandium oxide doped tungsten matrix that is sintered to appropriate density in a fashion comparable to that employed for fabrication of standard tungsten matrices for impregnated dispenser cathodes. The matrix is subsequently impregnated with a standard barium calcium aluminate impregnant comparable to those used in standard impregnated dispenser cathode applications. The result is a cathode with superior emission performance at temperatures as low as 800°-850° C in vacuum.

Inserts for use in hollow cathodes are fabricated in essentially identical fashion to standard tungsten matrix dispenser cathodes, entailing substantially simpler fabrication practices than those required for reservoir-type cathodes. However, as shown in Figures 9 and 10 the emission performance is comparable to the best of the other cathode types described here.

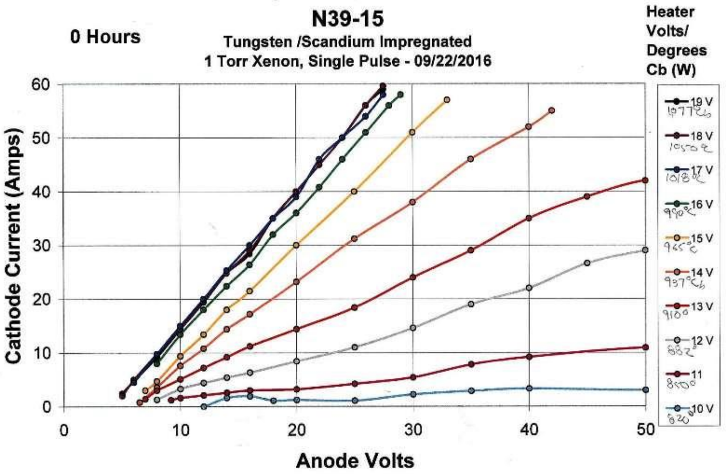

Figure 9. Xenon discharge I-V curves for hollow cathode with scandate cathode insert at zero hours.

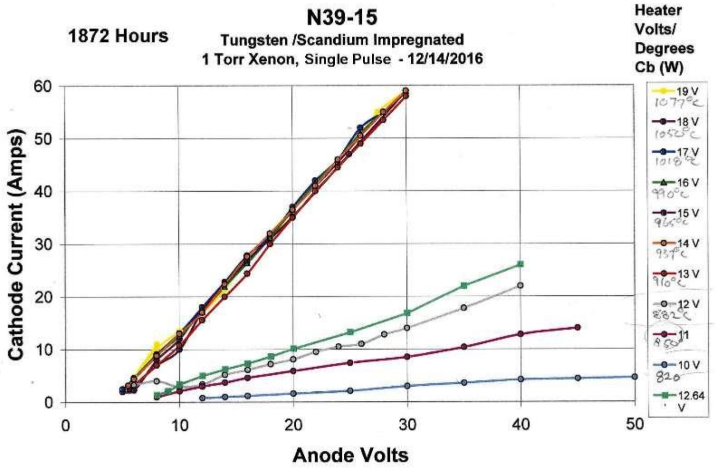

Figure 10. Xenon discharge I-V curves for hollow cathode with scandate cathode insert at 1872 hours.

When testing was initiated 50 A of discharge current was obtained at an anode voltage of 38 V and an operating temperature of 957° C. After 1872 hours of operation the same discharge current was observed at approximately 26 V on the anode and a temperature of 910° C.

Summary

The emission performance of each of the cathode types addressed above is summarized in Table I. As has been the case in the foregoing discussion the required anode voltage and operating temperature to achieve 50 A discharge current are used as the basis for comparison of performance.

Table I. Summary of Xenon Discharge Testing Results

Cathode Type	Operating Time (hours)	Anode Voltage (V)	Temperature (° C)
Reservoir-type with W emitter	0	50	1030
	8000	50	996
Reservoir-type with Ir-W emitter	0	42	938
	12000	39	964
Reservoir-type with Os-W emitter	0	35	955
	12000	40	908
Impregnated scandate emitter	0	38	957
	1872	26	910

Conclusions

The testing results summarized in Table I show that each of the three advanced cathode types provides notably superior performance relative to the reservoir-type employing a tungsten emitter. Although none of the three types have been optimized and development work on all is ongoing, it is clear that they hold promise for providing improved performance relative to current technology. It is believed that cathodes serving the requirements for high power, long life electric propulsion can be realized with further development of one or more of these technologies.

References

[1] James E. Polk and Angela M. Capece, "Materials Characterization of Impregnated W and W-Ir Cathodes after Oxygen Poisoning," *Applied Surface Science* **338** 27-33 (2015).

[2] G. Kornfeld, N. Koch, and H.-P. Harmann, "W/Os Mixed Metal Matrix Hollow Cathode Neutraliser HKN5000," IEPC-2005-298, 29th International Electric Propulsion Conference, Princeton, New Jersey (2005).

[3] N. Koch, H.-P. Harmann, and G. Kornfeld, "Status of the THALES Tungsten/Osmium-Metal Hollow Cathode Neutralizer Development," IEPC-2007-117, 30th International Electric Propulsion Conference, Florence, Italy (2007).