

Graphite Sublimation Tests for Target Development for the Muon Collider/Neutrino Factory

C. C. Tsai, T. A. Gabriel, J. R. Haines, and D. A. Rasmussen

Oak Ridge National Laboratory, P.O. Box 2008, MS-6169, Oak Ridge, TN 37831-6169, U.S.A.

Abstract—Graphite sublimation tests have been conducted in a high-temperature oven, which is operated either in high vacuum or in an 1-atm cover gas of helium (or argon). Preliminary data of the sublimation rate of graphite foils at ~ 2400 K in vacuum are consistent with theoretical prediction. Additional tests of graphite rods (15 mm in diameter and 300 mm long) have been conducted in high vacuum and in cover gases of helium as well as argon. The sublimation mass loss rate at 2350 K is 1.7 mg/h for static argon cover gas (>1 atm) and 0.78 mg/h for static helium cover gas. These values of sublimation mass loss rate for cover gas cases are lower than that of 5.8 mg/h in high vacuum. This unique approach of using cover gas to reduce sublimation rate could allow a robust radiatively cooled graphite target for the Muon Collider/Neutrino Factory as proposed in the conceptual design study. In this paper, the results of graphite sublimation tests, including the test setup and test procedure, are presented and discussed.

I. INTRODUCTION

A passively cooled graphite target was proposed for a 1.5-MW neutrino production research facility [1]. The conceptual design for the target study was a graphite rod (15 mm in diameter by 800 mm long) to be supported by graphite spokes, which are mounted on a water-cooled stainless steel support tube. The hot target is cooled mainly by heat radiation to the water-cooled surface of the support tube. The unique feature of this passively cooled target is its simplicity and favorable performance [2].

For 1.5-MW facility, the time-averaged power deposition in the target is 35 kW, and the volumetric power deposition is about 250 MW/m^3 uniformly along the axial length of the target. The target surface temperature required to radiate the deposited power is estimated to be 2123 K, resulting in a sublimation erosion rate of only $2.2 \text{ }\mu\text{m/d}$. However, if the axial power deposition were peaked a factor of 2, then the surface temperature would be 2533 K, surface erosion rate would be 2.8 mm/d , which is clearly unacceptable. To extend the power handling performance of the radiatively cooled graphite target, 1-bar helium cover gas was proposed as a means to greatly reduce the net erosion rate. To verify erosion rate in vacuum conditions and validate the cover gas concept, graphite sublimation tests have been conducted. The initial sublimation test of graphite foils [1] revealed that the

sublimation erosion rate under vacuum is consistent with the theoretical prediction.

Further test efforts have been done for graphite-rod specimens (15 mm in diameter and 300 mm long). For gathering sublimation erosion data under vacuum or with cover gases of helium and argon, a test apparatus was designed, fabricated, commissioned, and operated. The sublimation mass loss rate at 2350 K is 1.7 mg/h for static argon cover gas (>1 atm) and 0.78 mg/h for static helium cover gas. These values of sublimation mass loss rate for cover gas cases are lower than that of 5.8 mg/h in high vacuum. In addition, the test procedure and the sublimation data of the graphite rods are reported and discussed.

II. TEST SET-UP

The graphite rod sublimation erosion tests need an oven capable of heating the graphite rod to temperatures of ~ 2400 K under vacuum or in 1-bar of helium gas. The wall of the oven should be sufficiently cool so that the carbon vapor evaporated from the graphite rod could be condensed on it. Such an oven needs to be installed in a vacuum test chamber. Using the graphite rod as an electrical heater, the temperature of the graphite rod is controlled by the electrical heating current. The weight loss of the graphite rod is used to estimate the evaporation (or sublimation erosion) rate. To conduct such tests, we modified an existing test stand in the Fusion Energy Division at Oak Ridge National Laboratory.

The test stand has been modified and prepared as shown in Fig. 1. It consists of a vacuum test chamber with water-cooled copper feedthroughs on the side ports, an oven with a graphite rod electrical heater, a vacuum and gas feed system, and a temperature measurement system. The control consoles, associated power supplies, and electronic instrument and data acquisition system are not shown in the figure.

Working as an electrical heater, the graphite rod (300 mm long and 15 mm in diameter) is mounted and fastened to graphite terminals, which are fastened to the water-cooled copper rod vacuum feedthroughs of the test chamber. Enclosing the graphite rod and associated terminals, the water-cooled panel-coil heat shields (made of stainless steel cylindrical shells, ~ 160 mm in diameter) are installed to absorb the radiation heat from the hot graphite rod. In addition, graphite and tantalum plates are installed for reducing radiation heat loss at the open ends of the panel-coil heat shields. Such an oven has a cooled wall to condense carbon vapor and keep the test chamber near room temperature. Consequently, the

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graphite rod sublimation tests could be conducted at elevated temperatures variable up to 2400 K for 15 h or longer.

The vacuum and gas feed system provides a controllable environment for the graphite sublimation tests. The mechanical roughing pump and the turbo-molecular pump can evacuate the test chamber to a base pressure below 10^{-6} torr. Together with the vacuum system, the gas feed system can be used to feed pure helium gas (or argon) into the test chamber at pressures controllable from vacuum to 1 bar.

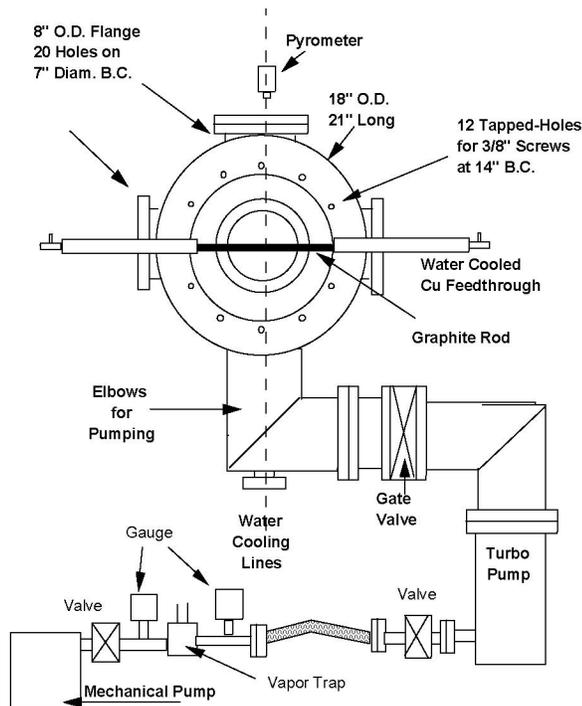


Figure 1. Test apparatus for graphite rod sublimation erosion tests.

The temperature measurement system consists of a two-color pyrometer and a quartz window. Viewing through the quartz window, the radiation signals of two adjacent wavelengths from the hot graphite rod are used to measure its surface temperature. This two-color pyrometer (IRCON Modline R) can measure temperatures from 1373 K to 2773 K.

During the tests, the output terminals of a dc power supply (rated at 30 V and 3000 A) are connected to the water-cooled copper feedthroughs. The voltage measured between the output terminals is the heating voltage V_h . The current flowing through the graphite rod is the heat current I_h .

The graphite rod is routinely heated up to elevated temperatures of 2400 K by ~ 1200 A of I_h . The majority of heat loss of the hot graphite rod is radiated to the surrounding water-cooled panel-coil heat shields. The radiation loss to the open ends of the heat shields was minimized by the graphite or tantalum plates. The tests can be conducted at steady state, for example, continuously over 15 h or longer.

An electronic balance with five significant digits is used to measure the mass of graphite rod. The mass of the graphite rod is measured before each test. Following the sublimation erosion

test, the mass of the graphite rod is measured again. The mass loss and test duration are recorded and used for estimating the average sublimation erosion rate of the graphite rod.

During the tests, we measure graphite rod temperature (T_{gr}), wall temperature of the test chamber, graphite terminal of the copper feedthroughs and the heat shields at each heating power level by using thermocouple, the heating voltage (V_h) and the heating current (I_h). We also recorded the pressure in the test chamber for the tests under vacuum. The values of V_h , I_h , T_{gr} , mass loss, and other temperatures measured are recorded. The data so collected are used for conducting posttest analysis.

III. TEST PROCEDURE

The graphite rod sublimation erosion tests were conducted with the following steps. First, a new graphite rod is heated under vacuum with a small increment of heating current. The impurity gas particles (such as air, water, or others) in the graphite rod are gradually baked out and pumped away. At each heating level, the heating voltage (V_h) and heating current (I_h) at the output terminals of the power supply is measured. The characteristics of electrical resistance of the graphite rod could be obtained and used to evaluate the quality of the test set-up. This baking step is done when the graphite rod is heated up to ~ 2300 K.

After being cooled down to room temperature, the test chamber is filled with pure helium to 1 atm. The graphite rod is removed for the mass measurement. Subsequently, the graphite rod is installed on the graphite terminals and inside the high-temperature oven. After the test chamber is evacuated to high vacuum, the graphite rod is gradually heated up by applying the heating current with small increments. The data of heating voltage, heating current, and graphite rod temperature are recorded. The graphite rod is baked at 2000 K under vacuum for at least 3 h. The sublimation erosion test of the graphite rod could be initiated.

The sublimation erosion test under vacuum is usually conducted at the desired temperature of 2350 K. This temperature of the graphite rod is kept constant during the test run for 5 to 8 h. After the test, the power supply is turned off, and the components inside the test chamber are gradually cooled down. The graphite rod is then removed for mass measurement. The mass loss so measured divided by the test duration is used to determine the average sublimation erosion rate.

For the helium cover gas, the test chamber is kept under vacuum for several hours after turning off heating power. After the components in the test chamber are cool, the vacuum system could be shut off, and the test chamber is filled with the cover gas. The graphite rod is then gradually heated up with small increments of heating current. Eventually, the graphite rod is tested at the desired temperature of 2350 K. This test with the helium cover gas was done for two cases: flowing gas and static gas. The test period was either 5 h or 20 h. After the test is done, the graphite rod is removed for mass measurement. The ratio of the mass loss to the test period is used to determine the average sublimation erosion rate.

IV. TEST RESULTS

The mass loss measurement data at 2350 K are listed in Table I. In addition to test duration and test environment, the steady state values of relevant heating parameters such as V_h , I_h , and R_h are also listed in the table. The data revealed the following features. The mass loss rate (ratio of mass loss over the test duration) is lower with helium cover gas. The loss rate for static cover gas is lower than that for the flowing cover gas. In addition, the value of the mass loss rate is reduced as the test duration is increased. This could be caused by impurities in the helium gas.

The heating power for the helium cover gas cases is slightly higher than that under vacuum. But the electrical resistance of the graphite rod is similar for both cases. Similarly, the mass loss rate with argon covered gas is measured to be 1.7 mg/h for test duration of 5.5 h.

II. DISCUSSION

Similar to that for the graphite foil as reported in [1], the measured mass loss rate for the graphite rod at 2350 K under vacuum is consistent with theoretical prediction [3], as shown in Fig. 1. The results validate the experimental procedure and apparatus for the graphite rod sublimation erosion tests under vacuum and with 1-bar helium environment. In the test set up, each end of the graphite rod had 38 mm mounted to the graphite terminal and ~ 40 mm yielding insignificant sublimation. The effective length of the graphite rod was ~ 150 mm. The effective area of the graphite rod contributed to the sublimation was ~ 75 cm². For a mass loss rate of 5.82 mg/h under vacuum conditions, the sublimation erosion rate is ~ 0.77 g/h/m².

The lower mass loss rate with the static helium cover gas confirms the recondensation of evaporated carbon materials. The data of the two static helium cases implied that the mass loss rate during the last 15 h of the 20-h test duration could be ~ 0.19 mg/h. Thus, the sublimation erosion rate with the static helium cover gas could be 30 times less than that under vacuum. Such test results conclude that the static helium cover gas significantly reduces the sublimation erosion rate and increases the target lifetime.

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TABLE I. MEASURED MASS LOSSES FOR SUBLIMATION EROSION TESTS

| Mass Loss Rate (mg/h) | Test Duration (h) | V_h (V) | I_h (A) | R_h (m Ω) | Cover gas (Vacuum or Helium) |
|-----------------------|-------------------|-----------|-----------|---------------------|------------------------------|
| 5.82 | 5 | 18.6 | 1214 | 15.32 | Vacuum |
| 3.4 | 5 | 18.9 | 1230 | 15.37 | Flowing helium |
| 2.56 | 5 | 18.9 | 1230 | 15.37 | Static helium |
| 0.78 | 20 | 18.9 | 1230 | 15.37 | Static helium |

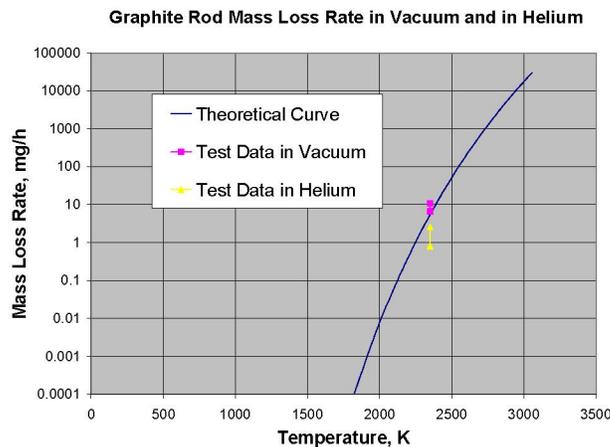


Figure 2. Comparison of measured mass loss rate of graphite rod to theoretical prediction.