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Iodine Beam Dump Design and Fabrication

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March 2017

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LIST OF ACRONYMS

HET	Hall effect thruster
IBD	iodine beam dump
TC	thermocouple
TM	Technical Memorandum

TECHNICAL MEMORANDUM

IODINE BEAM DUMP DESIGN AND FABRICATION

1. INTRODUCTION

During the testing of electric thrusters, high-energy ions impacting the walls of a vacuum chamber can cause corrosion and/or sputtering of the wall materials, which can damage the chamber walls. The sputtering can also introduce the constituent materials of the chamber walls into an experiment, with those materials potentially migrating back to the test article and coating it with contaminants over time. The typical method employed in this situation is to install a beam dump fabricated from materials that have a lower sputter yield, thus reducing the amount of foreign material that could migrate towards the test article or deposit on anything else present in the vacuum facility.

The iodine beam dump (IBD) described in this Technical Memorandum (TM) was fabricated to support the testing of low-power iodine Hall effect thrusters[1] (HET) as part of the iodine satellite project.[2] Iodine is being explored as an alternative to xenon, which is presently the propellant of choice for state-of-the-art HETs. Iodine stores as a dense solid at very low pressures, making it acceptable as a propellant on a secondary launch payload where high-pressure xenon gas would be problematic. Iodine has exceptionally high density-specific impulse, making it an enabling technology for near-term, small satellite applications and providing the potential for systems-level advantages over mid-term, high-power electric propulsion options. Iodine flow can also be thermally regulated, subliming at a relatively low temperature ($<$100 ºC) to yield iodine vapor at or below 50 torr (see fig. 1). At low power, the measured performance of an iodine-fed HET is very similar to that of a state-of-the-art xenon-fed thruster. Just as important, the current-voltage discharge characteristics of low power iodine- and xenon-fed thrusters are similar, potentially reducing development and qualification costs by making it possible to use an already-qualified xenon-HET power processing unit to deliver electrical power to an iodine-fed system.

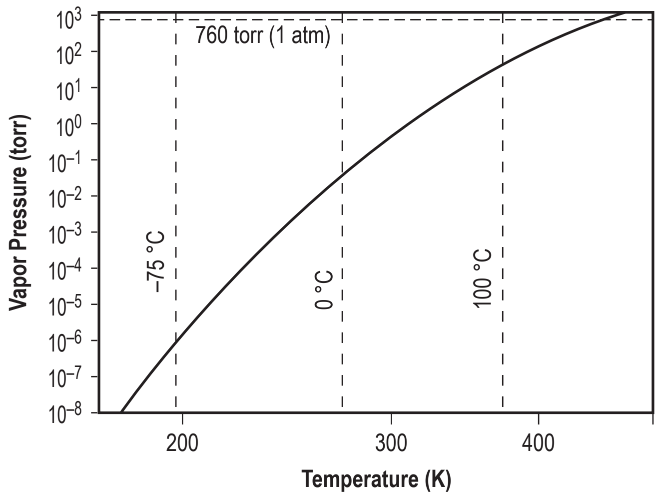

Figure 1. Vapor pressure curve for molecular iodine.[3,4]

In addition to using low sputter yield materials, the beam dump is designed specifically to condense gaseous iodine to a solid state, effectively 'pumping' the gas by sequestering it during a test to maintain vacuum conditions. This is similar to the manner in which standard cryopumps are used to capture gases to maintain vacuum conditions. The vapor pressure curve[3,4] shown in figure 1 shows that gaseous iodine is amenable to in-vacuum capture and sequestration at temperatures that are well above those of typical cryopumps that are cooled by gaseous helium (cooled to ~10–15 K to capture gaseous xenon) or liquid nitrogen. For example, when using gaseous iodine, the vapor pressure at a modest –75 °C (~200 K) is below 10^{-6} torr and the vapor pressure at –100 °C (~177 K) is below 10^{-8} torr. These temperature levels are readily achievable in recirculating refrigeration systems that, while being specialized, are still low cost relative to comparable recirculating cryogenic fluid refrigeration systems like those that employ liquid nitrogen or gaseous helium.

While the IBD has been specifically designed to accomplish iodine-fed HET testing, the low sputter yield surfaces of the beam dump will allow the IBD to protect the chamber during the testing of any type of electric thruster. Furthermore, the cooled IBD could also be used to capture and 'pump' other condensable propellants that might be tested in this facility.

The outline for the remainder of this TM follows. First, the requirements that were used for the IBD were reproduced and the subsequent design these requirements engendered are presented. The process for fabrication, assembly, and installation of the IBD is described next, with special attention given to the solutions that were developed for the unique issues that arose during the manufacturing process. Finally, temperature history profiles during IBD operation are presented as validation of the cooling and iodine sequestering capabilities of the IBD.

2. IODINE BEAM DUMP HARDWARE REQUIREMENTS AND DESIGN

The IBD consists of multiple flat aluminum surfaces that are covered on the plasma thruster facing side with a thin graphite sheet. The aluminum surfaces are chilled to a temperature where iodine will deposit as a solid on the panel while the graphite sheets protect the aluminum from sputtering damage. The surfaces are assembled to minimize the direct reflection of discharged iodine back towards the source being tested. To achieve this, the IBD was designed with a chevron-like shape (fig. 2) where no part of the surface lies perpendicular to the direct line of thrust.

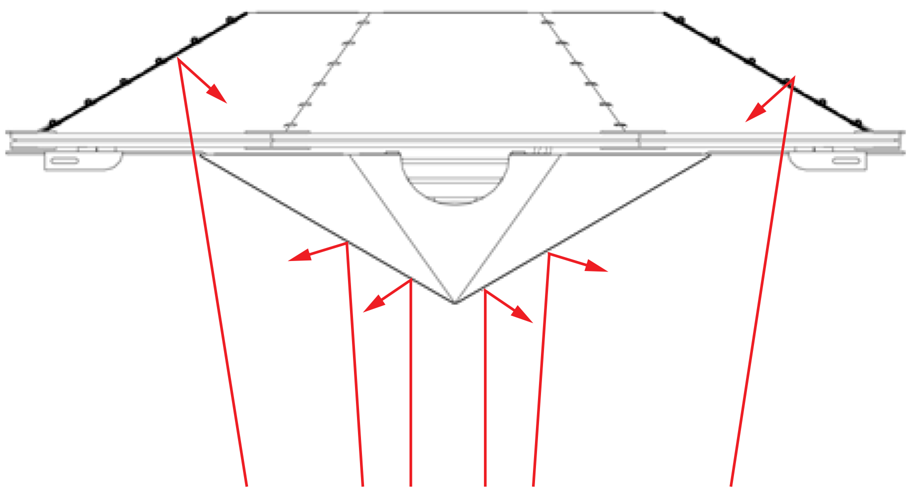

Figure 2. Side view of the IBD surfaces with the notional trajectories of incoming particles shown.

2.1 Materials

The cold surfaces are analogous to the evaporator of a common refrigeration cycle, absorbing energy while condensing iodine, with a pumped recirculating fluid transporting the heat outside the vacuum chamber. The use of aluminum versus copper reflects the desire to minimize the material reactivity with iodine while still maximizing thermal conductivity. The graphite sheeting facilitates sorption pumping or the adsorption of molecules on a very porous cooled material. GRAFOIL® is a patented, flexible material that is essentially pure graphite carried on a thin film of thermoplastic polymer, manufactured by GrafTech International Holdings, Lakewood, OH. An analogy is a thin layer of graphite on scotch tape. The composite material provides compliance and allows the extremely thin layers of graphite to hold their shape even as they are cut using conventional methods. The material can also be attached to a variety of surfaces using conventional, mechanical means. Graphite is commonly used as a filtration media because of its adsorbative properties. It fulfills a similar purpose on the iodine beam dump by trapping iodine. Furthermore, the sputtering yield (defined as the number of surface atoms removed for each incident ion) of graphite is typically much lower than that of metallic surfaces,[5] making the former well suited to protect the aluminum panels.

2.2 Sizing and Orientation

With the general shape of the beam dump defined, overall sizing of the cooling circuit results from matching the nominal cooling circuit length for the associated refrigeration system and fitting the final assembly into the vacuum chamber it protects. The shield was designed to accommodate two independent but equal-length cooling circuits that each have ~28 m (92.1 ft) of 1.27-cm (0.5-in) outside diameter tubing mechanically attached to the flat aluminum surfaces. As of this TM, only one of the two circuits is active with the chilled fluid provided by a single-output, MaxCool XC-8800MT recirculating cryochiller.

The IBD is installed in one end of a horizontally-oriented 2.75-m- (9-ft-) diameter vacuum chamber located in Building 4205 at NASA Marshall Space Flight Center. The beam dump is installed to protect one of the endcaps of this cylindrical chamber (fig. 3). The thruster under test is typically installed at the opposite end of the chamber in a horizontal orientation with the thruster exhaust directed towards the end where the beam dump is installed. This position places the direction of thrust perpendicular to the weight of the thruster, minimizing any coupling between those two forces during testing. It also allows for plasma measurements and imaging of the thruster in both the axial and transverse directions. Finally, the thruster plume can expand and move away from the thruster more freely along the axis of the vacuum chamber, reducing any reflection of plasma back towards the thruster and permitting more accurate thruster plume measurements.

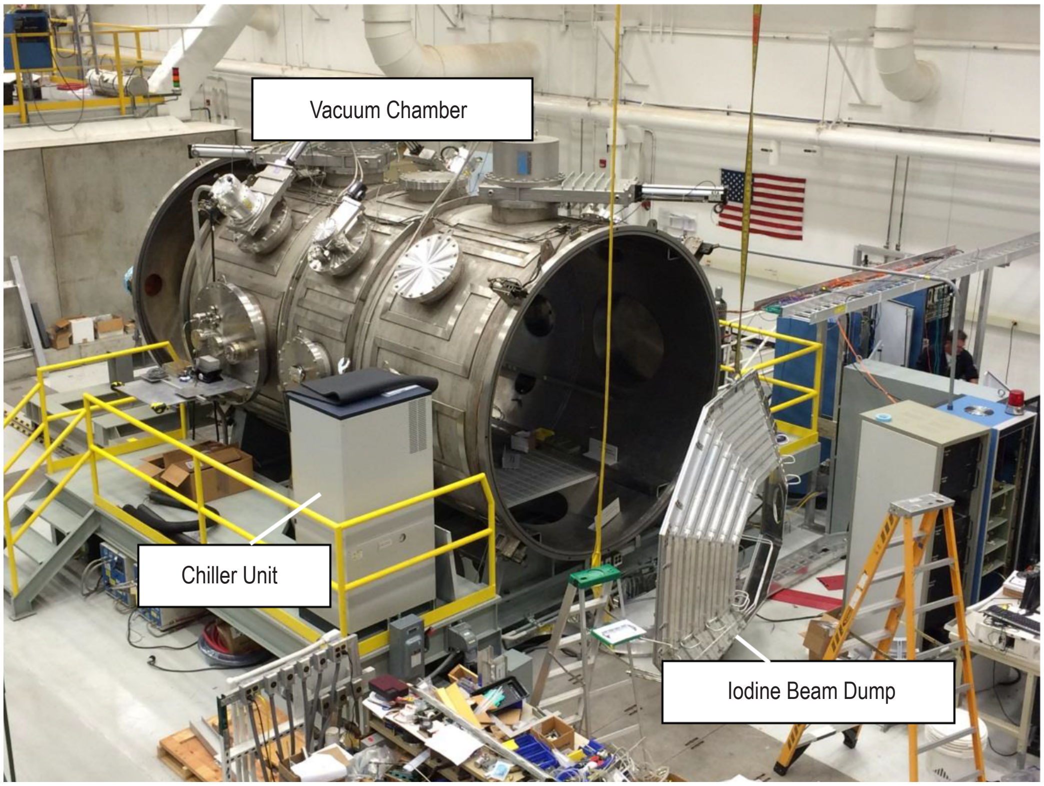

Figure 3. Photograph of the 2.75-m- (9-ft-) diameter vacuum chamber as the beam dump was being installed.

2.3 Design of Iodine Beam Dump Shields

The beam dump is designed with a center shield section and an outer shield section. The center shield section is angled such that any incoming particles that are not captured will reflect outward away from the chamber centerline. The outer shield section is angled to reflect particles inward such that they will cross the centerline of the chamber well before they make their way back to the thruster under test. Since the center of a plasma thruster beam is expected to contain a majority of the energy, the center section of the beam dump will be subjected to the greatest energy fluxes. A circular cutout in the design provides visual access via a vacuum chamber optical flange (fig. 4). The inner shield slightly overlaps with the outer shield when the beam dump is viewed in the axial direction, providing a complete line-of-sight protection of the vacuum chamber end-cap. The octagonal shape was chosen as the most simple to assemble using flat panel sections while still providing almost total protection of the vacuum chamber surfaces behind the beam dump.

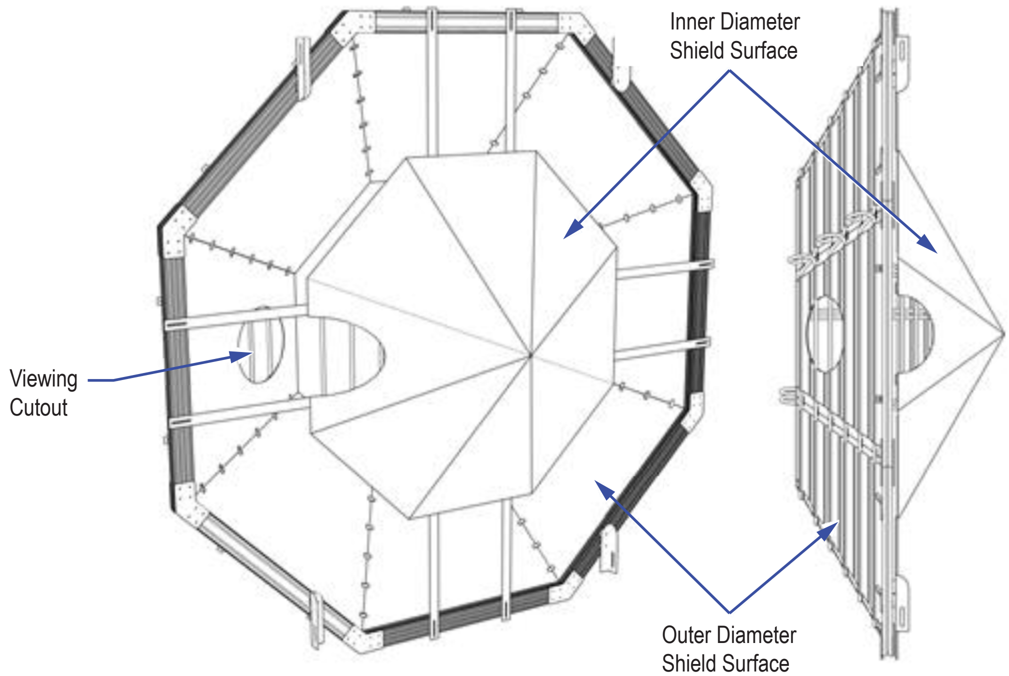

Figure 4. IBD assembly drawings showing inner and outer 'shield' sections.

2.3.1 Tubing and Extrusions

The beam dump is designed to be cooled by two separate Maxcool recirculating cryochillers. The refrigeration tubing is laid out in two independent flow paths, with the length of each path on the beam dump measuring approximately 26.5 m (87 ft) long and connected to its own cryochiller. As seen in figure 5, the refrigeration tubing is configured in an interwoven pattern with each circuit providing cooling to both the inner and outer shields, making it possible for the entire beam dump to be cooled by only one cryochiller.

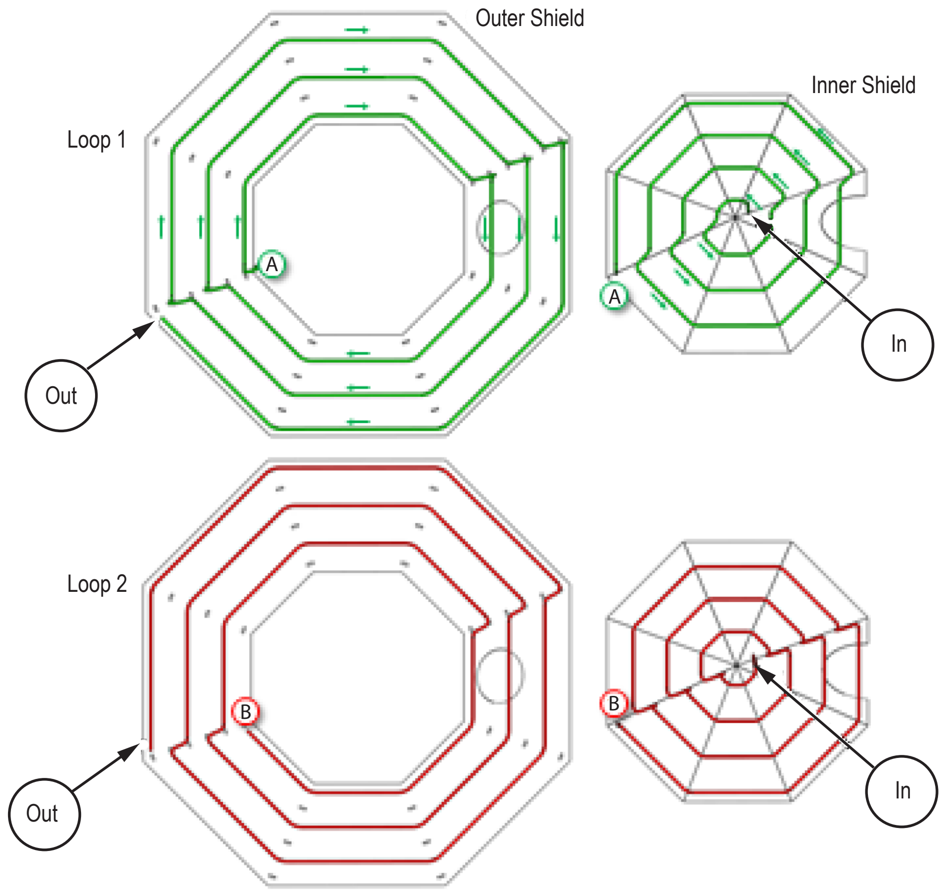

Figure 5. Mapping of the dual independent flow loops, each approximately 26.5 m (87 ft) long.

The tubing must maintain good thermal contact with the cryosurfaces at all times to keep the beam dump chilled during thruster operation. Welding of the tubing to the flat surfaces was considered but rejected. Aluminum is very effective at wicking heat away from the weld zone and the potential existed to burn through the tubing during the welding process. An alternative mechanical fastening technique was used instead in the IBD. Off-the-shelf aluminum extrusions that are designed to snap into place over tubing and distribute the cooling over a larger surface area were used to couple the tubing to the cryosurface. In this way, only seam welds between adjacent facets of each shield section and butt welds in the tubing itself were required.

Standard 80/20 aluminum extrusions were used to construct the primary support structure for the shield sections. This allows for flexibility in design and configuration and also permits multiple mounting options for instrumentation or other in-chamber instruments as testing requires. Raw materials were cut to fit using a water jet, allowing for highly predictable assembly.

Initially, it was speculated that computer numerical control tube bending could deliver the complex bends required for the assembly. However, it was determined that the required compound bends could not be performed by machine, so they were instead accomplished by hand. This task represented the most labor-intensive element of the fabrication process; the detailed craftsmanship required of the technicians to produce a high-quality final product cannot be overstated.

Aluminum tubing sections were butt-welded to form the cooling circuits. The butt welds were minimized by using whole 6.1-m (20-ft) sections of tubing, which were typically long enough to produce multiple passes on a shield section. The design of tubing paths and bends were such that two identical parallel flow loops were fabricated and laid onto the shield.

3. IODINE BEAM DUMP FABRICATION, ASSEMBLY, AND INSTALLATION

3.1 Fabrication and Assembly

Aluminum sheet metal measuring 0.318 cm (0.125 in) thick was used for both the inner and outer shields. Sheets were cut to yield 16 individual pieces (8 pieces each for inner and outer shield sections) using a water jet. The sheet metal pieces were then seam-welded to form the inner and outer shields (fig. 6).

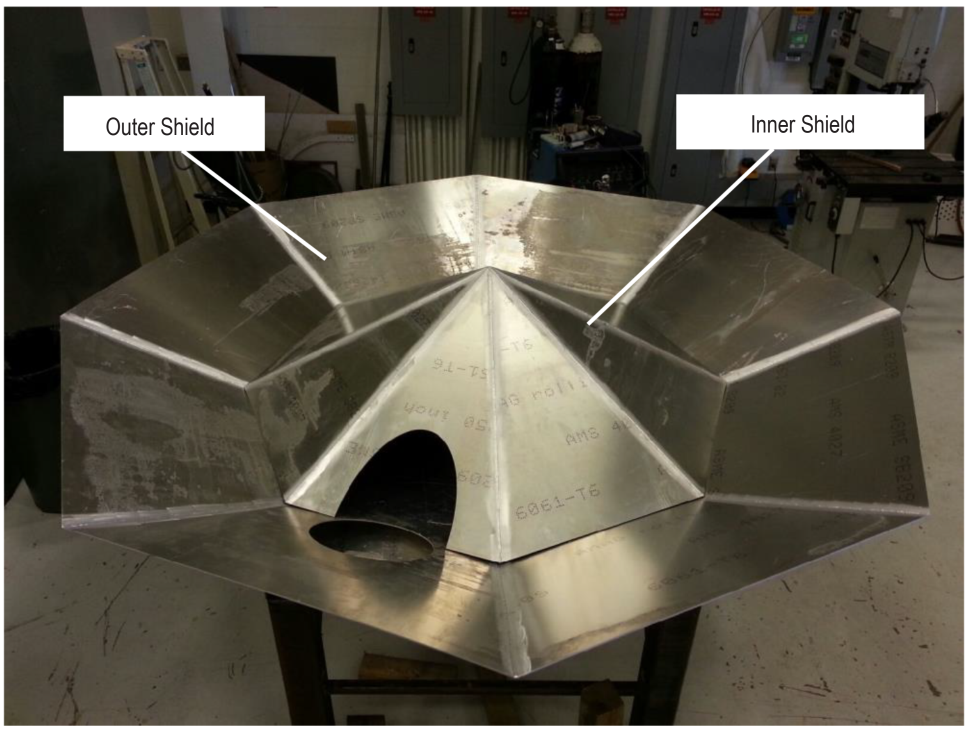

Figure 6. Inner and outer aluminum shield sections after being welded.

3.1.1 Extrusions

Snap-on aluminum extrusions measuring 1.2 m (48 in) long were used to couple the refrigerant-filled aluminum tubing to the shield surfaces. The ends of the extrusions were cut using the water jet such that they possessed the correct angles and lengths to match the width of the sheet metal shield sections (fig. 7). The extrusions were match-drilled and riveted in place on the aluminum sheet metal shield sections (fig. 8) using a predefined spacing schedule. Minor modifications were made to individual extrusion sections as needed to compensate for imperfections and nonregular tubing bends and welds.

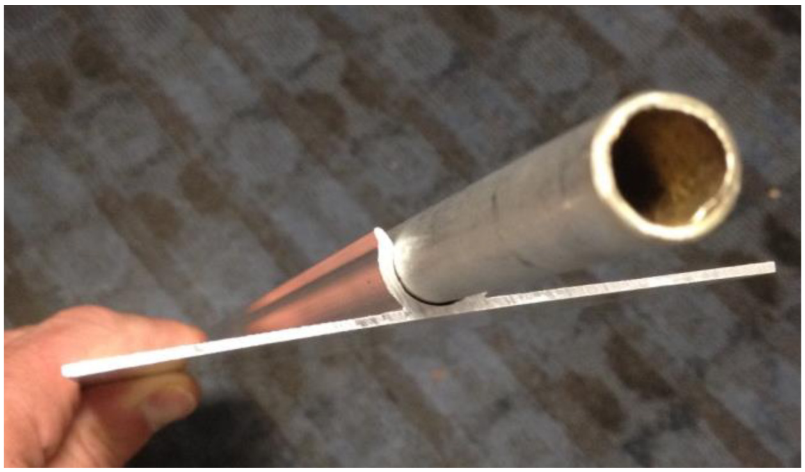

Figure 7. Snap-on aluminum extrusions with a tube snapped in place.

Figure 8. Tubing bent and installed in extruded channels.

3.1.2 Tubing

The aluminum tubing was terminated using stainless steel-to-aluminum, bi-metallic transition joints (figs. 9 and 10) to facilitate interfacing with an all-stainless steel vacuum chamber feedthrough. Each shield section flow loop was proof tested to 1,000 psig prior to integrating both shield sections together. The full beam dump was again proof tested as a unit to 1,000 psig prior to installation in the vacuum chamber.

Figure 9. Aluminum (left part) to stainless steel (right part) explosively welded transition joint.

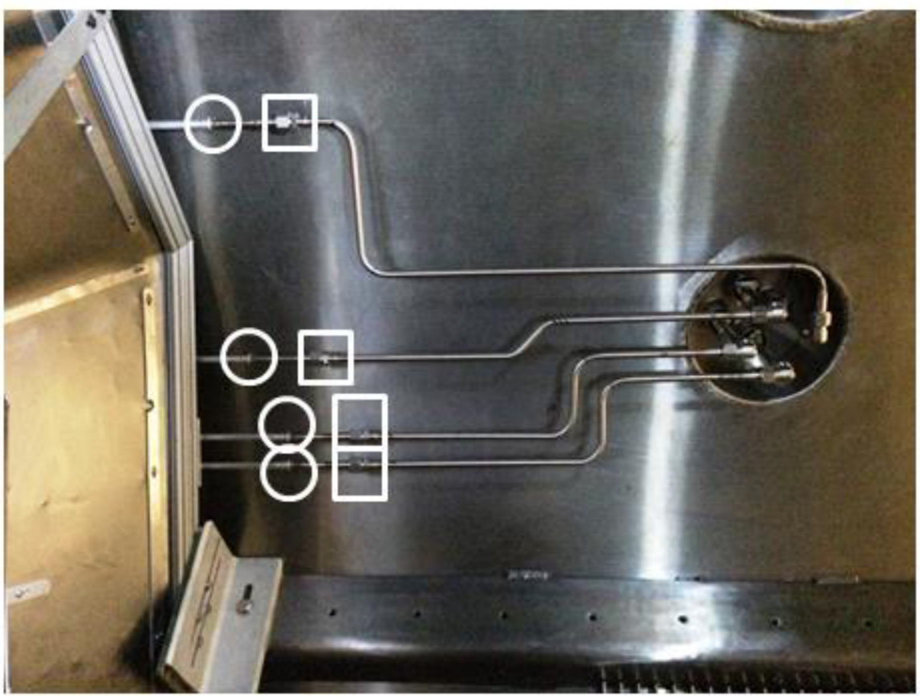

Figure 10. In-chamber tube terminations. Aluminum/stainless steel transition joints circled, face-sealing metal-to-metal stainless steel mechanical fittings in squares.

The off-the-shelf, snap-on aluminum extrusions were used to distribute the cooling over a larger surface area and facilitate a connection between the aluminum refrigeration tubing and the cryosurface (figs. 11 and 12). In this way, only seam welds between adjacent facets of each shield section and butt welds in the tubing itself were required.

Figure 11. View of tubing installed on center shield section of beam dump.

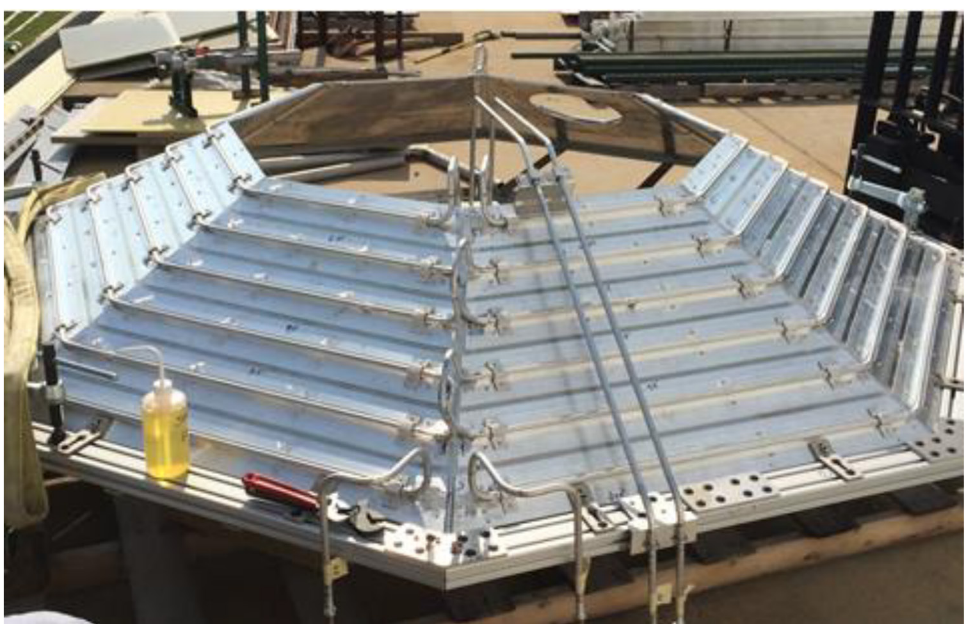

Figure 12. View of tubing installed on outer shield section of beam dump.

The stainless steel tubing sections comprise the final connections between the beam dump tubing and the vacuum chamber feed-through. These tubing sections employ mechanical, metal-to-metal, flat disk-style, face seal fittings (Swagelok VCR®, Solon, OH) to allow for disconnecting of the system in the event that modifications are required in the future (fig. 13). Outside the vacuum chamber, insulated copper tubing connects the feed-through flange and the refrigeration unit. These lengths utilize metal-to-metal, O-ring style fittings (Parker UltraSeal®, Cleveland, OH) to mate with the factory-installed terminations on the refrigeration unit. After assembly and installation, a helium leak check was performed on the entire tubing system.

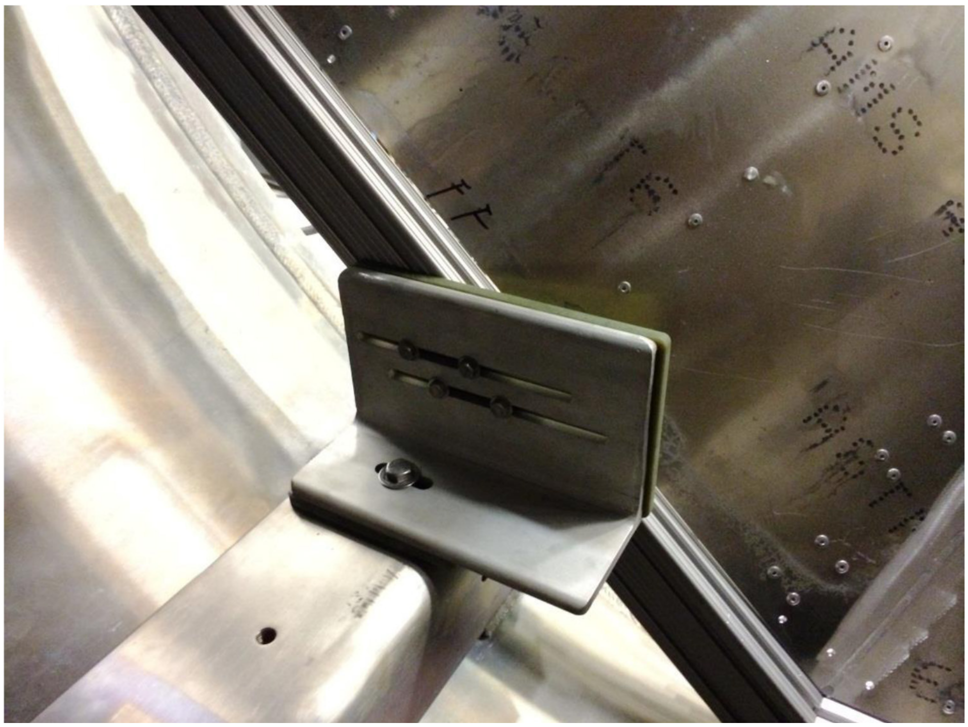

Figure 13. Chamber internal mounting bracket with fiberglass thermal insulation blocking.

3.2 Installation

The vacuum chamber is equipped with heavy stainless steel angles welded along its length in four quadrants: NE, SE, SW, and NW when looking at the chamber end-on. These angles have tapped holes along their length that were used to physically support the weight of the beam dump via intermediate angle brackets. The brackets were thermally insulated from the chamber structure using 1.27-cm- (0.5-in-) thick, G-10 fiberglass blocking. All stated interfaces were cut with adjustability in mind to compensate for any out-of-round or as-built fabrication deviations.

3.2.1 GRAFOIL Sheeting

GRAFOIL sheeting was cut using a water jet in shapes that mated to each octant of each shield with approximately 2 inches of overlap beyond weld seams. These sheets were then fastened to the shield sections using battens to distribute support (figs. 14 and 15). The sheeting was sandwiched between the bracket and the chamber-mounted angle and also between the bracket and the 80-20 beam dump structure. Both the GRAFOIL and the battens are considered to be consumable and are fastened from one side of the beam dump using tapped holes in the shield. This allows the GRAFOIL to be replaced using simple tools at regular intervals as needed.

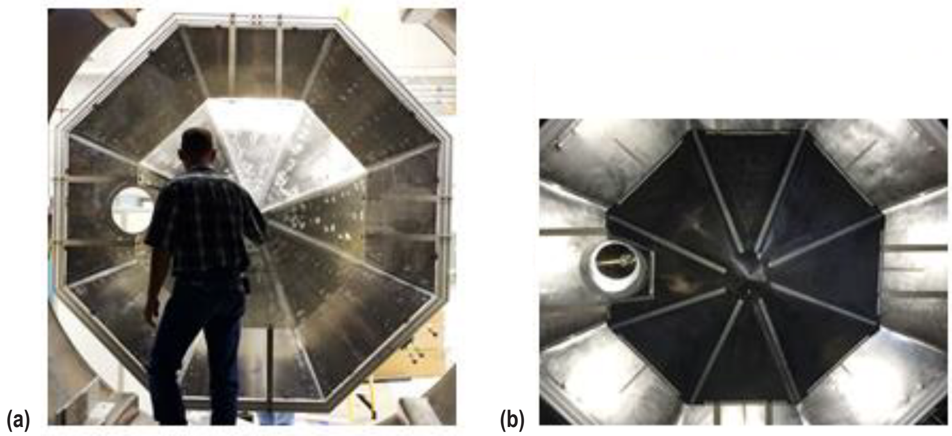

Figure 14. Beam dump shields: (a) Without GRAFOIL and with GRAFOIL installed on center section.

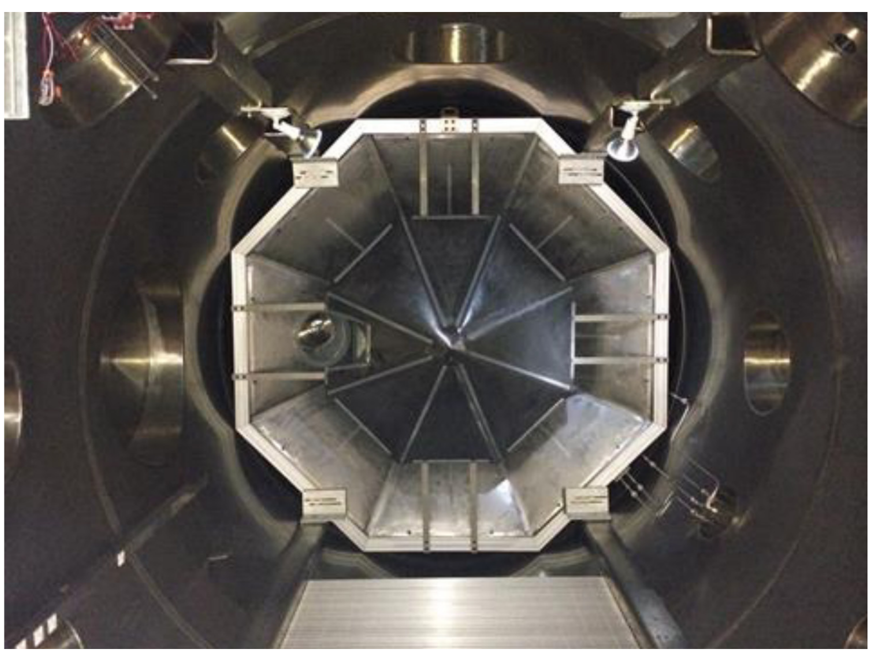

Figure 15. Beam dump in vacuum chamber with GRAFOIL completely installed.

3.2.2 Cooling Line Transitions and Vacuum Feed-Throughs

The chamber feed-through is specially designed to minimize heat transfer between the bulk vacuum chamber mass and the refrigerant. This is accomplished by emulating the construction of a vacuum-jacketed line. The thermal conduction pathway is a 2-inch-diameter tube welded to the refrigeration tube well away from the flange. This configuration has a very small cross-sectional area and a relatively long length that effectively acts as an insulator or stand-off between the refrigeration tubing and the chamber feed-through (fig. 16).

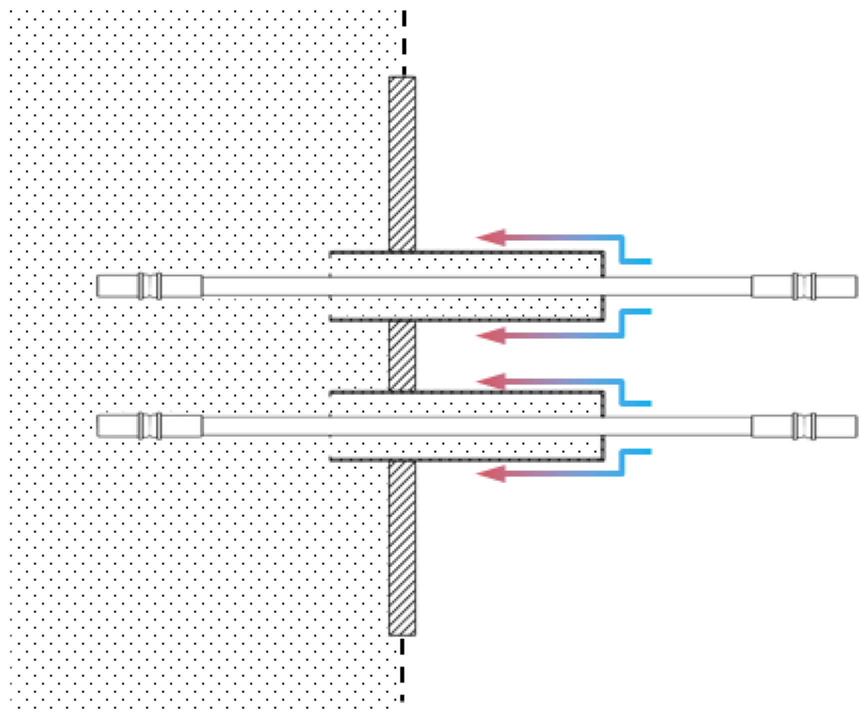

Figure 16. Flange cross section showing vacuum (dotted region at left). Arrows show the parasitic cooling of the vacuum chamber flange, with this cooling minimized by conduction-limited pathway.

4. CHECKOUT TESTING AND RESULTS

To demonstrate the operation of the system, a test run was performed with multiple thermocouples (TCs) attached to the locations shown in figure 17. The vacuum chamber was evacuated to ≤10^{-5} torr pressure levels before the beam dump cooling cycle was started ($t = 0$). The liquid exiting the refrigeration system is below –100 °C. The temperature on all four TCs (fig. 18) drops quickly when cooling is applied, with the inner two (TC1 and TC2) dropping fastest and to the lowest steady-state levels of approximately –100 °C. This result can be understood since the thermally-conductive pathways from the inner section to the vacuum chamber wall are limited. In contrast, the outer surfaces have a larger conductive pathway to the warmer chamber wall.

Figure 17. Beam dump image showing the location of four TCs used to measure the temperature at these locations as a function of time during one IBD cooldown cycle.

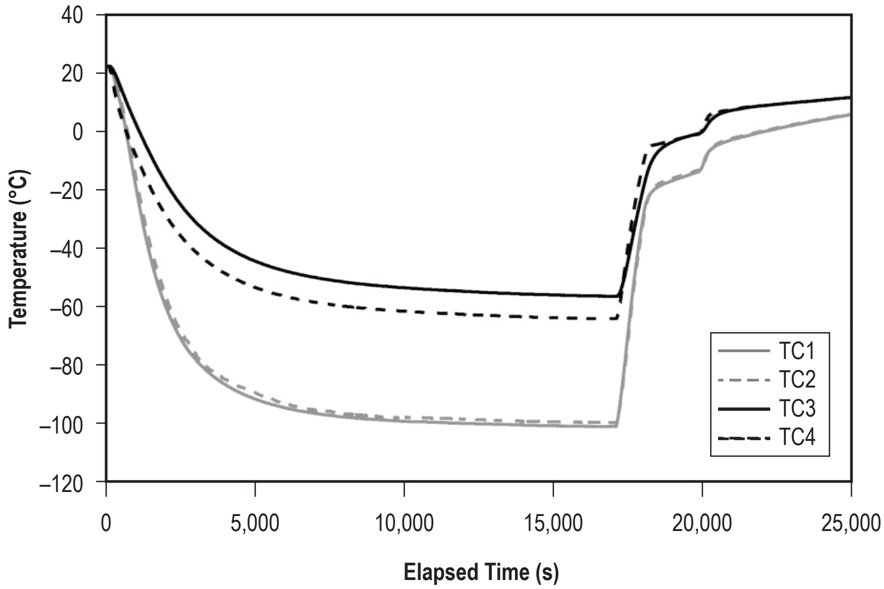

Figure 18. Thermocouple-measured temperatures on the IBD during one cooldown/warmup cycle. At ~17,000 s, the refrigeration unit was switched from refrigerant cooling to heating mode.

The radiative pathways from the inner sections to the chamber wall are also somewhat obscured by the outer sections, while the outer sections have a much wider view of the warmer chamber wall. It should be noted that because the TCs are separated from the cooling fluid by multiple sections of panel and GRAFOIL, the temperatures measured by the TCs are not the temperatures of the cooling fluid or even the tubing on the backside of the panels, which during cooldown will be even colder than the TCs. At roughly $t = 17{,}000$ s, the refrigeration unit was switched into 'warmup' mode, pumping heated fluid into the cooling circuit to quickly bring the IBD back to room temperature (a task that would take significantly longer relying strictly on parasitic heating of the beam dump by the ambient environment).

5. CONCLUSIONS

The iodine beam dump was successfully installed in the vacuum chamber in the summer of 2014 (fig. 19). In checkout testing, the refrigeration system demonstrated the capability to cool the beam dump to a temperature below –100 ºC. While the IBD has been specifically designed to accomplish iodine-fed HET testing, the use of low sputter yield GRAFOIL on the beam dump surfaces allows the IBD to protect the chamber from high-speed exhaust ions emitted during the testing of any type of electric thruster. Finally, within a given operational range, the cooled IBD can capture and 'pump' other condensable propellants that might be tested in this facility.

Figure 19. Iodine beam dump installed at chamber end showing backside, refrigerant tubing.

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14. ABSTRACT
The design and fabrication details for an iodine beam dump used to support the testing of iodine-fed Hall effect thrusters are described. The beam dump serves the dual purposes of pumping the gaseous iodine by condensing it on cooled surfaces in the same manner that a cryopump operates and protecting the vacuum chamber in which it is installed from plasma ion sputter damage. The surfaces of the beam dump are chilled by flowing recirculated liquid coolant through a circuit of tubes that are mechanically attached to the beam dump panels. The liquid exits the refrigeration system below –100 °C, quickly reducing the temperature of the panels inside the vacuum chamber by thermal conduction across the mechanical attachments. Two circuits were installed on the beam dump to accommodate a second refrigeration unit, which could be procured and installed at a later date for minimal additional cost, doubling the cooling capacity of the system from 4 to 8 kW. Low sputter yield GRAFOIL sheets are installed on the sides of the panels facing the plasma source. These GRAFOIL sheets, composed primarily of graphite, have a low sputter yield making them a particularly good candidate for protecting the beam dump aluminum panels. The iodine beam dump is presently installed and operates as designed, cryopumping iodine vapor and protecting chamber surfaces from plasma sputtering.

15. SUBJECT TERMS
beam dump, condensable propellants, cryopump, iodine propellants, plasma thrusters

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