National Aeronautics and Space Administration

Advanced Materials for Electric Propulsion

Principal Investigator: Bryan McEnerney (353); Co-Investigators: Richard Hofer (353), Celia Chari (California Institute of Technology), Katherine Faber (California Institute of Technology)

Program: FY21 R&TD Topics **Strategic Focus Area: Electric propulsion**

Objectives

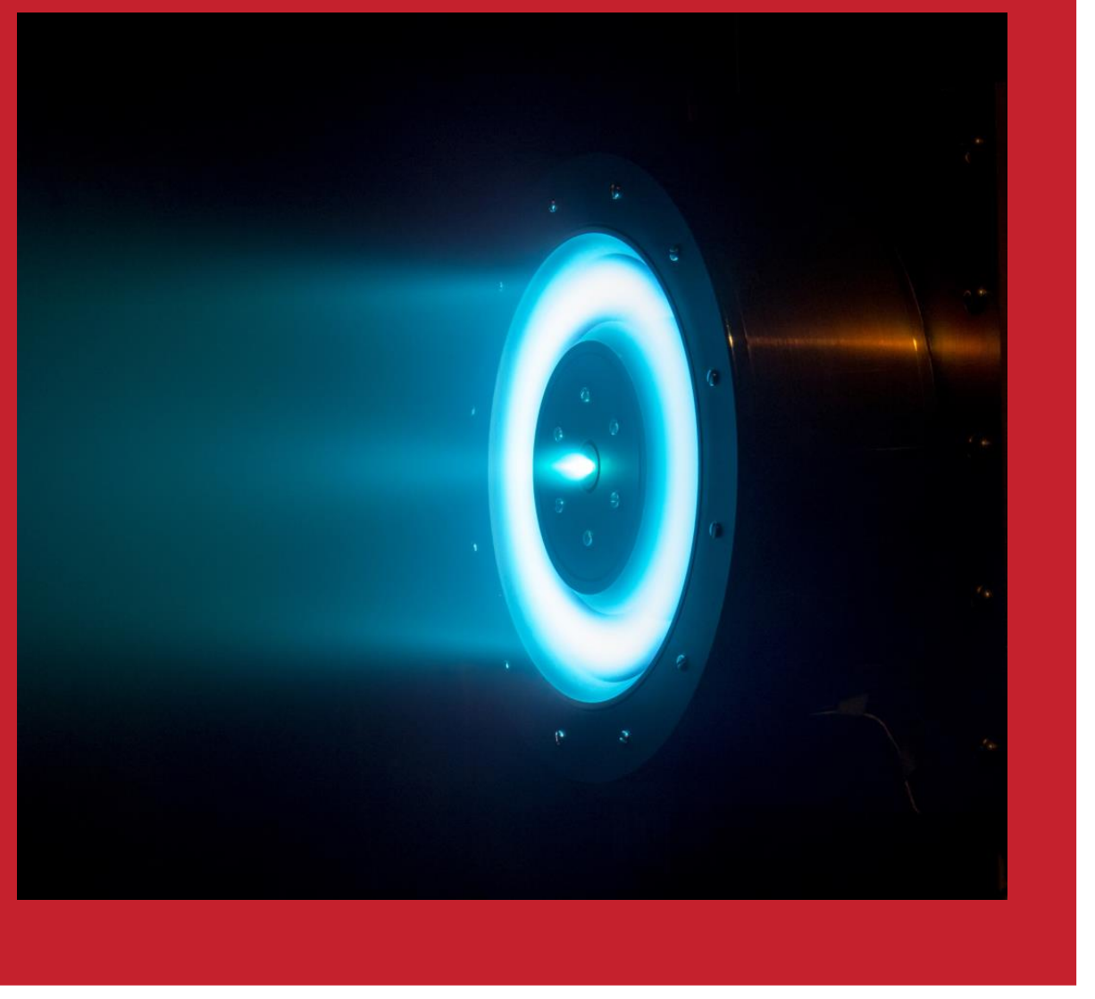
The state-of-the-art dielectric for electric propulsion (EP) systems is a boron nitride-based monolithic ceramic, which is expensive, challenging to machine and prone to significant variability in mechanical performance. The approach under development is revolutionary, as it allows for the use of low-cost materials (e.g., graphite), with dielectric layers grown and deployed where needed, and which additionally provides the scalability needed for future JPL missions.

The proposal objectives are:

a) to develop an advanced ceramic solution for EP dielectric systems, specifically boron nitride (BN) grown from graphite using a powder-based carbothermic reaction process refined at Caltech,

b) to demonstrate the viability of the dielectric layer on an aerospace-grade graphite,

c) to perform thruster testing using a BN-modified graphite channel to clearly demonstrate the performance benefits.



Background

Advanced electric propulsion systems, such as the Hall Thrusters that will be flown on JPL's Psyche mission, require high-performance dielectric systems to provide electrical isolation, thermal management, sputter resistance from plasma bombardment, and secondary electron emission for moderating plasma temperature. Various grades of boron nitride (BN) are typically used in Hall thrusters, but BN is expensive, difficult to fabricate at large sizes, and has poor thermal and mechanical properties. Worse still, BN procured from commercial sources for flight have recently demonstrated significant variability (right), increasing technical risk and cost.

An equally important consideration is that the incumbent material does not lend itself well to scaling to larger sizes needed for future systems operating at 20-50 kW will require new solutions.

Failed HP26 BN with visible macrocracking

Significance/Benefits to JPL and NASA

The FY21 results demonstrated the ability to produce thick BN layers (> 150 µm) on that portion of the graphite coupon exposed to the powder bed, with vapor phase transport (the proposed mechanism) providing BN thickness up to 75 µm. This enables direct powder-based carbothermal reaction along the critical annular wall, with complementary vapor-phase processing for other complex shapes, e.g., non-line of sight surfaces, for complete structural protection. While the 5 cm diameter tube furnaces used in current processing limited the size of BN/graphite bi-materials produced, the approach can be readily scaled for larger graphite coupon dimensions.

The resistivity testing indicated that a minimum thickness of 35 µm provided an acceptable dielectric response for Hall effect thrusters. The processing data demonstrated an ability to routinely exceed this thickness value, demonstrating the applicability for current Hall effect thruster systems. The combination of conversion layer thickness and resistivity will be validated during the FY22 testing campaign.

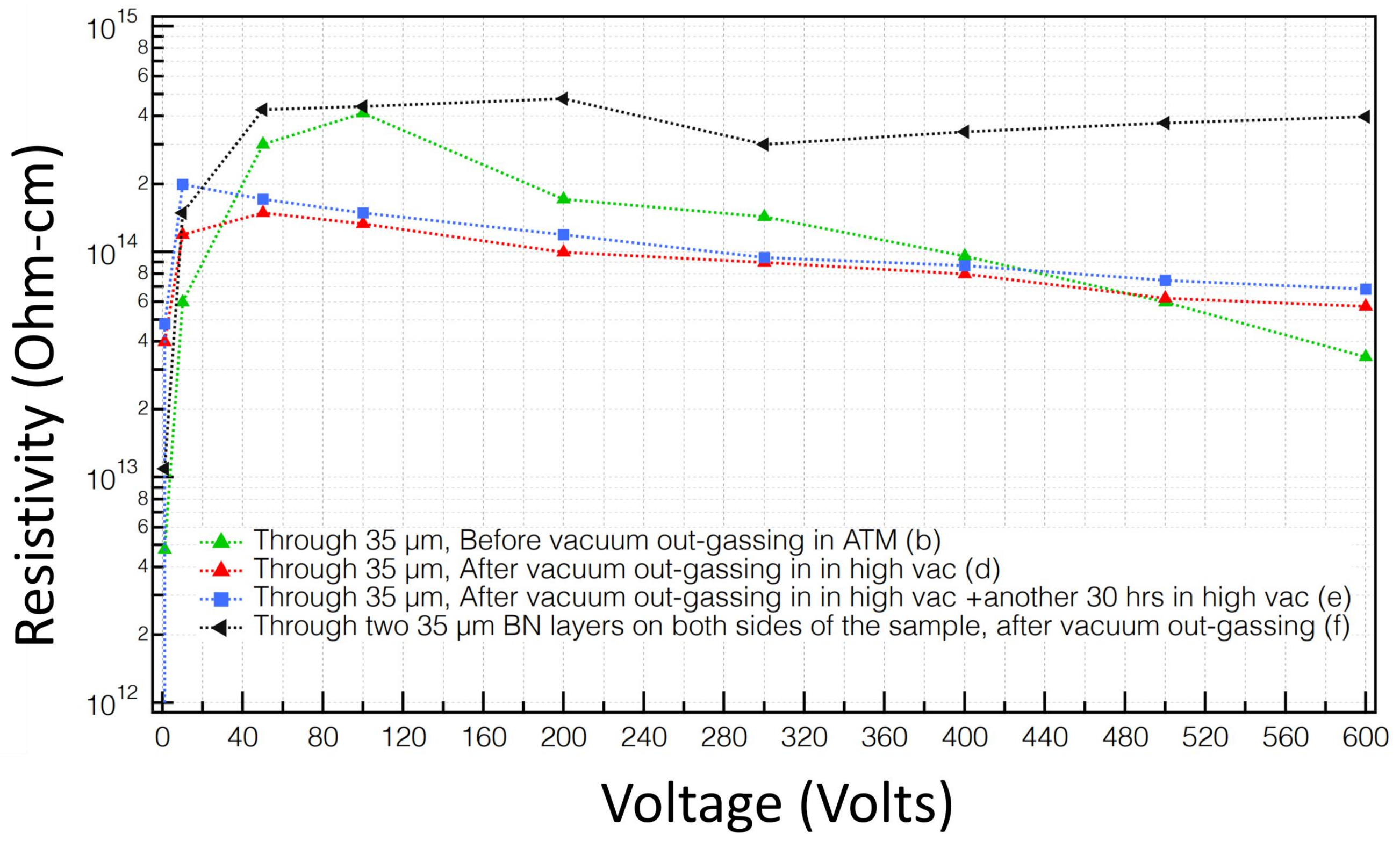
The FY22 testing of the BN/graphite on the H9 thruster is the first development of a materials system specifically designed for Hall effect electric propulsion systems. The technical approach is unique in focusing on a composite solution.

Approach and Results

The proposed approach focuses on the BN growth process development and associated physical, electrical and mechanical characterization leading to a system proof-of-concept candidate thruster assembly.

✻ Studies were undertaken at various times and temperatures, up to 1700 °C, to investigate the development of the BN-conversion layer during a single step. Conversion layers could form via the carbothermic reaction of B_2O_3 (both liquid and vapor phases) into BN. A significant concentration of B_2O_3 vapors present within the closed crucible made it possible to convert all exposed graphite surfaces into BN (below left).

✻ A time/temperature relationship for BN conversion layers (below center), both primary powder bed surfaces and vapor-converted surfaces (below right), was established, resulting in a deeper understanding of the reaction kinetics and processing capabilities.

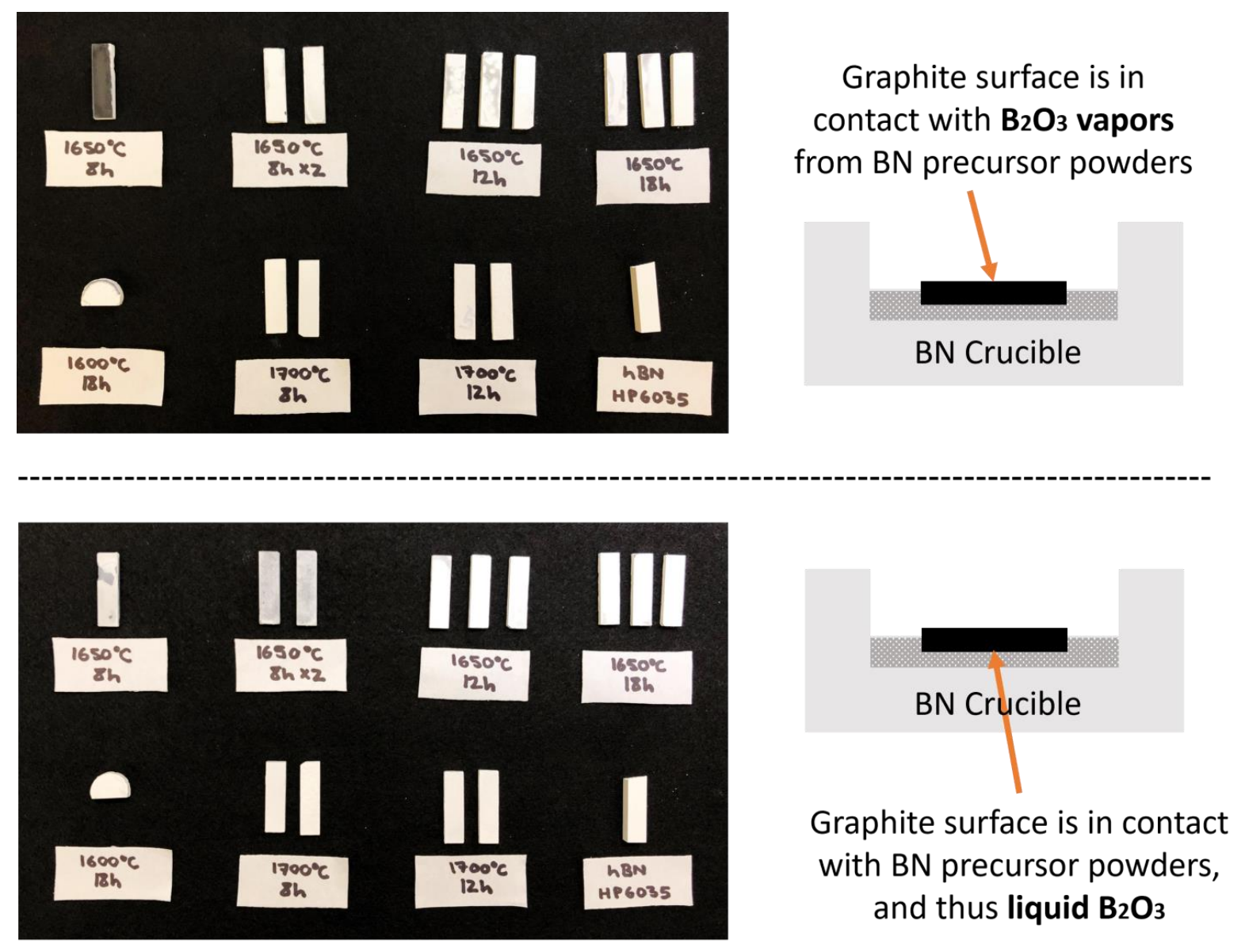


Resistivity measurements of C/BN bi-material with a 35-micrometer thick BN layer

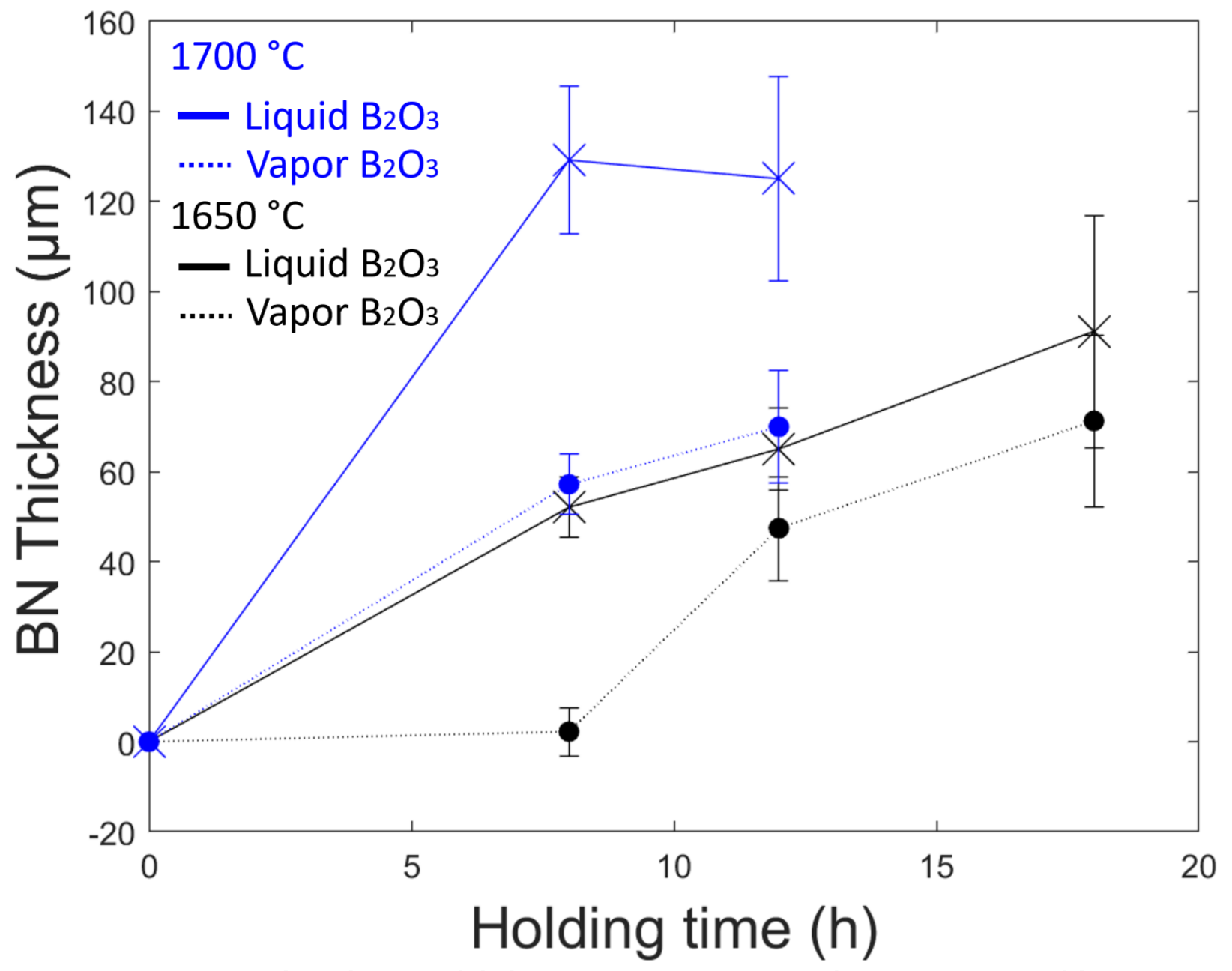
✻ Electrical resistivity of the BN was tested at JPL, indicating values of 1.03 x 10^{13} Ohm-cm up to 1.99 x 10^{14} Ohm-cm with a BN-conversion layer thickness of 35 µm. Further, the resistivities were measured under vacuum (2.75 x 10^{-5} Torr minimum) after a variety of out-gassing conditions (above)

✻ Coupons were thermally cycled to 250 °C at JPL to determine, via a laboratory bench test, if the BN conversion layers adhered to the graphite. Results confirmed adhesion, with only minor signs of wear around edges and corners of the BN layer

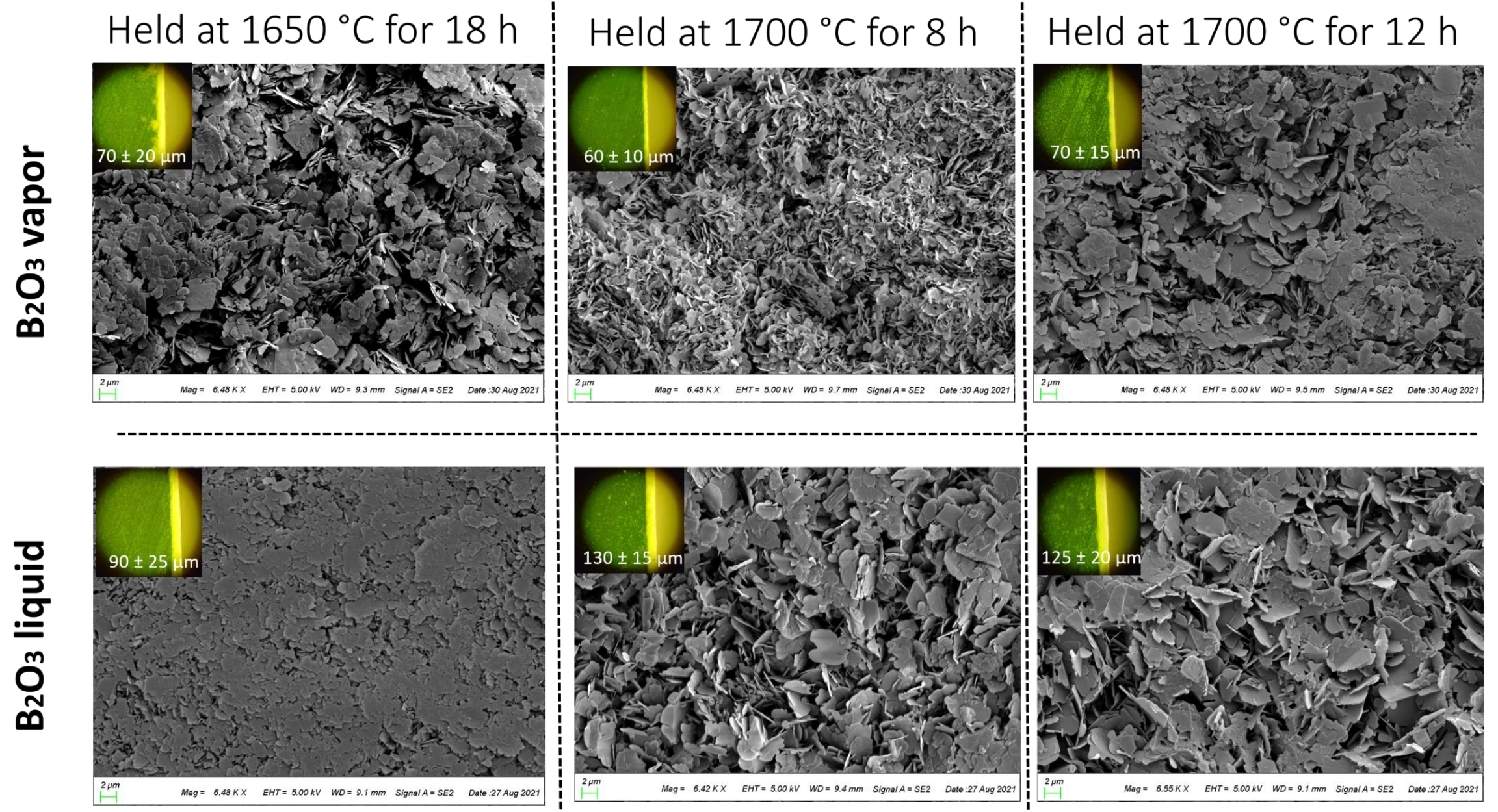
✻ A series of coupons were fabricated for inclusion in the proposed and funded FY22 H9 thruster testing campaign, to understand the effects of thermal cycling, high temperature (>300 °C) exposure during operation, and to identify if the conversion layers remained adherent after on/off operability cycles for the H9 thruster.



Comparison of BN layer coloration, showing sides that reacted with boria vapor and boria liquid



BN conversion layer thickness vs. process/temperature/time



Scanning electron micrographs of the BN layer morphology. Insets indicate BN layer thickness in micrometers.

Publications and Presentations

[1] C.S. Chari & K.T. Faber (2020, January). Multifunctional ceramic layers of hexagonal boron nitride and graphite. Presented at the 44th International Conference on Advanced Ceramics and Composites of the American Ceramic Society, Daytona Beach, FL.

[2] C.S. Chari & K.T. Faber (2021, February). Influence of Boria on the Oxidation of Aluminum Nitride. Presented at the 45th International Conference on Advanced Ceramics and Composites of the American Ceramic Society Virtual.

[3] C.S. Chari & K.T. Faber (2021, October). Effect of Boria on the Oxidation Behavior of Aluminum Nitride. Poster to be presented at The Materials Science & Technology technical meeting and exhibition MS&T21, Columbus, OH.

[4] C.S. Chari & K.T. Faber (manuscript in preparation), "Oxidation Resistance of AlN/BN via Growth of $Al_{18}B_4O_{33}$ Crystals"

[5] C.S. Chari, K.T. Faber, B. W. McEnerney, R. R. Hofer, C. M. Marrese-Reading, J. A. Wollmershauser (2022, January). Hexagonal boron nitride and graphite bi-materials for electric propulsion. To be presented at the 46th International Conference on Advanced Ceramics and Composites of the American Ceramic Society, Daytona Beach, FL.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Bryan W. McEnerney
Email: Bryan.Mcenerney@jpl.nasa.gov

Clearance Number:
RPC/JPL Task Number: R20108