Virtual Research Presentation Conference

Advanced Materials for Electric Propulsion

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Program: Topical R&TD
Assigned Presentation #RPC-176

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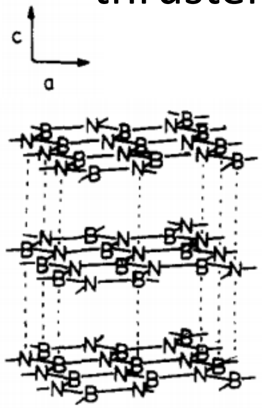
Tutorial Introduction

Abstract

The incumbent technology for dielectric channels for Hall effect electric propulsion systems is a boron nitride-based material which has shown increasing variability and poor properties over recent years and cannot physically scale in size to support the next generation of thrusters. The work contained herein is focused on the development of an advanced approach to create a dielectric layer on graphite using a multi-step carbothermal reduction process, which results in an integrally bonded layer offering controlled placement of the dielectric, with the processing and scaling advantages of graphite.

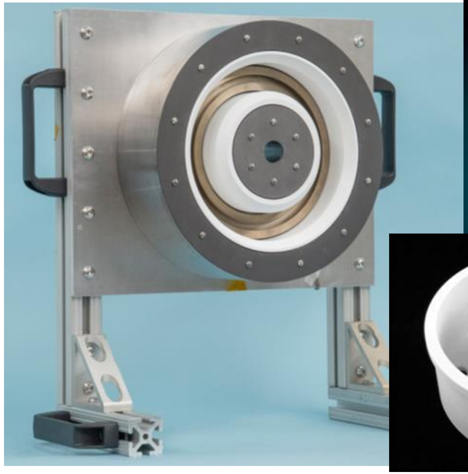
Problem Description

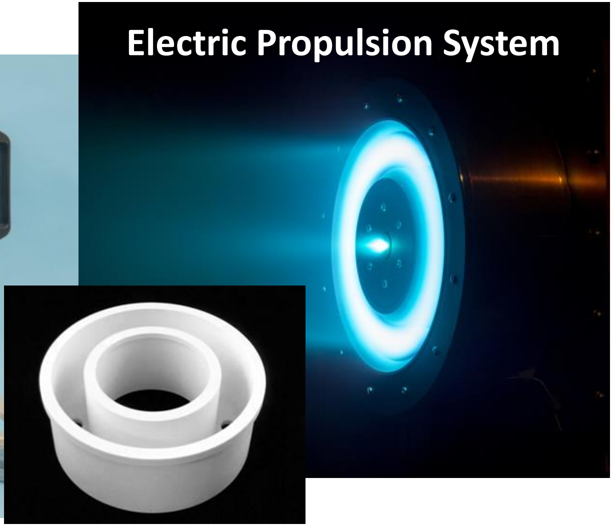
- Hexagonal boron nitride (h-BN) is widely used for its insulating properties, e.g. thrusters in electric propulsion systems.



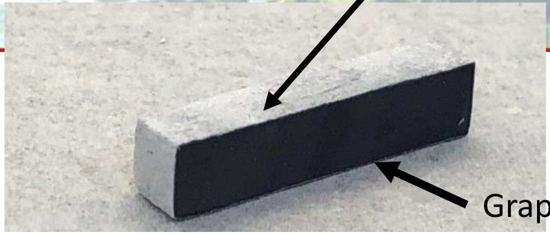
h-BN

- Hexagonal structure (a = 2.46 Å, c = 6.74 Å)
- Dielectric
- Resistant to oxidation up to 1000 °C
- Susceptible to damage



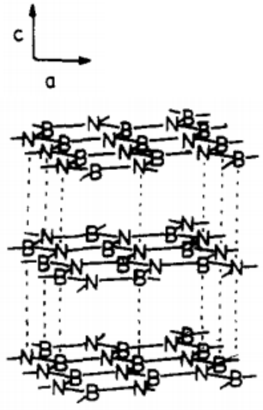


Hofer et al. “The H9 Magnetically Shielded Hall Thruster”, Presented at the 35th International Electric Propulsion Conference (2017)
Oshima et al. “Ultra-thin epitaxial films of graphite and hexagonal boron nitride on solid surfaces”, *J. of Phys.: Condensed Matter* (1998)



Problem Description

- Proposed solution: h-BN/Graphite bimaterial system



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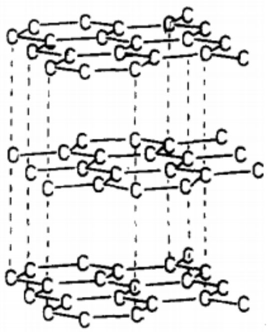

Graphite

- Hexagonal structure
  (a = 2.50 Å, c = 6.67 Å)
- Conductive
- More compliant than h-BN
- Poor resistance to oxidation at high temperatures
- **Similar coefficient of thermal expansion as h-BN**

Hofer et al. “The H9 Magnetically Shielded Hall Thruster”, Presented at the 35th International Electric Propulsion Conference (2017)
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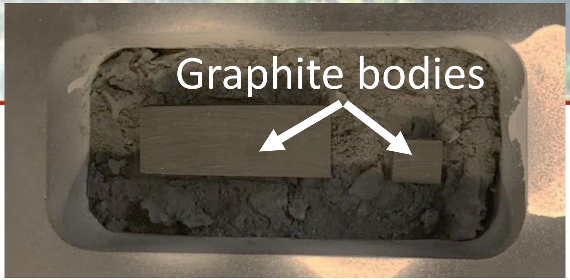
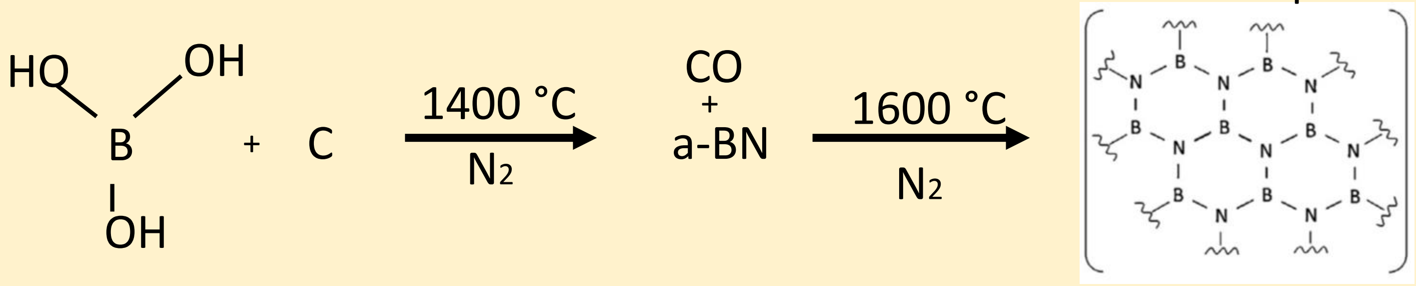
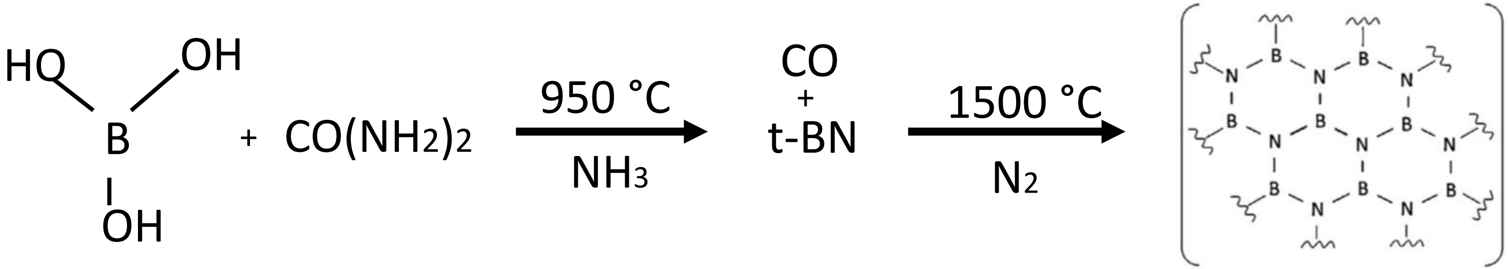


Methodology – BN/Graphite Bimaterial

- Carbothermal Reduction Reaction: Boric acid is reduced into BN in the presence of C.

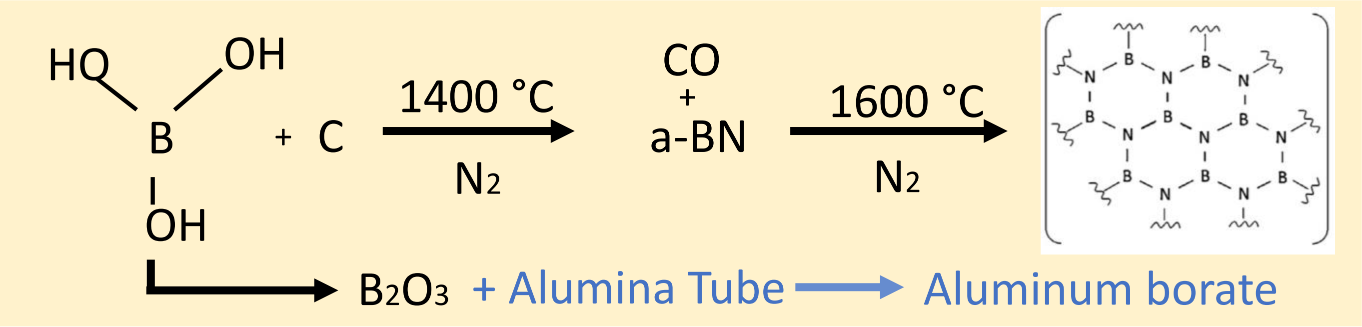


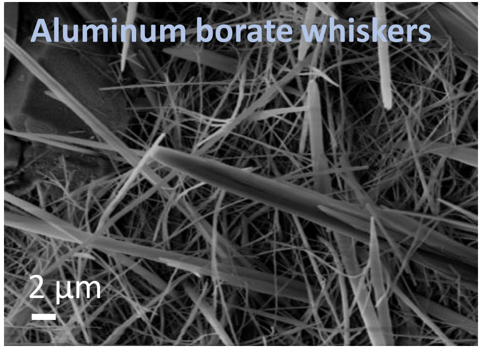
- Amide Reaction: Boric acid reacts with urea forming turbostratic BN that can densify into h-BN.



Results – Unanticipated Reactions

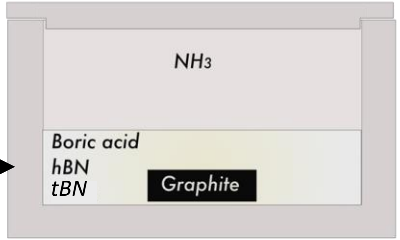
High temperature reactions with B_2O_3 can be problematic…



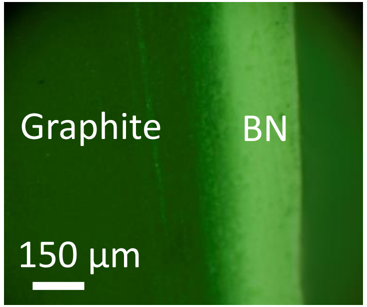


Alternative set-up was developed this FY using:

i) Lower concentrations of boric acid
ii) SiC tube
iii) BN crucibles with lids



t =240 ± 30 µm



SiC tube
(max. working T = 1500 °C)

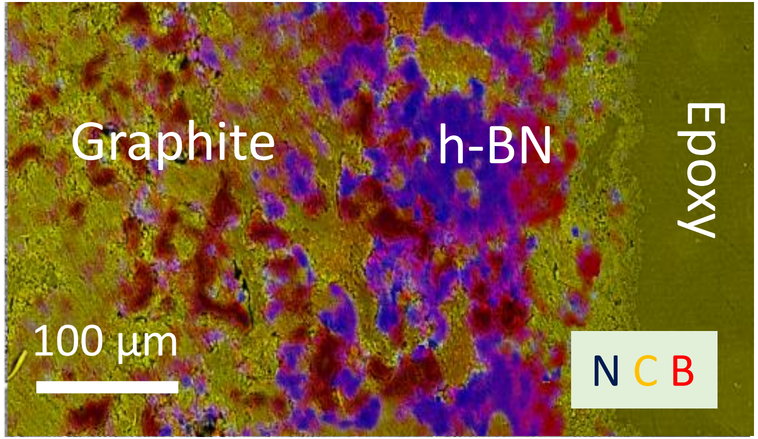
Results – Alternative Synthesis of BN/Graphite Bimaterial

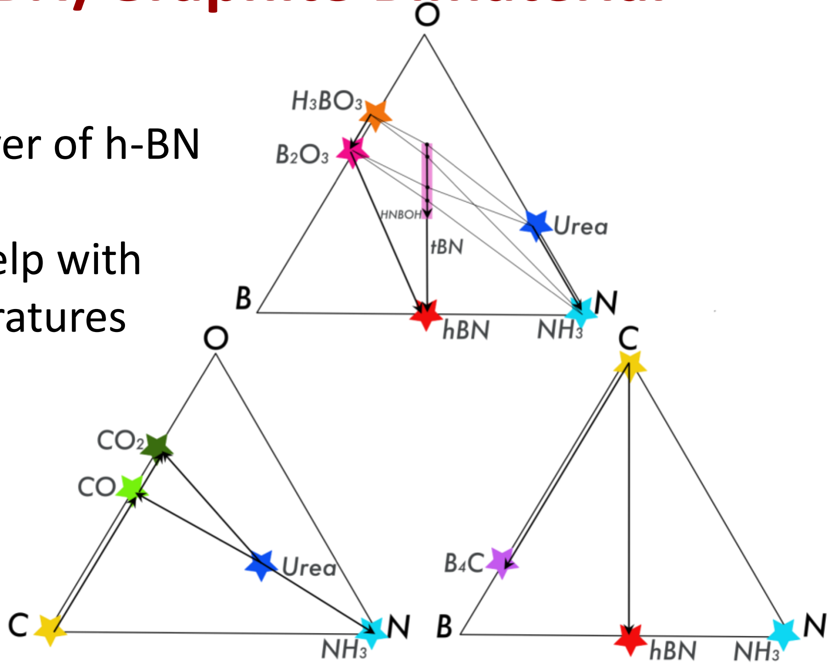
Hybrid approach for developing BN/C layers

i) Carbothermic reaction replaces graphite with layer of h-BN

ii) Boron carbide layer located at the interface

iii) Turbostratic BN formed by amide reaction can help with the densification of the BN layer at lower temperatures



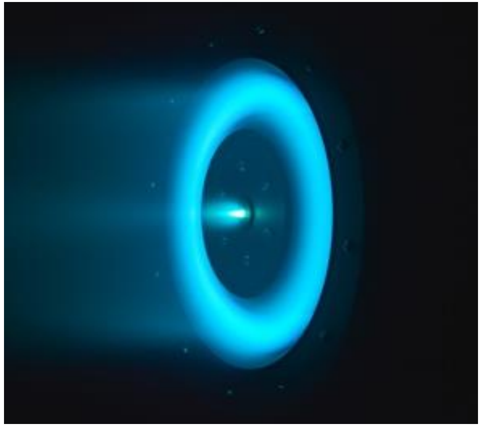


Hubacek et al., "Preparations and Properties of a Compound in the B-C-N System", *J. Solid State Chem.*, **114** (1995)

Alkoy et al., "Crystallization Behavior and Characterization of Turbostratic Boron Nitride", *J. Eur. Ceram. Soc.*, **17** (1997)

Results – Carbon-wall Hall Thruster

- Performance of the magnetically-shielded H9 with graphite walls was measured in JPL's Owens Vacuum Chamber
  - 800 V operation demonstrated for the first-time, a 267% increase from previous JPL work at 300 V
  - Zero issues with electrical isolation
  - Average thrust efficiency of carbon within -1.6% of BN
- In FY21, this performance baseline will be compared with C-BN channels.
- Design concepts and plasma simulations were also developed for use in FY21 where the C-BN channel will be fabricated.

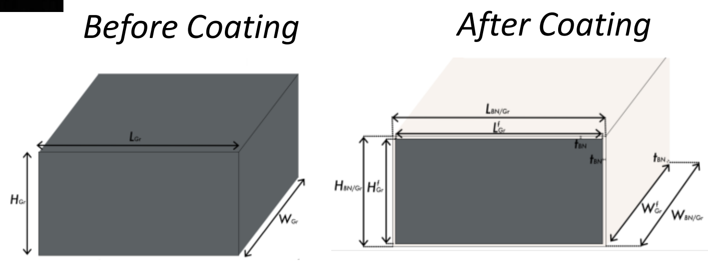


JPL's H9 with graphite walls operating at 800 V, 9 kW

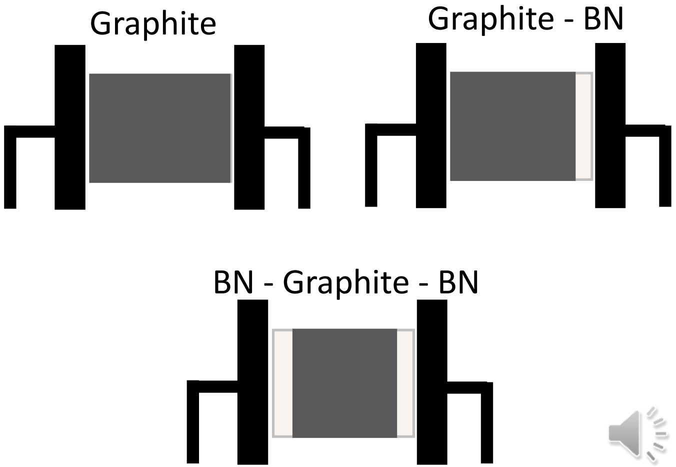
		H9 - BN walls			H9 - C walls			% change C relative to BN		
Vd (V)	Id (A)	Thrust (mN)	Total Isp (s)	Total Eff	Thrust (mN)	Total Isp (s)	Total Eff	Thrust (mN)	Total Isp (s)	Total Eff
300	20	379.1	2020	0.619	378.0	2017	0.616	-0.3%	-0.2%	-0.5%
300	15	290.1	1950	0.607	285.4	1917	0.588	-1.6%	-1.7%	-3.1%
400	15	347.7	2230	0.626	342.4	2214	0.613	-1.5%	-0.7%	-2.1%
500	15	394.7	2460	0.629	389.8	2443	0.617	-1.2%	-0.7%	-1.9%
600	15	436.2	2690	0.634	433.9	2682	0.629	-0.5%	-0.3%	-0.8%
800	11.25	391.0	2950	0.621	387.8	2933	0.614	-0.8%	-0.6%	-1.1%

Next Steps

- Dimensional analysis: precise tracking of volume change after BN-forming reaction. Aim to control thickness of BN layer by using tailored amounts of boric acid-based precursor for any graphite sample



- Resistivity measurements: use source measure unit (SMU) or electrometer to measure resistance of h-BN coatings and detect current leakage



- Graphite candidates: compare different grades of graphite to find the best candidate for EP Hall thrusters e.g. G540 (Tokai Carbon); DFP-1, AXF-5Q, ZXF-5Q (Entegris, POCO Graphite)

Publications and References

Publications & Presentations

[1] C.S. Chari & K.T. Faber (2020, January). Multifunctional ceramic layers of hexagonal boron nitride and graphite. Paper 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 (2020). “Influence of Boria on the Oxidation of Aluminum Nitride Ceramics”. Manuscript in preparation.

References

[1] T. E. O’Connor, “Synthesis of Boron Nitride”, J. Am. Chem. Soc., 84, 9 (1962)

[2] J. Thomas et al., “Turbostratic Boron Nitride, Thermal Transformation to Ordered-layer-lattice Boron Nitride”, J. Am. Chem. Soc., 84, 24 (1963)

[3] Mashnitskii et al., “High Temperature Graphite Protective Coatings”, Refractories and Industrial Ceramics, 12, 11-12 (1971)

[4] Rusanova et al. “Reaction Sintering of Boron Nitride”, Soviet Powder Metallurgy and Metal Ceramics, 12 (1979)

[5] Hubacek et al., “Preparations and Properties of a Compound in the B-C-N System”, J. Solid State Chem., 114 (1995)

[6] Alkoy et al., “Crystallization Behavior and Characterization of Turbostratic Boron Nitride”, J. Eur. Ceram. Soc., 17 (1997)

[7] Oshima et al. “Ultra-thin epitaxial films of graphite and hexagonal boron nitride on solid surfaces”, J. of Phys.: Condensed Matter (1998)

[8] Hofer, R. R., Cusson, S. E., Lobbia, R. B., and Gallimore, A. D., "The H9 Magnetically Shielded Hall Thruster," Presented at the 35th International Electric Propulsion Conference, IEPC-2017-232, Atlanta, GA, Oct. 8-12, 2017, 2017.

[9] Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Magnetic Shielding of Walls from the Unmagnetized Ion Beam in a Hall Thruster," Applied Physics Letters 102, 2, 023509 (2013).

[10] Hofer, R. R., Kamhawi, H., Mikellides, I., et al. "Design Methodology and Scaling of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," 62nd JANNAF Propulsion Meeting, 2015.

[11] Hofer, R. R., Jorns, B. A., Brophy, J. R., and Katz, I., "Hall Effect Thruster Electrical Configuration," United States Patent No. 10,480,493 (Nov. 19, 2019).

[12] Goebel, D. M., Hofer, R. R., Mikellides, I. G., Katz, I., Polk, J. E., and Dotson, B. N., "Conducting Wall Hall Thrusters," IEEE Transactions on Plasma Science 43, 1, 118-126 (2015).

[13] Shark, S. W., Hall, S. J., Jorns, B. A., Hofer, R. R., and Goebel, D. M., "High Power Demonstration of a 100 kW Nested Hall Thruster System," AIAA-2019-3809, August 2019.