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International Round-Robin High-Enthalpy Test-Facility Campaign

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Abstract

Advancing the understanding of high-temperature materials, such as ceramic matrix composites (CMCs), under conditions relevant to extreme thermal environments requires access to consistent and well-characterized material response data. While high-enthalpy test facilities have a longstanding history of advancing the understanding of high-temperature materials, it is well known that no singular facility can fully replicate all conditions necessary to develop a comprehensive and robust material response. Therefore, emerging from discussions on this topic during a collaborative workshop at the Third International Conference on High-Speed Vehicle Science and Technology (HiSST) held in Busan, South Korea in April 2024, a round-robin test campaign is proposed. The two-fold outcomes of the proposed test campaign are to foster international collaboration and understanding of international high-enthalpy facilities, as well as to cultivate an understanding of material degradation through testing at multiple facilities allowing dissemination to the international community through HiSST. Through this effort, a comprehensive documentation of international facility capabilities will be compiled to support informed test planning and validation within the research community. Since each of these facilities are unique, a systematic approach will be used to relate specific key-capabilities to participating contributors. In collaboration with each facility and using a common material set for testing (polytetrafluoroethylene (PTFE), graphite, silicon carbide (SiC), and/or ultra-high temperature CMC), the proposed campaign will document a range of material responses such as non-oxidizing and oxidizing material failure. Each facility's "tribal" knowledge from both historic, and newly generated data, will be leveraged at varying levels of participation to foster mutual growth and understanding. The proposed individually funded test campaign is targeted to document the unique capabilities and constraints at participating high-enthalpy test facilities. It aims to provide the international community with a comprehensive understanding of both new and existing ground-based test facilities for characterizing material behavior under high-enthalpy conditions, while fostering enhanced international collaboration.

Keywords: *Aerothermal Testing, High-Temperature Materials, Arc-Jet Testing, CMC Oxidation, Plasma Wind Tunnel*

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Nomenclature

AEDC – Arnold Engineering Development Complex

AHF – Aerodynamic Heating Facility

CBNU – Chonbuk National University

CIRA – Italian Aerospace Research Center

DLR – German Aerospace Center

CMC(s) – Ceramic Matrix Composite(s)

H1 – High-Enthalpy Ablation Test 1

H2 – High-Enthalpy Ablation Test 2

H3 – High-Enthalpy Ablation Test 3

HiSST – High-Speed Vehicle Science and Technology

ICP – Inductively Coupled Plasma

IHF – Interactive Heating Facility

JAXA – Japan Aerospace Exploration Agency

LaRC – Langley Research Center

LCAT – Large Core Arc Tunnel

MIDJet – Microwave Driven Jet

OFHC – Oxygen Free High Conductivity

PTF – Panel Test Facility

PTFE – Polytetrafluoroethylene

SiC – Silicon Carbide

TAPT – Technion Arc Plasma Tunnel

TFF – Turbulent Flow Facility

TGA – Thermogravimetric Analysis

TPS – Thermal Protection System

UHT – Ultra High Temperature

VKI – Von Karman Institute

1. International Round-Robin High-Enthalpy Test-Facility Campaign

The proposed approach fosters mutual growth of high-enthalpy facility testing capabilities, as well as material behavior, by evaluating degradation mechanisms through collaboration with international facilities.

1.1. Overview of Approach

Advancing the use of high-temperature materials in extreme environments requires reliable data that correlates aerothermal material response with empirical results obtained in representative test conditions. Given the high cost associated with producing these ground-based test environments, it is essential to establish a common baseline of material data. These materials will serve as a reference point to a broad understanding of material degradation, supporting the advancement of future high-temperature material applications. Thus, the proposed approach to the collaborative round-robin high-enthalpy testing campaign consists of four coupled objectives:

- Grow international collaboration in high-temperature material testing and evaluation
- Understand capabilities of existing and emerging test facilities
- Expand the empirical data for high-temperature material responses, including passive-active, transition, and active-passive oxidation regimes
- Distribute a comprehensive high-enthalpy testing document to support the broader research and development community

In an effort to reduce potential material variance, a common set of test materials is desired. Targeted common materials for evaluation are Polytetrafluoroethylene (PTFE), graphite, silicon carbide (SiC), and an Ultra-Hight Temperature Ceramic Matrix Composite (UHT-CMC). Collaborators at each test facility should understand their individual physical constraints and identify their own unique down-selected test geometry, such as a slug, wedge, or cone. Through active engagement with collaborators, the aim is to capture and compile best practices in pre-test calibration, setup, and execution to enhance the quality and repeatability of measurements across the high-enthalpy-testing community. Additionally, collaborators' insights and experiences will support the creation of guidance documents for common test instruments, such as thermocouples, pressure transducers, and heat-flux gauges, in addition to the best practices for leveraging non-contact measurement techniques like pyrometry and high-speed imaging. Results and related information will be consolidated from each collaborator to support future comparative studies, feedback, and continuous improvement.

Participation in this collaborative effort offers a unique opportunity for each facility to engage directly with an international network of experts focused on high-enthalpy testing. Through open communication and shared testing experiences, participants can identify potential gaps or limitations within their own setups by discussion of how others approach similar challenges related to flow characterization, measurement techniques, or test design. This initiative creates a platform to ask technical questions more freely, explore alternative methodologies, and even arrange visits to other facilities during testing. These interactions not only deepen technical understanding but also foster long-term relationships across the international community. Ultimately, the success of this effort depends on active participation. By committing internal resources and supporting this initiative with the intention of fostering open collaboration, the campaign aims to be mutually beneficial by enhancing the collective knowledge base while enabling each facility to strengthen its capabilities and contributions to future advancements in high-temperature materials and extreme environment testing.

1.2. Proposed Schedule Outline

A proposed outline has been laid out in Fig. 1. This collaborative high-enthalpy testing campaign timeline is broken down into three key phases: Test Planning, Executing Facility Testing, and Deliverables. The planning phase, initiated with the 2025 HiSST Conference, focuses on establishing collaboration, gathering facility capabilities and information, and setting up recurring communication. This phase culminates in a comprehensive graphical representation of each facility's capabilities by Q2 of 2026.

Following the planning phase, the execution phase spans from Q2 to Q4 of 2026. This phase involves sample procurement, pre-test evaluation, and material testing. A coordinated timeline is desired for testing across all participating facilities. Each test facility will operate within its constraints and use the proposed common test materials, identified test geometries, and potential instrumentation outlined earlier.

Post-test activities begin in late Q4 2026, emphasizing collaborative facility analysis, report generation, and data compilation into a final report by Q1 2027. The conclusion of this effort is to deliver the final report to HiSST and follow-up with a comprehensive workshop to disseminate findings to the broader community for further discussion and foster newly identified collaboration efforts. This timeline ensures both depth and breadth in capturing empirical data and fosters international collaboration across the full lifecycle of the campaign.

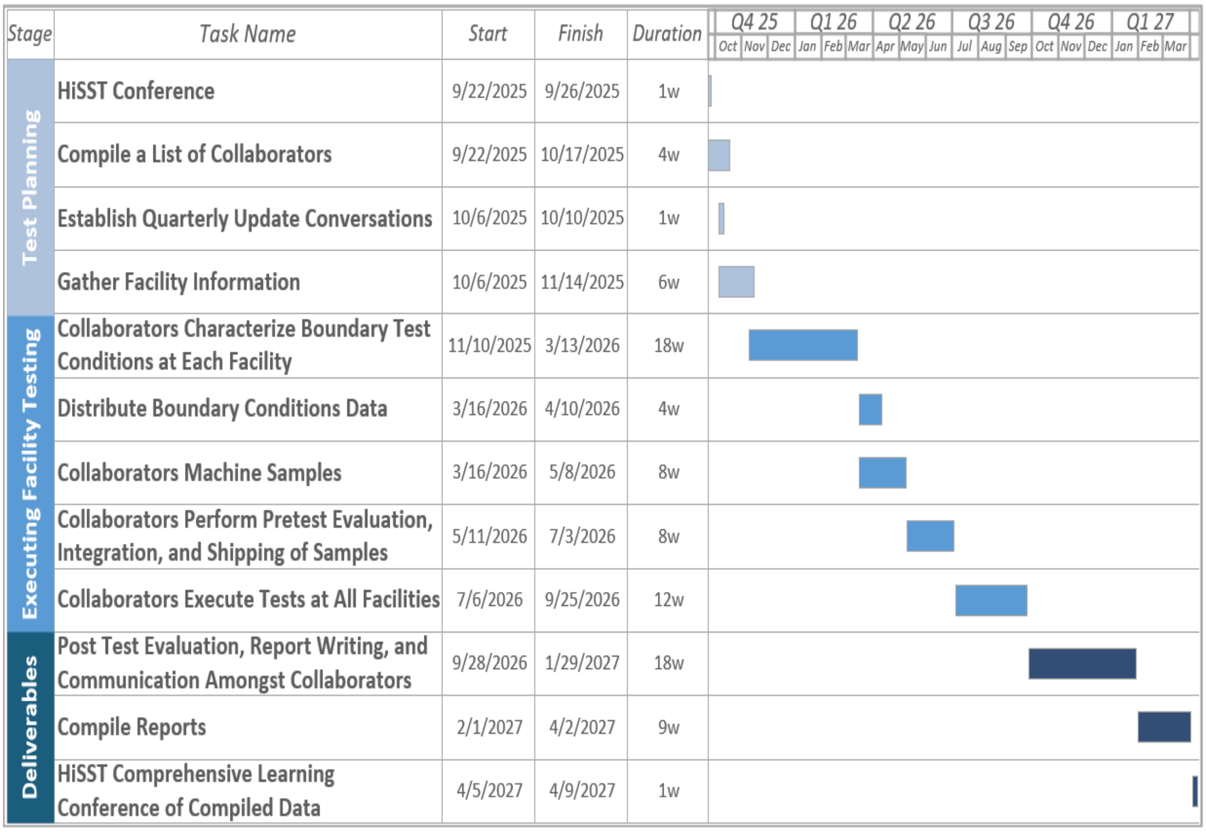

Fig. 1 Notional Schedule for International Round-Robin High-Enthalpy Test Facility Campaign

1.3. Potential Collaborators and Locations

There are several types of high-enthalpy testing facilities found in various international locations that are of interest. In addition to those described here, there may be alternative types of high enthalpy facilities available and of interest that are not mentioned in this section.

The most common types of high-enthalpy facilities operated by the United States government are the Huels and segmented type arc jets. The Huels type arc jet has a simple construction that allows for less maintenance and is vortex stabilized [1-2]. Due to its construction, the Huels type arc jet produces an arc that discharges in an inconsistent manner, which leads to poor repeatability of testing conditions [1-2]. The segmented type arc jet has multiple segments between the anode and cathode where the test gas enters the arc jet [1-2]. This segmented structure requires more frequent inspection and maintenance than the Huels type arc jet, however, the segments result in better stabilization of the arc which leads to excellent test repeatability [1-3].

Other types of high-enthalpy facilities that are more commonly operated in the United States by industry or academia groups include Inductively Coupled Plasma (ICP) jets and microwave plasma torches. Similar to the Huels and segmented type arc jets, ICP jets are also electrically powered, whereas the microwave plasma torch uses microwave power to create a high-enthalpy stream [4-5]. Both ICP jets and microwave plasma torches are electrodeless, resulting in less contamination in the testing stream compared to arc jets; however, they typically generate less power than arc jets [4-5].

Arc jets, ICP jets, and microwave plasma torches can be found in numerous international locations, but limited documentation is found on many of the facilities. This test campaign is a proposed solution to the inherent lack of accessible documentation on the facilities of interest and emerging international facilities. A list of facilities of interest where documentation has been found is outlined with their global locations and operating powers in Fig. 2. While this list touches on numerous facilities in the United States, Europe, and Asia, there are undoubtedly other high-enthalpy facilities that are not named here.

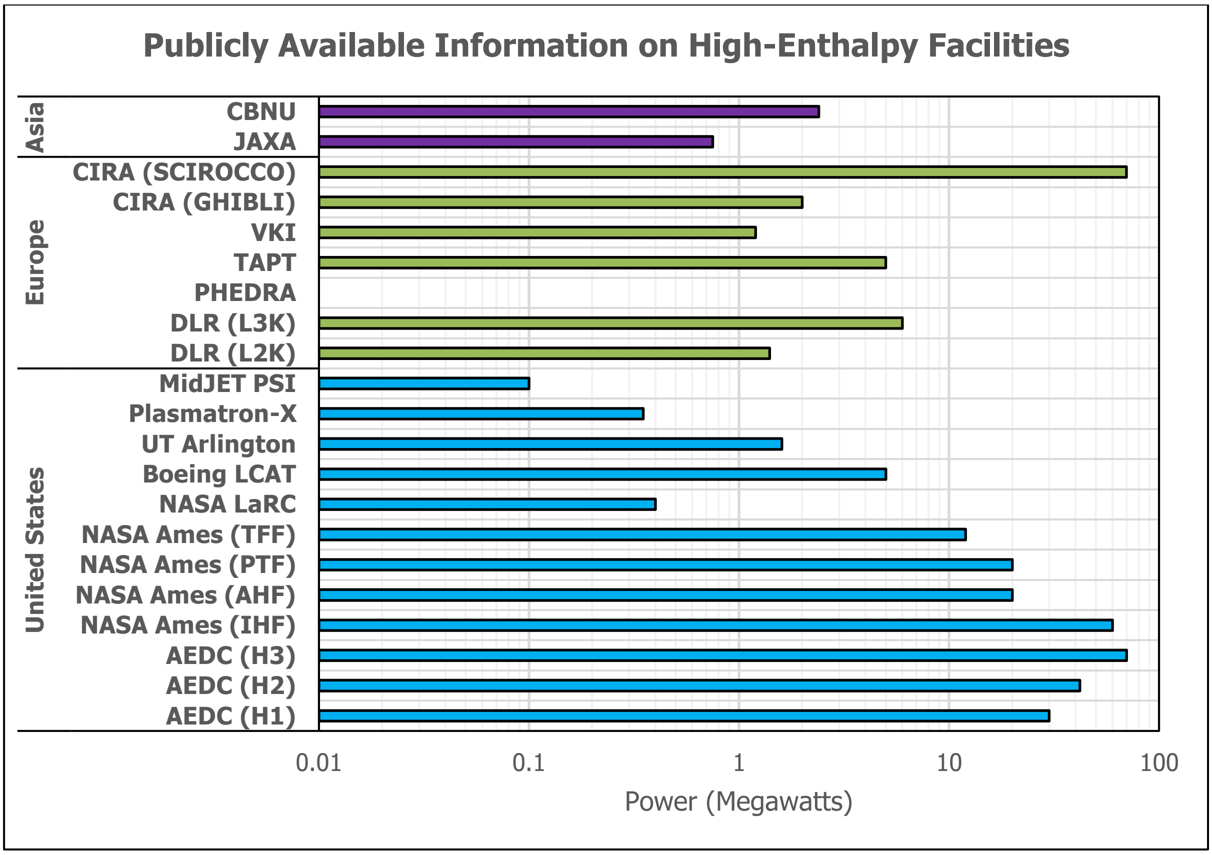

Fig 2. Scaled depiction of High-enthalpy facility power supply comparison in (MW) [5-9]

In the United States, there are twelve known arc jets of interest. Of these twelve high-enthalpy facilities, six are segmented type arc heaters, four are Huels type arc heaters, one is an ICP jet, and one is a microwave plasma torch [5-7, 10-13]. These high-enthalpy facilities are operated by NASA and the United States Air Force as well as private companies.

Throughout Europe, there are seven known high-enthalpy facilities of interest located in Italy, Germany, Belgium, Israel, and France. The segmented type of arc jets in Europe include Italy's two arc jets at the Italian Aerospace Research Center (CIRA), the German Aerospace Center (DLR) L3K, and Israel's Technion Arc Plasma Tunnel (TAPT) [6]. There is also one Huels arc jet, the DLR L2K, and one ICP jet, Belgium's Von Karman Institute (VKI) facility [6]. Documentation has not been found that explicitly states what type of arc jet the French PHEDRA facility, but it has been described as a vortex stabilized dc-arc torch[14].

In Asia, arc jets are located at Chonbuk National University (CBNU) in Korea, and at the Japan Aerospace Exploration Agency (JAXA) Mitaka Wind Tunnel. These two facilities are both segmented type arc jets [15-16].

1.4. Potential Methods of Heat Flux Measurement

Quantifying how facilities measure heat flux in high-enthalpy tests is critical for correlating test conditions to material performance. There are several methods for measuring heat flux. A few documented methods include slug calorimetry, null-point calorimetry, Gardon gauges, and gradient gages.

Slug calorimeters are commonly used to measure heat flux within the core stream and are made of Oxygen Free High Conductivity (OFHC) copper [17]. Their design and usage are standardized in ASTM E457. Slug calorimeters directly measure the temperature response of a material exposed to a high-enthalpy stream over time. This temperature versus time data is used to calculate the heat flux from known thermophysical material properties of the calorimeter using Eq. 1 [18-20].

$$q_c = \rho C_p l \left(\frac{\Delta T}{\Delta \tau}\right) = \left(\frac{MC_p}{A}\right)\left(\frac{\Delta T}{\Delta \tau}\right) \quad (1)$$

Null-point calorimeters are similarly made, using a semi-infinite solid with a thermocouple at its null-point. These calorimeters are often used to map the distribution of stagnation point heat flux across the entire cross-sectional core flow that represents a high enthalpy stream [21] at a specific axial distance that is perpendicular to the flow direction. The fabrication and implementation of null-point calorimeters are described in ASTM E598. These calorimeters can be manufactured in common geometries as seen in Fig. 3.

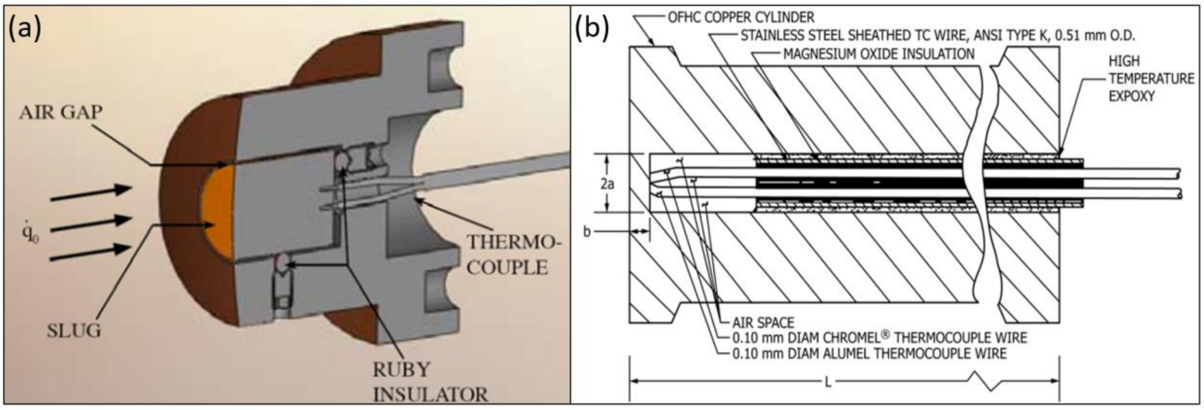

Fig 3. (a) Slug calorimeter and (b) null point calorimeter [18, 22]

Gardon gauges are constructed with a thin, circular piece of constantan foil and have a body made from OFHC copper [18]. A diagram of the construction of a Gardon gauge can be seen in Fig. 4.

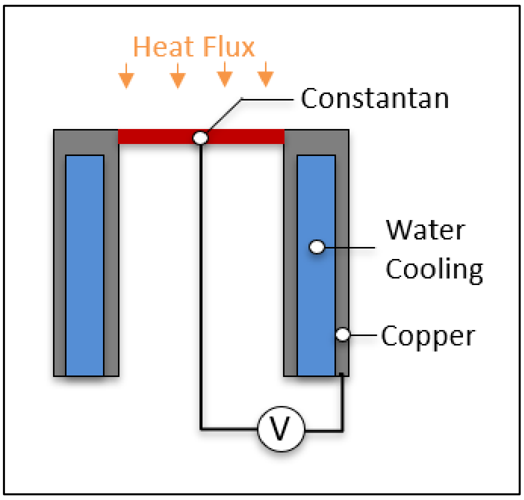

Fig 4. Gardon gauge diagram [23]

The Gardon gauge is placed into a high enthalpy stream where thermal energy makes an impact on the foil. The absorbed heat flows radially into the copper body which stores the heat and allows the center of the foil to heat to higher temperatures [24]. The temperature difference between the center of the foil and the outside edge of the foil is measured, resulting in a thermoelectric potential that is linearly proportional to the heat flux [23].

Gradient gages, also known as wire-wound or Schmidt-boelter gages, are commonly used as a substitute for Gardon gauges due to the fact that gradient gages can measure a wider range of heat fluxes [25]. A diagram of a simple gradient gage can be seen in Fig. 5. The gradient gage uses a thermopile to measure the temperature gradient of the aluminium wafer normal to the surface of the gage [25]. A voltage proportional to the heat flux is then generated between the two constantan wires [26].

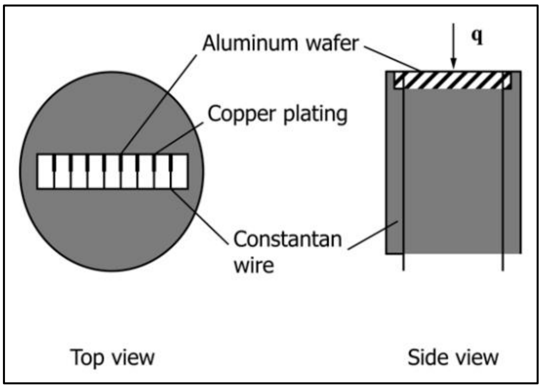

Fig 5. Gradient gage diagram [18]

1.5. Potential Material Failures

A key objective of this international round-robin high-enthalpy testing campaign is a compilation of material degradation results from each collaborator to expand understanding of material performance across multiple facilities and conditions.

In alignment to reduce potential variance in materials, this round-robin campaign is focusing on readily available materials such as PTFE, graphite, and SiC. While the failure mechanisms of PTFE (a non-charring ablator) and graphite (erodes due to being oxidized) are relatively well understood, further investigation is needed to characterize the high-enthalpy failure behavior of SiC. SiC plays a critical role as a primary constituent in ultra-high-temperature ceramic matrix composites (UHTCMCs). Understanding its behavior under extreme thermal and oxidative environments is essential for advancing the performance and reliability of high-temperature material systems used in harsh operating conditions. An objective for this international round-robin high-enthalpy testing campaign is to expand on the knowledge of SiC oxidation found in referenced material [27-28]. These references indicate SiC undergoes passive oxidation, a transition stage, and active oxidation. Figure 6. depicts the selected common materials as they are exposed to a high-enthalpy gas stream and undergo reactions with oxygen.

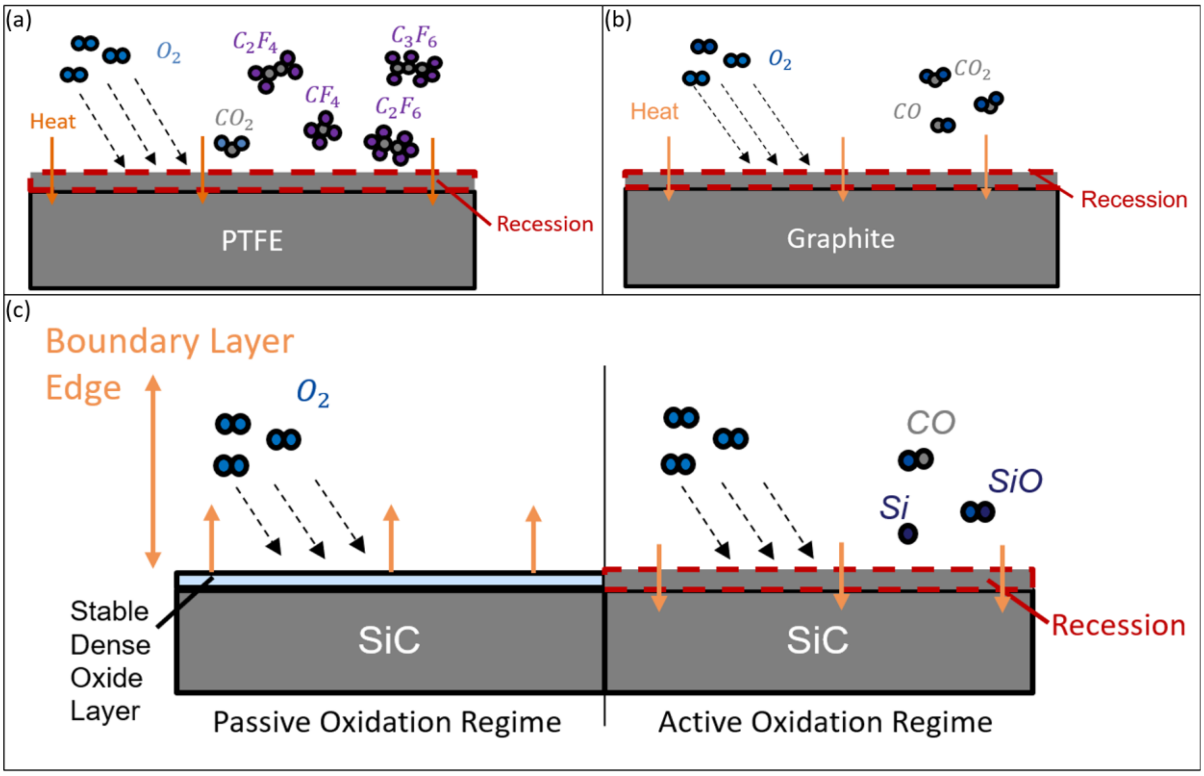

Fig 6. (a) PTFE non-charring ablation diagram, (b) Graphite surface oxidizing diagram, and (c) SiC Passive/Active oxidation diagram

The type of oxidation that SiC experiences depends on the temperature and oxygen partial pressure. Passive oxidation of SiC is mostly observed at lower temperatures and/or higher pressures, while active oxidation generally occurs in high temperature and/or low-pressure environments [29]. Eq. 2-5 represent the reactions that occur during the oxidation process of SiC [29].

$$SiC(s) + O_2(\mathrm{g}) \rightarrow SiO_2\,(s) + C(gr) \tag{2}$$

$$SiC(s) + \frac{3}{2}O_2(g) \rightarrow SiO_2(s) + CO(g) \tag{3}$$

$$\boldsymbol{SiC(s) + O_2(g) \rightarrow \mathrm{SiO}(g) + CO(g)} \tag{4}$$

$$SiC(s) + \frac{1}{2}O_2(g) \rightarrow \mathrm{Si}(g) + CO(g) \tag{5}$$

The reaction that occurs during the passive oxidation of SiC is represented by Eq. 2, where SiC reacts with oxygen to form the protective silicon dioxide layer, which inhibits oxygen penetration into the underlying substrate and thus greatly reduces the recession rate to near-zero. As the temperature rises, the formation of CO promotes a blowing effect that decreases oxygen at the wall which is depicted in Eq. 3. Eq. 4 represents a transition stage where there is an active depletion of the protective oxide layer while SiC is actively reacting with oxygen to form the volatile silicon monoxide gas. Eq. 5 depicts when the protective oxide layer is fully depleted and there is an active formation of silicon gas.

By mapping out the unique effects observed by all participating facilities, all collaborators can contribute to a deeper, more unified understanding of material degradation mechanisms across international high-enthalpy ground-test environments, which in turn will reduce uncertainty related to the mechanisms described above. Through this sustained effort, the hope is that each active participant will benefit from collective discussions regarding the relationships between the tools and methodologies used to evaluate material behavior. These discussions can initiate continued collaboration across this international network, strengthening both technical insight and cooperative research. By generating a consistent and shareable dataset, this effort highlights both the technical rigor of the results and each facility's ability to address differences across test conditions. Ultimately, this work will strengthen confidence in material characterization and performance modeling, particularly for emerging UHTCMCs, and contribute to the broader understanding of high-temperature material behavior in extreme environments.

2. Conclusion

By conducting an international round-robin high-enthalpy testing campaign with flexible levels of participation, the aim is to foster and strengthen global collaboration among the international testing community. This paper highlights key areas that require further investigation in order to capture the full breadth of high-enthalpy testing capabilities around the world. A summary of facility capabilities will be distributed to the HiSST community at the conclusion of this effort. As a secondary interest, this study will also expand the cumulative knowledge of material degradation through the capture of "tribal knowledge" and associated test data to enable collective breakthroughs. Leveraging each facility's participation, this study will further cultivate understanding of the well-known, but not fully understood, active oxidation of SiC, and the conditions necessary to gain relevant information. Since "No Single Ground-Based Facility" [9] can fully replicate all operating conditions, this round-robin study will reduce uncertainty by leveraging alternative test facilities that provide the international community with validated insights into material behavior under extreme conditions.

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