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Seal Materials and Sealing Technologies for Hypersonic Vehicles

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The Defense Systems Information Analysis Center (DSIAC) received an inquiry regarding the state of materials and methods available for sealing the external joints in the outer mold line and the engines of U.S. Department of Defense hypersonic weapon systems. In this technical inquiry response report, DSIAC subject matter experts provide a discussion of the needs for the seals and what materials and methods are available based on publicly available information and references.

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TI Research

A chief service of the DoDIAC is free technical inquiry (TI) research limited to four research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. Given the limited duration of the research effort, this report is not intended to be a deep, comprehensive analysis but rather a curated compilation of relevant information to give the reader/inquirer a "head start" or direction for continued research.

Abstract

The Defense Systems Information Analysis Center (DSIAC) received an inquiry regarding the state of materials and methods available for sealing the external joints in the outer mold line and the engines of U.S. Department of Defense hypersonic weapon systems. In this technical inquiry response report, DSIAC subject matter experts provide a discussion of the needs for the seals and what materials and methods are available based on publicly available information and references.

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1.0 TI Request

1.1 Inquiry

What sealing materials, methods, and technologies are available for hypersonic vehicles?

1.2 Description

The Defense Systems Information Analysis Center received an inquiry regarding available sealing materials, methods, and technologies for hypersonic vehicles. The area of interest was in the state of materials and methods available for sealing the external joints in the outer mold line (OML) and the engines of U.S. Department of Defense (DoD) hypersonic weapon systems. Subject matter experts compiled information available from public sources on hypersonic seal materials and methodologies. These findings are presented herein.

2.0 TI Response

Owing to the current political climate with near-peer adversaries and the continued situation in Ukraine, the development and deployment of these weapon systems are of particular interest to both the DoD and the country at large. This report provides a discussion of the needs for the seals and what materials and methods are available based on open-source information and references.

2.1 Introduction

One piece of technology that is often overlooked is a critical piece of the integration required for hypersonic vehicles' area seals and materials for seals. "Hypersonic vehicles require high-temperature seals to block hot gas flow at the intersection of static [OML] panels, movable flaps and rudders, windows, and engine components" [1]. Typical materials for seals, such as elastomeric materials and flexible graphite, cannot withstand the rigors of hypersonic environments. These seals must endure very high temperatures; steady-state and transient, localized heating from shock waves; high aerodynamic loads; high-fluctuating pressure loads; potential for sever flutter, vibration, and acoustic loads; and, finally, erosion from the airflow over the vehicle and through the engine.

It is specifically noted that much of the materials research and integration into aerobodies for hypersonic applications has moved into the classified regime, but this work hopes to provide the reader with basic materials and an understanding of the topic.

The temperature distribution over a hypersonic aerobody varies greatly, depending on the design of the body and its mission. Generally, the leading edges (most commonly the nose and wing-facing materials) can see temperatures as high as 4,000 °F (as a point of reference, a blast furnace used to melt steel will typically operate at or about 3,000 °F). An example of the temperature profiles for a notional aerobody is shown in Figure 1.

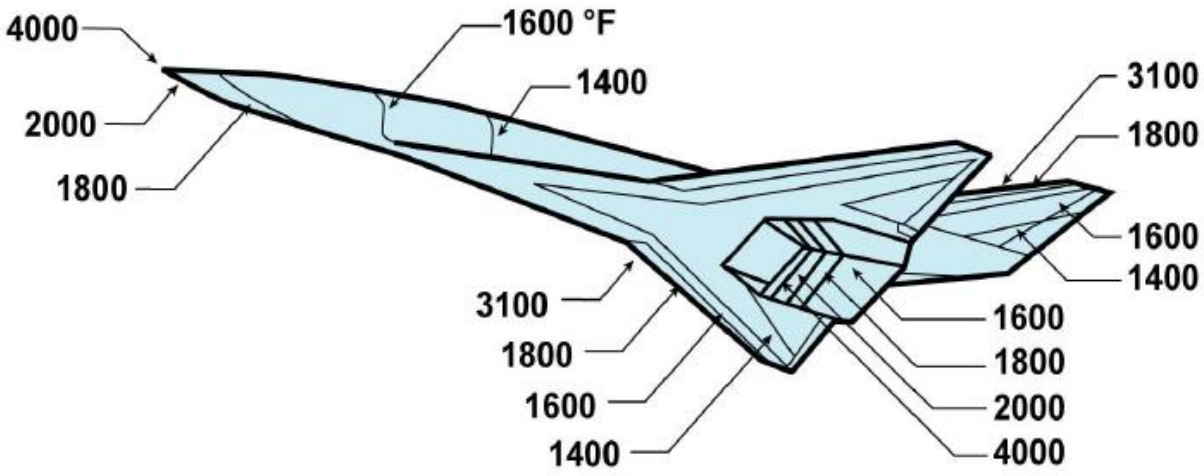

Figure 1. Predicted Equilibrium Surface Temperatures for Hypersonic Cruise on a Notional National Aeronautics and Space Administration (NASA) Vehicle at Mach 8 and at an Altitude of 88,000 ft [2].

Materials that are specifically designed for use in high-temperature environments (such as carbon-carbon, silicon carbide, silicon nitride, refractory metals, etc.) are not suitable for sealing, as they do not have the flexibility to stretch and compress, especially to deal with the movements associated with flight-control surfaces and thermal expansion and contraction of different materials used on different parts of the aerobody.

A short course produced by Steinetz [2] discusses many of the different issues and requirements associated with sealing hypersonic systems. At the time, NASA was pursuing hypersonic transport technologies (not for weaponry). The hypersonic systems immediately in demand by the DoD are typically one-use systems (as a terminal weapon system), but there are areas of overlap.

2.2 Vehicle Seal Locations

Areas of interest for the DoD application of a terminal weapon system still include the control surfaces (examples shown in Figure 2), which, to some extent, are mission dependent for DoD-specific systems but can include:

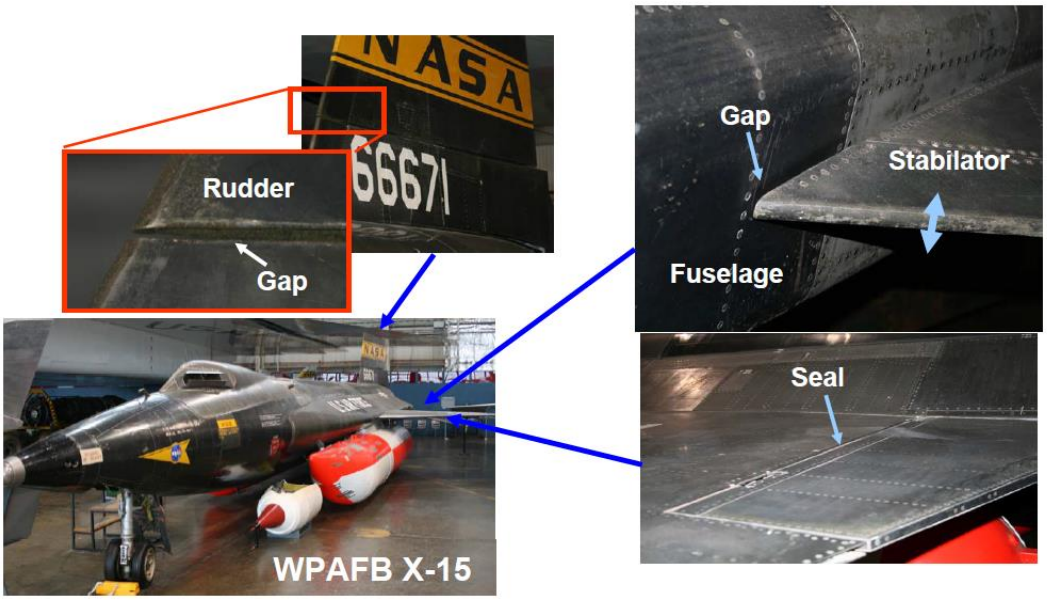

Figure 2. Control Surfaces That Require Different Degrees of Sealing, Using the X-15 as an Example [2].

- Rudders
- Elevons (Note: elevons are combined control surfaces on an aerobody, primarily delta wing and tailless designs. These surfaces act as both elevators and ailerons [to control pitch and roll, respectively]. An example of these, for context, is shown in Figure 3.)
- Body flaps

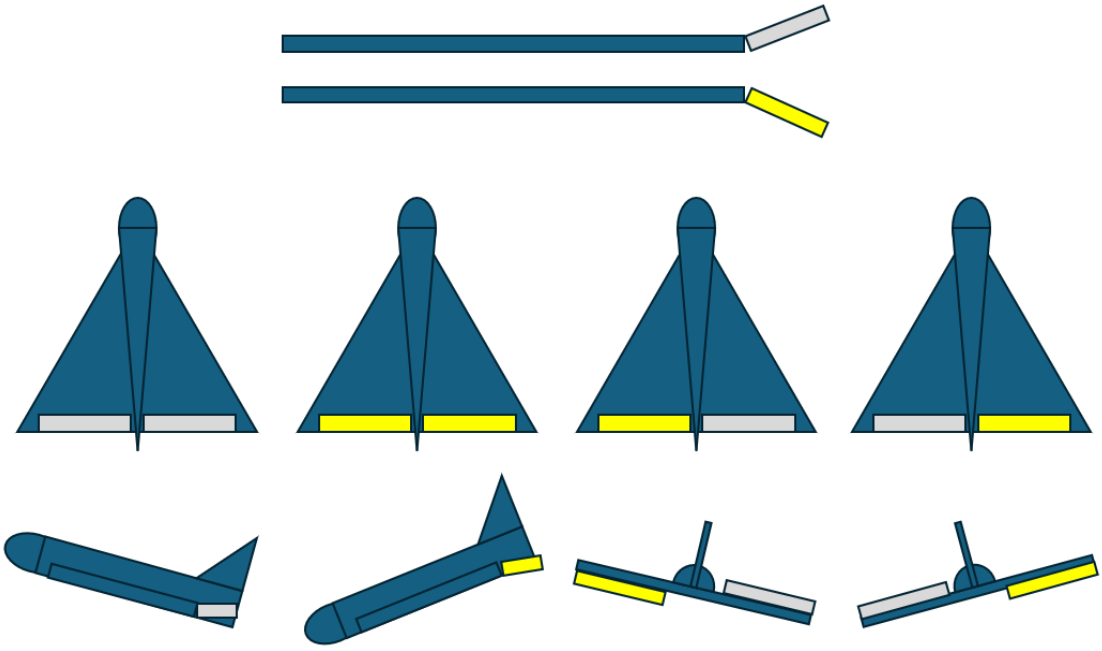

Figure 3. A Diagram of Elevons That May Be Used on Hypersonic Weapon Systems *(Source: D. Motes).*

For the thermal protection system(s), the most common areas requiring seals are for:

- Leading edges
- Gaps/seams between different pieces of the assemblage
- Engine/airframe interface as applicable

Finally, other miscellaneous areas need to be addressed, most commonly:

- Landing-gear doors
- Cargo-bay doors
- Payload-bay doors
- Crew access doors
- Canopy

In general, as the initial DoD applications are as a terminal weapon system, many of the miscellaneous areas that need to be addressed are extraneous.

2.3 Performance Requirements

There are a number of general performance requirements for hypersonic seals. These include but are not necessarily limited to:

- High-temperature resistance
- Good heat-insulating properties to block the flow of heat into internal components
- No leakage to block the physical flow of hot gases into the internal airframe components
- Smooth OML to not induce turbulence across slipstream
- Good flexibility to conform to the complex geometries of the airframe
- Good resilience to maintain contact with opposing surfaces under highly dynamic conditions and potentially over many cycles (Figure 4 shows an example permanent set in a braided ceramic rope seal. If this occurs during flight, it can open up gasp in the airframe and allow hot gases to enter, as well as induce turbulence)
- Good wear resistance to maintain seal integrity over dynamic conditions and potentially a large number of cycles, depending on the mission profile

2.4 Seal Designs

As stated earlier, hypersonic seals must endure very high temperatures; steady-state and transient, localized heating from shock waves; high aerodynamic loads; high-fluctuating pressure loads; potential for sever flutter, vibration, and acoustic loads; and, finally, erosion from the airflow over the vehicle and through the engine.

Figure 4. Permanent Set in a Braided Ceramic Rope Seal [2].

Seal design is driven by a set of requirements that may be specific to each individual hypersonic craft and the particular mission profile:

- Leakage limits (in particular, a problem around control surfaces)
- Temperature and pressure (varies as a function of vehicle trajectory, dynamic pressure, and angle of attack)
- Gap change associated with differential expansion rates of the adjoining structures
- Life driven by system-level requirements (for these purposes, control surfaces)

In some cases, multilayer coatings/sealants are used at joints (with higher-temperature materials comprising the inside and lower-temperature, more elastic materials making up the inside material systems) [3].

Note that, for advanced hypersonic vehicles like those considered here, materials such as ceramic matrix composites that have higher heat conductivity are required and, therefore, more heat will be transferred to seals (higher temperatures, less margin). This becomes an additional problem that must be dealt with, both ensuring that seals do not fail and do not pass heat on into the interior if they remain intact.

In concert with designs, NASA has developed a hypersonic seal testing roadmap (Figure 5) with primary areas including:

- Hot compression testing
- Hot scrub testing
- Seal-flow testing
- Arc-jet testing
- Thermal-acoustic testing (in development as of the production of the original short-course material)

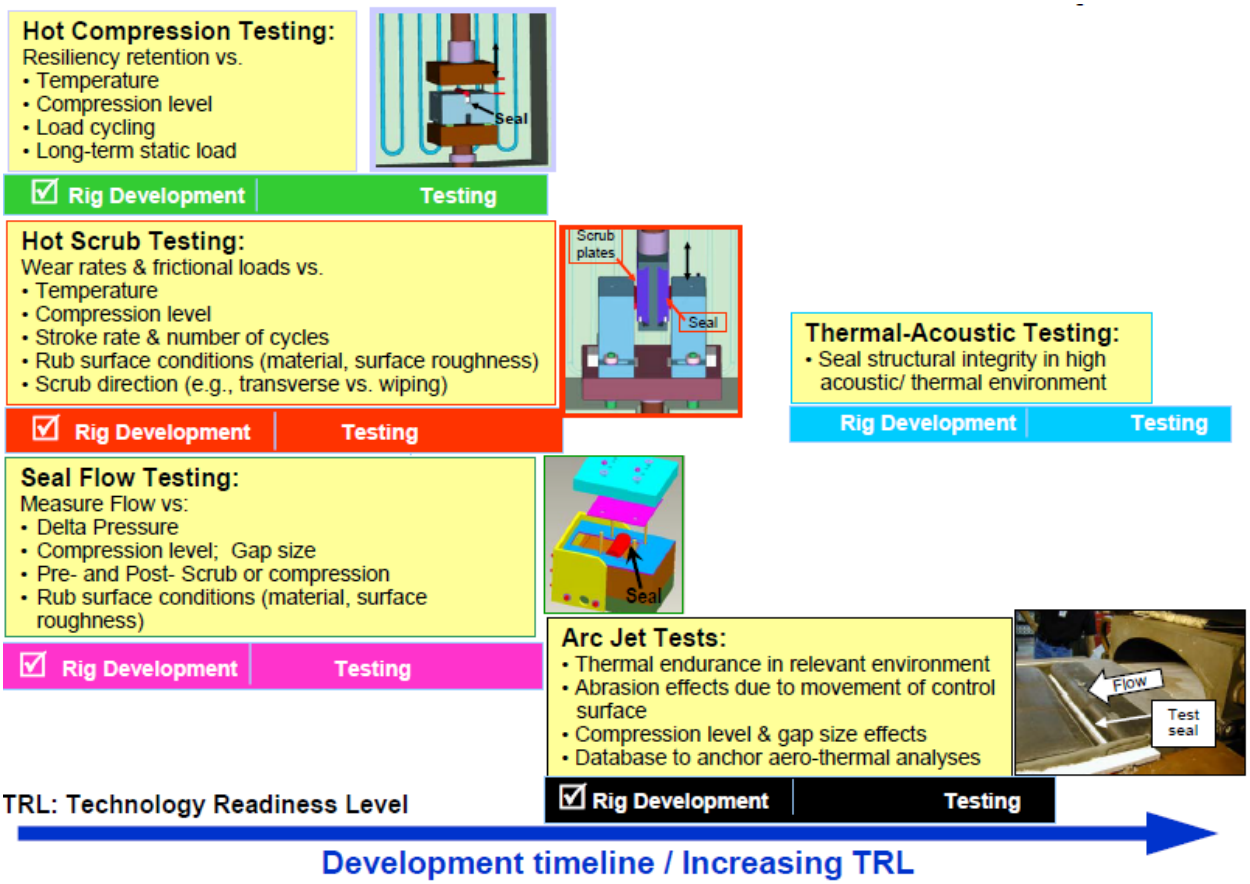

Figure 5. NASA Control Surface Hypersonic Seal Evaluation and Testing Roadmap [2].

Further information on each of the different roadmap tests is available in the work by Steinetz [2].

2.5 Material Choices

With the exception of capsule-type re-entry missions (for returning Earth-orbiting or lunar space missions or probes that are required to re-enter a foreign atmosphere), much of the work done by NASA has focused on reuseable, future hypersonic point-to-point transport system demonstrators and, for a long time, the Space Shuttle.

Traditionally, elastomeric gap filler is used to fill gaps within and on aerostructures. Materials for this are often elastomeric in nature to allow the degree of flexibility and resiliency necessary to perform the job. However, these materials have glass transition temperatures that are significantly lower than the operating temperatures that would be expected for a hypersonic vehicle, meaning that they are in suitable for use. Even flexible graphite, having use temperatures of up to 1,200 °F, is not able to withstand the environment for long periods. In addition, there are a number of gasket materials available that offer higher-temperature

performance. However, the key difference between seals and gaskets is that gaskets are primarily static seals used between flat surfaces (such as the head gasket on an internal combustion engine). Seals are used in more dynamic applications, often between moving parts.

Due to the nature of the problem and the wide range of requirements, no one material can perform all the functions needed for hypersonic sealing. However, cleverly coupled and integrated material systems can achieve goals.

2.5.1 Control Surface Seals

For control surface seals, spring tube thermal barriers are used (these are sometimes also called braided rope, braided spring, or pillow seals). These items have previously taken the form of an Inconel X-750 spring tube with a Saffil core (polycrystalline alumina fibers) and a Nextel 312 ceramic fabric sheath to allow conformance and reliance while simultaneously preventing heat/gas flow and using the ceramic fiber exterior for its high-temperature resistance. Depending on requirements, other different materials can be substituted in (such as refractory materials for the spring-like titanium-zirconium-molybdenum alloys).

Additional future work relevant to the DoD hypersonic vehicle mission profile has recommended the use of:

- Novel designs that can conform to vehicle structural deformations
- Seal material that can bear higher temperatures to permit high-Mach-number flights
- High-temperature seal energizers to ensure proper preload against the mating surface (such as ceramic spring tubes, rather than high-temperature metallic tubes)

Ceramic seals have been tested and confirmed to work, but these do suffer from poor compression properties due to their brittleness, and they cannot be applied to corner clearances. Li et al. [4] modified existing metallic seals for corner clearance use and examined the effects of replacing the interior material with aluminum silicate, quartz, and mullite fibers.

2.5.2 Propulsion Seals

For the types of engines that will power air-breathing hypersonic weapon systems after booster rockets are expended, moveable panels are required throughout the engine. Seals are therefore required to protect against damage to the actuations systems and reduce engine parasitic losses (Figure 6).

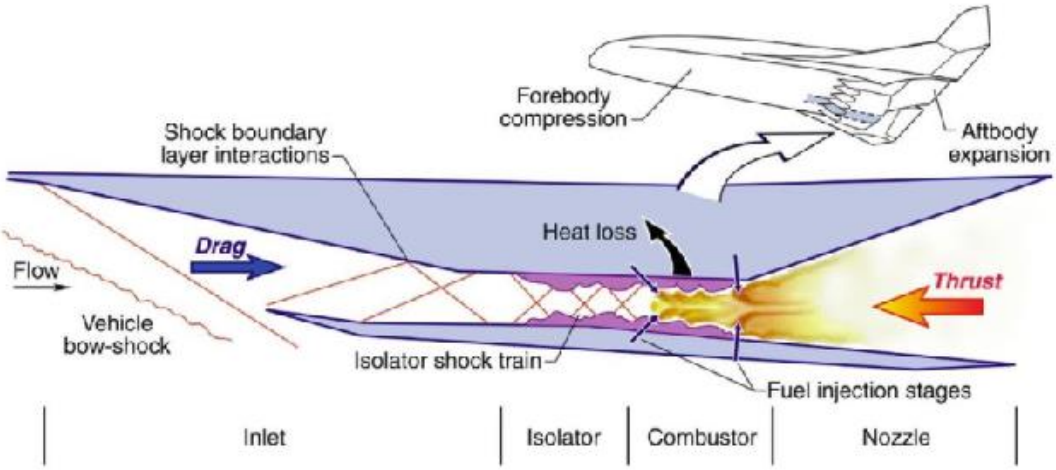

Figure 6. Layout and summary of maintaining combustion in a supersonic airflow [NASA Langley].

For hypersonic engine seals, the paramount goal is preventing hot engine gases and fuel-enriched mixtures from leaking past the seal system. The seals must withstand gas temperatures in excess of 4,000 °F and very high heat fluxes, while operating consistently at 1,500–2,500° F, with minimum cooling of any kind. In addition, the seals must operate successfully in a chemically hostile environment (oxidization and hydrogen embrittlement) and survive high vibration and acoustic levels.

Leakage limits for the seals are generally thermally driven to ensure that the inlet seals prevent aerodynamic loss/day and overheating of the hinge and drive mechanisms. For the combustor/nozzles, seals may be used to limit coolant flow into the combustion chamber, prevent leakage of gases into backside structural cavities, and prevent unburned fuel from reaching the backside cavities.

For propulsion seals, braided rope seals (Figure 7) and wafer seals (Figure 8) have been proposed. In this configuration, braided rope seals are characterized as having:

- High-temperature, high-pressure operation
- Good conformability to distorted walls
- Good for static or low sliding distance/speed applications
- Braiding material allows for transpirational cooling

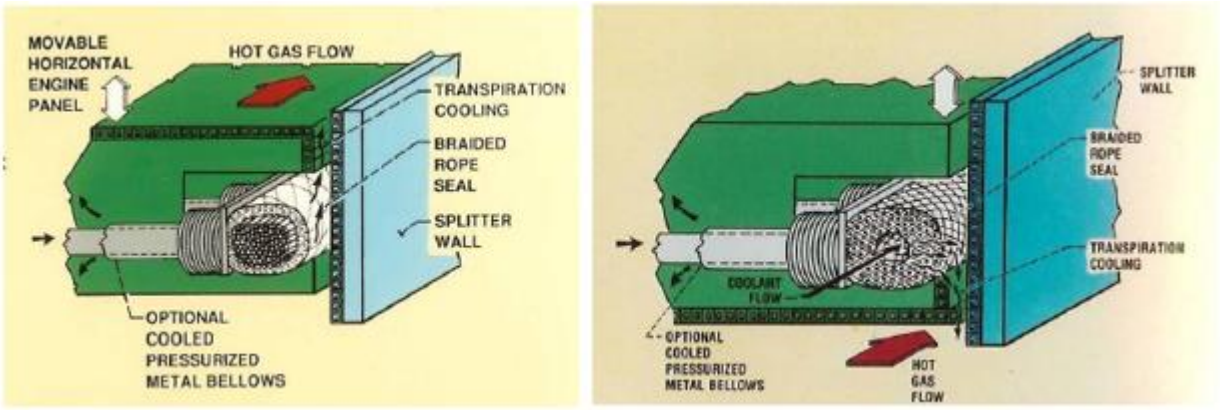

Figure 7. Diagrams of Braided Rope Seals for Use in a Ram/Scramjet Propulsion System [2].

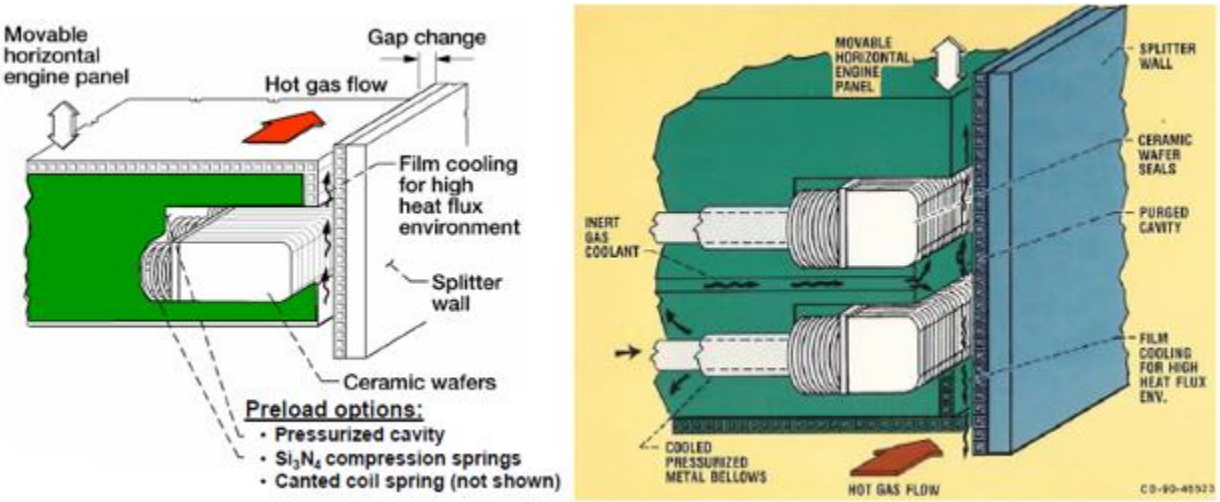

Figure 8. Diagrams of Wafer Seals for Use in a Ram/Scramjet Propulsion System [2].

Some of the issues that are encountered when using braided rope seals include:

- The ceramic fibers damage easily (a metal sheath can be used as before, but this limits useful temperatures)
- For large gap changes, a preload system is required
- Porosity is high unless a high degree of longitudinal fibers are used

Wafer seals are characterized as having:

- The potential for very high service temperatures (in excess of 2,300 °F)
- Flexibility through the sliding of adjacent wafers
- Very low leakage
- Excellent durability

Some of the issues that are encountered for wafer seals include:

- Ceramic wafers may damage very thin heat exchanger walls (this was noted to require testing in previous work)
- Ceramic wafers have a lower coefficient of thermal expansion than metals

2.6 Continued Research

NASA continues to request proposals for ultrahigh-temperature elastomer sealing materials for hypersonic/high-speed technology as part of the small business innovative research (SBIR) program. However, applications for extreme-temperature resistance include perflouroelastomers (FFKM), fluorinated elastomers, fluorosilicones, and silicone rubbers, as all cannot sustain temperatures higher than 620 °F (for FFKM). Additions to these materials, unless specifically incorporated into the molecular structure, do not address the matrix being made of a comparatively low-temperature material, meaning they are ill suited for hypersonic applications.

In 2019, the U.S. Air Force (USAF) funded research into improved designs for hypersonic seals. In particular, these focused on OML seals with all of the same performance requirements discussed in this work and also specified that electromagnetic shielding testing be performed (this particular request for proposal was a targeted SBIR topic, AF191-101 [1]). This was built upon in 2022 by a direct-to-phase-ii request for proposal (RFP). The USAF expressed a desire for the development, fabrication, and testing of advanced rope (or pillow) seals, with possible uses on hypersonic propulsion systems (the RFP mentions scramjet and rotating detonation engines).

2.7 Conclusions

There are available solutions for sealing hypersonic vehicles, but, as with many areas associated with the integration of hypersonic systems, there is significant room for improvement, at least over what is available publicly and not on a classified level. Conventional high-temperature material systems will not suffice as velocities climb past Mach 5 and will certainly not be suitable for numbers in excess of Mach 10. Research and development is continuing, both publicly available and likely under controlled unclassified information status, as well as part of classified program development programs.

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Biography

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