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High-Temperature Optical Window Design

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SUMMARY

A high-temperature optical window is essential to the optical diagnostics of high-temperature combustion rigs. Laser Doppler velocimetry, schlieren photography, light sheet visualization, and laser-induced fluorescence spectroscopy are a few of the tests that require optically clear access to the combustor flow stream. A design was deveoped for a high-temperature window that could withstand the severe environment of the NASA Lewis 3200 °F Lean Premixed Prevaporized (LPP) Flame Tube Test Rig. The development of this design was both time consuming and costly. This report documents the design process and the lessons learned, in an effort to reduce the cost of developing future designs for high-temperature optical windows.

BACKGROUND

At the beginning of any design task, it is important to break down the project into its individual pieces. In the case of a high-temperature window for the LPP Combustor Rig, there were two major components to address: first, an optical window, and second, a means of attaching the window to the combustor. Developing the design requirements for such a task was critical for producing even preliminary concepts. By defining all the necessary testing requirements, operating environments, and other pertinent boundary conditions at the outset, a list of the information that we needed for the initial design could be developed. Some of the things we needed to know were

(1) The physical geometry of the hardware into which the window was to be placed and any preferential window positioning required, both axially (in the flow direction) and radially (perpendicular to the flow direction)

The location of the window was important because it could significantly influence the window retainer design.

(2) The details of the operating environment of the combustor, including maximum temperature, maximum pressure, the temperature and pressure versus the time transient operating profiles, typical operating points, combustor chemistry (products being consumed, mass flow rates, etc.)

(3) The types of tests for which the window would be used (i.e., schlieren photography, laser Doppler velocimetry, etc.)

Each of these different tests may operate at unique optical frequency bands and have different window quality requirements. This means that the window should be optically transparent in the frequency bands at which the test equipment operates, thereby reducing any window effects on the test results. Some of these tests could require multiple windows oriented 90° apart.

For example, a light sheet visualization test requires three windows in the same plane, each located 90° from the adjacent window. A sheet of light is passed through two windows located 180° apart, and then a camera photographs the events from a window located perpendicular to the light sheet.

(4) The consequences of introducing a foreign substance into the flowstream to film-cool the window

What gases might be allowed and at what quantities? How much of a foreign substance could be introduced into the flowstream before it became a significant factor in the flow of the combustor gases?

A foreign substance introduced into the combustor may interact chemically with the gases being measured in the flowstream and adversely affect the results of the test. The chosen gas should be one that can be accounted for in the testing being performed in the combustor and one that is chemically inert to the combustor gases being analyzed.

(5) The size and shape of the window that would optimize access to the combustor

If three-dimensional mapping along the length of the combustor cross section were necessary, consideration would have to be given to a square or rectangular window instead of a more structurally efficient round window.

All of these items needed to be addressed to produce an optimized window design. If all such information can be tabulated at the onset of the design process, it greatly increases the efficiency of the design effort and, therefore, reduces the design cost and schedule. That is probably the single most important lesson learned through the development phase of the LPP Combustor Rig high-temperature window design.

Development of the LPP Combustor Window Design Parameters

The initial statement of work for developing the LPP Combustor Rig high-temperature window design requested conceptual studies of various configurations for three windows in the research rig. The LPP Combustor Rig (shown in fig. 1) is used for NO_x research experiments at temperatures as high as 3500 °F. The rig was to be modified to include optical windows for droplet size measurements, laser Doppler velocimetry, schlieren photography, and high-speed photography.

Initial design parameters.—The first step in the design process was to develop a set of design parameters. These design parameters were developed from the statement of work and from discussions with the LPP Combustor Rig research scientists and test engineers. The initial design parameters were

(1) Three-dimensional access to the entire 26.72-in.-long combustor section. (The combustor cross section is a 3.00- by 3.00-in. square.)

(2) A minimum of three in-plane viewing ports to perform the NO_x research testing

(3) A window that could withstand the maximum operating parameters of the rig: maximum combustor operating pressure, 450 psig; combustor mass flow rate, 10.0 lb/sec; and maximum combustor temperature, 3500 °F. (These design parameters were obtained from the original combustor rig engineering design report (see ref. 1).)

(4) No foreign substances could be introduced into the combustor flowstream. (The combustor gas to be tested was a mixture of jet fuel and air.)

Each of these initial design parameters except the requirement for three in-plane viewing ports was modified by the time the design process was finished. In part this was due to the research scientists' initial requirements being set very broadly in an effort to encompass every possible operating condition that might be encountered in the LPP combustor rig. But as the research scientists developed a list of actual test points to operate the rig and the design engineers began analysis of various window configurations, the design parameters were refined to make the window design technically feasible.

Modification of design parameters.—Although three-dimensional access to the entire combustor section was desired, preliminary analysis indicated that complete access with a single combustor tube was not possible. The design engineers and research scientists settled on a compromise that provided access to a limited portion of the combustor section at any one time. Complete optical access to the entire length of the combustor was available by using multiple combustor tubes with varying window axial positions.

The LPP combustor rig was originally designed for a 450-psig operating pressure, 10-lb/sec combustor flow, and a 3500 °F combustor temperature. The design engineers were unable to develop a concept for a window that could safely operate at these maximum operating conditions and still meet all the other design requirements. The research scientists then developed a list of test points with which the windows would be used. From this list of test points emerged a new set of combustor operating parameters to apply to the proposed window, which were much less severe: the combustor maximum pressure was reduced to 300 psig; the maximum operating temperature, to 3200 °F; and the combustor mass flow rate, to 3.25 lb/sec.

The third design parameter to be modified during the design process was the restriction from introducing a foreign substance into the combustor flowstream. The purpose of the optical window was to permit measurements of chemical concentrations and flow patterns within the combustor flowpath. Introduction of a foreign substance into the flow stream would taint these measurements unless this foreign substance could be accounted for in the test measurements being taken. Because film-cooling of the window offered the only viable option for dealing with the thermal gradients, the third design parameter was rewritten to state that no obtrusive foreign substance could be injected into the combustor flow stream.

A nitrogen-film-cooled window design was ultimately decided on because it would provide the safest window (see FINAL WINDOW DESIGN). Film cooling was selected because the film could be restricted to a thin layer (less than 0.150 in.) at the surface of the window. Nitrogen gas was selected as the film cooling gas because it does not react with the products of combustion forming in the combustor tube.

Optical Material Considerations

While the design parameters were being established, a parallel effort was initiated to select an optical material and to design a method for affixing the material in the combustor rig.

Material properties.—The selection of the optical material was the most significant step in the design process. Without the proper optical material, there could be no combustor window. The optical material had to be transparent within a specific wavelength band, and it had to be capable of withstanding the severe environment of the LPP Combustor Rig. To select the optimum material, certain material characteristics were defined and compared one against the other. These properties included the material's optically useful transmissivity band, Young's modulus, thermal coefficient of expansion, ultimate strength, temperature capability, and the like. These properties, along with the material's cost and manufacturing size limitations, were evaluated. Table I details some of the materials evaluated and their applicable material characteristics. Table II presents the manufacturing size limitations and the relative cost of producing an optical window of these same materials.

Effect of loading.—There are three types of loads that could affect the window stress level in this application. The first load is pressure, in which stress is simply a function of the pressure and the square of the thickness of the window (ref.2):

$$\sigma_{\mathrm{PRESSURE}} = \frac{6M}{T^2} \tag{1}$$

where M = moment, and T = plate thickness for a circular plate simply supported at the edges.

This equation shows that the window pressure stress level can be reduced by simply increasing the window thickness. The material with the highest allowable bending stress limit would be the most efficient window material if the window were exposed to pressure loading only.

The second, and more interesting, loading on the window is thermal. Thermal gradients produce thermally induced stresses within the window material. Note that for a simply supported flat plate with a linear thermal gradient through the thickness, the thermal stress is zero. In reality, a linear thermal gradient is almost impossible to obtain. Therefore, let us review the material characteristics that tend to reduce the internal thermal stress for a given thermal gradient. The equation (ref.2) for thermal stress is

$$\sigma_{\mathrm{THERMAL}} = EA\ dT$$

where E = Young's modulus, A = the coefficient of thermal expansion, and dT = the thermal gradient.

This equation shows that a material with a lower Young's modulus and a lower coefficient of thermal expansion will have a net thermal stress that is lower than that of a material with higher values for these two properties.

The third type of loading that affects the stress level within the window is the mount clamping load. If the window is affixed unevenly within a retainer, tension stresses are induced in the window even before any combustor flow is initiated. With any window material, it is important to use uniform edge compression loading in affixing the window within a retainer to minimize tension stress levels. Most optical materials have compression stress limits 5 to 10 times greater than the tension stress limits, so tension loading is important.

Optical material selection.—In reviewing table I, we can see that all four materials meet the optical transmissivity range requirement. However, table II indicates that both CVD diamond and, to a lesser extent, Spinel & Alon can be eliminated from consideration because of material size limitations. That leaves just two potential materials from which the window can be made: quartz and sapphire.

Sapphire would seem to be the superior material if useful temperature limit and material ultimate strength were the only considerations. This would be true if the window experienced only pressure loads. Quartz, however, has two interesting material characteristics that ultimately made it the material of choice for the LPP Combustor Rig application; it has both a low modulus of elasticity (one-fifth that of sapphire) and a low thermal coefficient of expansion (one-tenth that of sapphire). The equation for thermal stress (eq. (2)) produces an overall thermal stress for quartz that is one-fiftieth that of sapphire for identical thermal gradients. To compare the effect of both pressure and thermal loads, a structural analysis was performed with both sapphire and quartz used as the window material. The thermal stresses that developed in the sapphire window were so high that the quartz window, with its low tensile stress limit but lower thermal stress level, provided the highest overall minimum factor of safety for the system.

WINDOW SYSTEM DEVELOPMENT AND EVOLUTION

Several window geometries and cooling schemes were considered before the final LPP window design evolved. The details of each concept are not what is important; what *is* important are the problems that each design presented and how each of these problems was resolved to eventually obtain the final LPP combustor high-temperature window design. Each concept had good and bad features; the good features were continued to each successive design, and the bad features were redesigned for improved performance.

First Design

One of the original requirements was that full access to the combustor be provided without disturbing the combustor flow. The logical initial concept was, therefore, a tube made from an optically clear window material, with the internal geometry of the tube matching the combustor flowpath geometry. The optical tube would be externally air-cooled to reduce the effective temperature of the tube. Sapphire was chosen as the optical material because of its high melting point, since external air cooling could bring the maximum window temperature down only a few hundred degrees Fahrenheit. With the combustor flow at 3500 °F, some type of cooling was required or the sapphire tube would melt. A very elementary analysis of this type of system pointed out two problems: (1) the thermally induced stresses in the tube greatly exceeded the material strength, and (2) a sapphire tube was very expensive to manufacture. There were no known materials that could be substituted for sapphire and yield acceptable results, so this design was eliminated. We learned from this concept that three individual windows spaced 90° apart were required to meet the combustor testing requirements. A single 270° or 360° window could not survive the severe operating environment unless there were a significant advancement in the development of optical materials.

Second Design

The next design proposed was three individual window assemblies located 90° apart. Each window assembly consisted of a double-walled sapphire window that was air-cooled to reduce the temperature of the window and the metal window retainer (see fig. 2). The size of the window assembly was determined by the combustor flowpath geometry and window fixture requirements. High-pressure air would be passed between a thin, inner sapphire window and a thicker, outer sapphire window. A more effective heat transfer medium (i.e., water) was considered, but the optical distortion resulting from passing a laser or camera image through a turbulent water flow was deemed unacceptable. The thin inner window would be designed to carry the thermal load, whereas the thick outer window would carry only the pressure load.

This design was evaluated and a few problems were found. First, the inner window relied on the combustor's ceramic liner to maintain its position. One basic problem with ceramics is that they are very weak if loaded in tension or bending. The loads on the inner window were low, but not low enough for the ceramic liner to handle. Experience with ceramic liners has shown that ceramics tend to erode and fall apart over time when subjected to only LPP Combustor Rig thermal loads. Additional tension loads resulting from the forces applied by the window assembly would just aggravate the ceramic decay problem. Second, a double window would present twice as many refractive surfaces for the light beam as a single window would. From Snell's law (ref. 3), we know that as a light beam encounters a window surface, it is refracted because the index of refraction of the air is different from that of the window material. The more refractive surfaces that the optical beam encounters, the more optical distortion there is, and therefore, the less possible it becomes to accurately map the combustor flow. Third, the air could not provide enough cooling to maintain sufficiently low temperatures in the metal window retainer. And finally, the window assembly was not modular and, therefore, would require extensive assembly and disassembly time. Each window would have to be assembled on the combustor test rig versus being independently assembled on the bench and installed as a module into the combustor rig.

As this window system was being developed, a couple of other important features that were needed in the design were being explored. One was the need for some type of high-temperature sealing material, and the second was a need for a ceramic coating to protect the metal window retaining structure from the high-temperature combustor gas. The research work done in these two areas resulted in selection of a high-temperature (Grafoil) gasket, which could seal in environments (nonoxidizing) as hot as 5000 °F, and a zirconium oxide coating, which would serve as an excellent thermal barrier or insulator between the metal window retainer and the combustor flow.

Third Design

The next design concept was a combined air- and water-cooled double-walled sapphire window assembly module (fig. 3). This concept eliminated some problems of the previous design (e.g., it used water cooling to reduce the window retainer metal temperatures to acceptable limits and offered a modular design, which made bench assembly and disassembly easy). However, some of the previous problems persisted; a double-walled window would still produce higher optical distortion, and the external air cooling to the inner "hot" window would not adequately reduce the thermal stress levels of the window. The concept of a doubled-walled window was just not going to work without a super window material (which currently did not exist). This design did provide some usable ideas, such as modular assembly and water cooling as an adequate method of maintaining acceptable window retainer metal temperatures. (See ref. 4 for additional details on all the preceding window design concepts.)

Final Solution

Because of the major problem of maintaining acceptable window thermal stress levels, we decided to investigate the designs of other high-temperature components that were able to survive extremely high-temperature and high-pressure environments. Turbine airfoils are a good example. In modern, high-efficiency, high-temperature turbine airfoil designs, a film of a cooling gas is applied to the external surface of the component to shield the blade or vane from the extremes of the environment. We decided that this idea could be used to shield the combustor-exposed surface of an optical window and still allow the combustor mapping to be performed without a major impact on the results. In order for this idea to work in this combustion application, the cooling gas would have to have a minimized mass flow rate, be nonreactive with the combustor flow, and stay close to the window surface (i.e., not penetrate the gas stream where the combustor mapping was taking place). We proposed this concept to the research scientists, who accepted it as being the only viable solution to the problem. The research scientists then established a maximum allowable mass flowrate for the cooling gas film at all the windows assemblies in the combustion rig: It could be no larger than 10 percent of the minimum expected combustor mass flowrate.

FINAL WINDOW DESIGN CONSIDERATIONS

Film Cooling

A design concept with a film-cooled window was developed. A cooling gas would be injected into the combustor flowpath just upstream of the window, thereby shielding the window from the severe combustor environment. Because of the need to prevent disturbance to the combustor flow, only a small amount of a nonreactive gas would be used, and the gas would be introduced into the flowpath parallel to the combustor flow to minimize penetration into the combustor flowstream.

Selection of A Cooling Gas

Three different cooling gases were considered: air, argon, and nitrogen. Air was reviewed first because it was available in the test cell at high pressure and was relatively inexpensive. However, air contains many different elements and some of these elements could react with the products of combustion flowing down the combustor. Thus, the use of air as the cooling gas for the window was rejected. Argon was considered next because it is an inert gas and, therefore, would not react with the products of combustion within the combustor. However, in the quantities required to cool all three window assemblies, argon would be too expensive. Finally, nitrogen was considered and ultimately chosen as the cooling gas for the windows. Nitrogen, although more expensive then air, is relatively inexpensive and was already available in the test cell at high pressure. Furthermore, nitrogen, as a single element, could be accounted for in the combustor testing being done with these optical windows.

Final Optical Material Selection

Not only was the type of cooling gas film a concern but also the type of window material. As explained in the optical material considerations section, the material of choice for this design was narrowed down to either sapphire or quartz. If the thermal gradients within the window material could be almost completely eliminated, then sapphire would be the material of choice because of its high strength. But if thermal gradients did exist, then quartz might prove a better choice because its mechanical characteristics tend to reduce the effect of thermally induced stresses. A detailed thermal and stress analysis, in which both sapphire and quartz were used as the window material, was performed to determine which material would produce the window with the highest operating factor of safety. Both steady-state and transient thermal and pressure data were used to ensure that the materials were analyzed under the worst-case operating conditions. The minimum factor of safety for the quartz window was found to exceed that of the sapphire window by a factor greater then two. The details of the quartz window analysis are described in reference 5.

The combustor window design was influenced more by thermal loading then by pressure loading. Even though the window would be actively cooled by a film of nitrogen gas, the mixing of the nitrogen with the combustor gas as the flow progressed down the surface of the window would generate a thermal gradient within the window. The leading edge of the window (furthest point upstream in the combustor) would be substantially cooler than the downstream edge because the hot and cool gases would be mixing at the surface of the window within the combustor. This mixing problem could be eliminated by injecting a substantially higher amount of film cooling gas into the combustor, but a higher volume of cooling gas would definitely affect the combustor mapping test results. This leading- to trailing-edge thermal gradient also affected the geometry of the final quartz window design.

As the length of the window was increased in the combustor flow direction, the thermal gradient across the window surface increased similarly. If the window were made to be too long, the thermal gradient would be too high for even the quartz material to survive. Thus, the window length was optimized at 1.5 in. long on the basis of the operating conditions of the LPP Combustor rig and the minimum factor of safety that the design engineers and research scientists found acceptable.

AS-BUILT WINDOW DESIGN

Figure 4 shows the final design of the high-temperature window assembly for the LPP Combustor Rig. It is a single film-cooled window retained by a water-cooled window jacket. This design was the result of incorporating all the good features of each of the previous design concepts with the idea of film cooling the hot-gas-exposed window surface; thus a workable, manufacturable, and economically feasible design was created. The window assembly was sized to optimize combustor access. The window itself is rectangular, and the retainer is angled to permit viewing of the combustor flowpath corners. The window's length was optimized in the combustor flow direction, as explained previously, and in the combustor cross-sectional direction as permitted by the physical hardware constraints of the combustor flowpath cross section. The thickness of the quartz window was set to provide an adequate factor of safety based on pressure, thermal, and mounting loads.

Nitrogen Film Cooling Supply Case

The supply case for the cooling nitrogen film was designed to offer optimum film cooling to the window, with additional nitrogen flow capability available if future testing should require higher flowrates. The cooling gas is to be injected parallel to the combustor flow approximately 1.000 in. upstream of the window so as to reduce the thermal gradient across the surface of the window. During the analysis of the thermal distributions across the window surface, the thermal gradient in the window was found to be slightly higher if the cooling gas was injected into the combustor at the leading edge of the window surface rather than slightly upstream of the leading edge.

Water-Cooled Window Jacket

Although the window jacket's primary function is to retain the quartz window, it was designed with a cooling scheme that optimizes the cooling at the point where the heat load is greatest. In the area directly exposed to the combustor flowpath, the velocity of the cooling water's flow was maximized to maximize the heat transfer from this area. A zirconium oxide coating was added to the combustor-gas-exposed surface to add additional thermal protection.

Other Features

Between the window jacket and the quartz window is a thin layer of Lytherm ceramic paper. This material acts both as a cushion between the fragile quartz window and the metal housing and as a thermal barrier between the window and the housing. This thermal barrier is important because the window's thermal stress would be increased if the window were being cooled along all four edges by the water-cooled window jacket. Other important features incorporated into the window assembly design include a high-temperature (Grafoil) gasket to seal the window to the window retainer, and a zirconium oxide coating on the metal window assembly components to provide a thermal barrier between them and the combustor gases. All the metal components directly exposed to the combustor flow are made of Waspaloy. This material was chosen for its superior strength at elevated temperatures. It will allow the window assembly to survive in the LPP Combustor Rig environment for a short period of time even if the zirconium oxide coating spalls off during the operation of the combustion rig.

Combustor Housing

The last significant feature of the window design is that the combustor housing, which contains the window assemblies, was designed to optimize combustor viewing. To accomplish this, the combustor tube was designed so that the aft combustor flange was a separate piece; thus, the flange diameter and flange bolt pattern of the combustor tube are identical on both ends. By simply unbolting the combustor at both ends and flipping the combustor tube axially, two different window axial positions can be viewed with the same combustor tube housing. If the combustor were flipped, though, the ceramic liner inside would have to be replaced because the window assemblies within the combustor tube would need to be rotated to allow the nitrogen to flow downstream across the window surface. The cost of these modifications would be minimal compared to the cost of machining another combustor tube.

All the information reported herein about the final window design is explained in greater detail in reference 5.

CONCLUDING REMARKS

A relatively large, three-dimensional optical access to a high-temperature high-pressure combustor had never previously been achieved. Before such a window could be designed, a system was needed that would operate safely in a high-pressure high-temperature combustion environment. In addition, this system had to meet all the requirements set forth by the combustion research scientists at the NASA Lewis Research Center. This report documents the design of such a window. It is our hope that it will serve as a starting point for future high-temperature window designs and that the time spent performing this task can be time saved by design engineers in the future.

REFERENCES

1. Jensen, F.C.: Engineering Report, Fuel Vaporization Test Rig, CE-5B, ERB. December 1978. NASA Lewis Research Center internal document.
2. Young, W.C.: Roark's Formulas For Stress And Strain, Sixth Edition, McGraw-Hill Book Company, 1989.
3. Avallone, E.A.; and Baumeister, T.: Mark's Standard Handbook for Mechanical Engineers, Ninth Edition, McGraw-Hill Book Company, 1987.
4. Roeloffs, N.F.: Conceptual Engineering Report, 3500 °F Fuel Vaporization Rig or 3500 °F Lean Premixed Prevaporized (LPP) Flame Tube Test Rig, NASA Contract NAS3-25767, Task Order 36, April 1990. NASA Lewis Research Center internal document.
5. Roeloffs, N.F.: Engineering Report, CE5 LPP Combustion Rig High Temperature Window, NASA Contract NAS3–25767, Task Order 85, August 1992. NASA Lewis Research Center internal document.
6. Crystal Systems Catalog: HEM Sapphire, Crystal Systems Co; 27 Congress St. Salem, MA., 1970.
7. Hartnett, T.M.; and Gentilman, R.L.: Optical and Mechanical Properties of Highly Transparent Spinel and Alon Domes, SPIE, Vol. 505, Advances in Optical Materials, 1984.
8. Corning Technical Products Division Catalog: Fused Silica, Corning Glass Works, Corning, New York, August 1991.
9. Clay, R.D.; and Clay, J.P.: Diamond For Optical Material, SPIE, Vol. 505, Advances in Optical Materials, 1984.

TABLE I.–COMPARISON OF OPTICAL MATERIAL PROPERTIES

Material	Optical transmissivity band (≥ 80 percent), μm	Melting point, °F	Maximum useful temperature, °F	Young's modulus, E, psi	Thermal coefficeint of expansion, α	Poisson's ratio	Ultimate strength at 70 °F, psi	
							Compression	Tension
Sapphire (ref. 6)	0.25 to 4.5	3727	2500 to 3000	51×10^6	5.3×10^{-6}	0.29	350 000	[a]60 000
Spinel & Alon (ref. 7)	0.30 to 5.0	3884	————	40×10^6	5.6×10^{-6}	0.24	390 000	16 000
Quartz (ref. 8)	0.18 to 3.3	3146	1800 to 1900 (strain point)	10×10^6	5.3×10^{-7}	0.165	166 000	7 100
CVD diamond (ref. 9)	N/A	——	2192	142×10^6	7.2×10^{-7}	0.20	N/A	387 000

[a] At 932 °F, ultimate tensile strength = 39 000 psi.

TABLE II.–OPTICAL MATERIAL PRODUCIBILITY AND COST COMPARISON

Material	Producibility size limitations		Relative cost
	Diameter, in.	Thickness, in.	
Sapphire	8.0	7.0	high
Spinel & Alon	5.0	0.20	high
Quartz	40.0	4.0	low
CVD diamond	0.158	——	very high

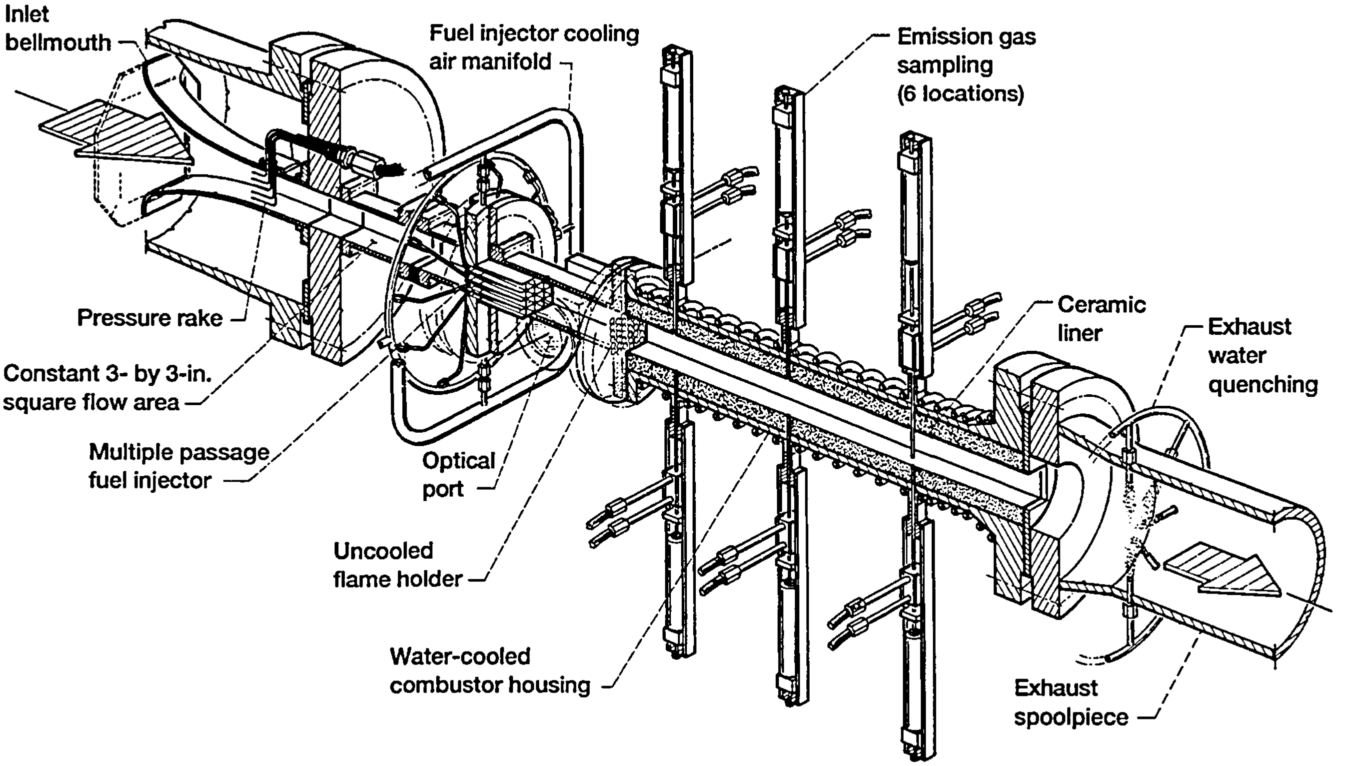

Figure 1.—Lean Premixed Prevaporized Combustor.

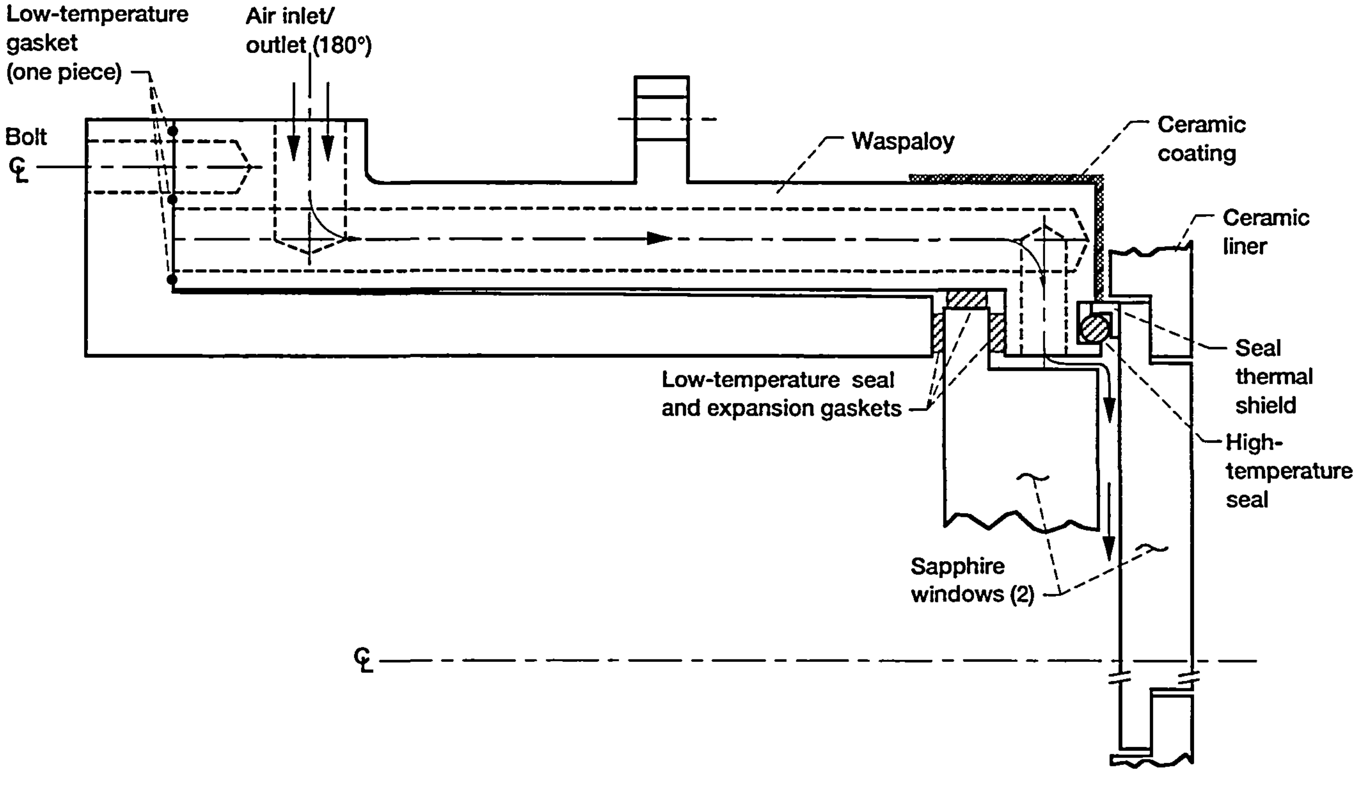

Figure 2.—Air-cooled window assembly (window viewing area ≈ 2.00-in. diam).

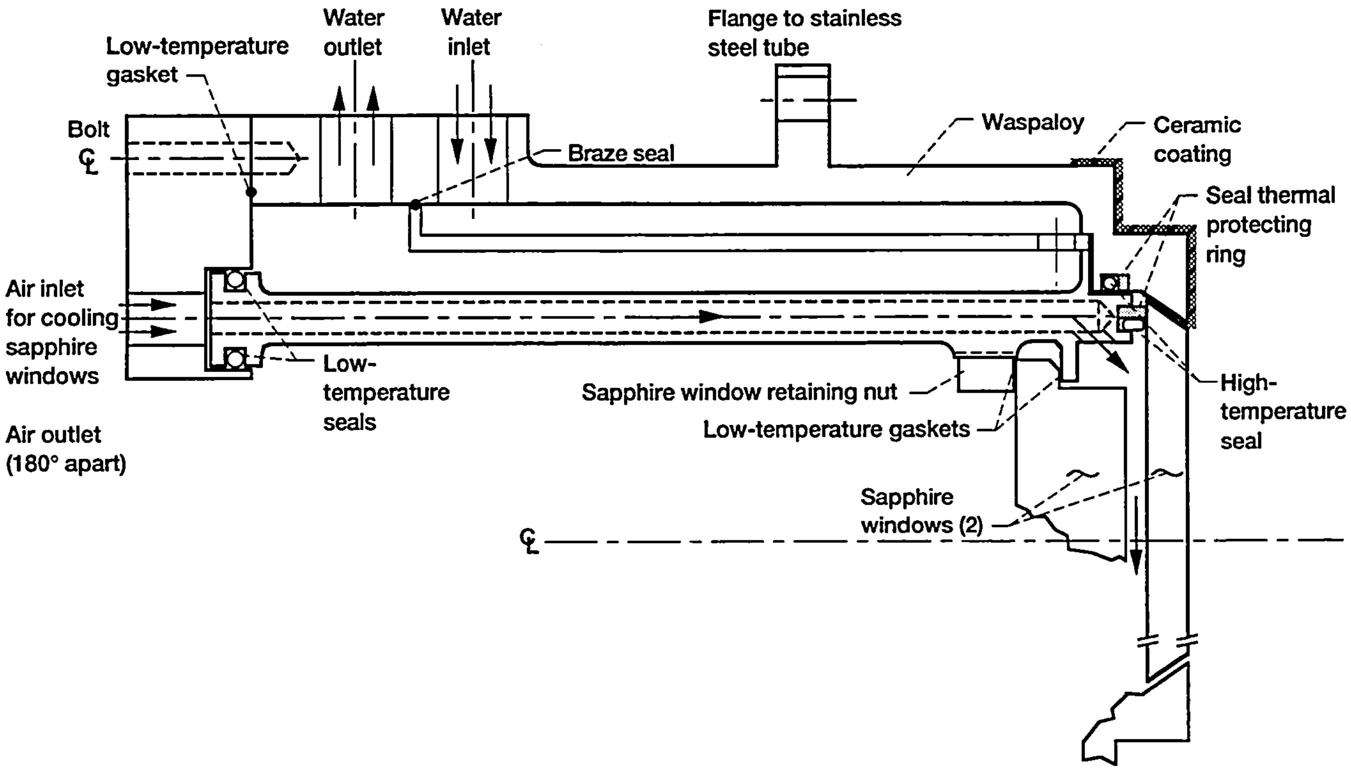

Figure 3.—Water- and air-cooled window assembly (window viewing area ≈ 1.20-in. diam).

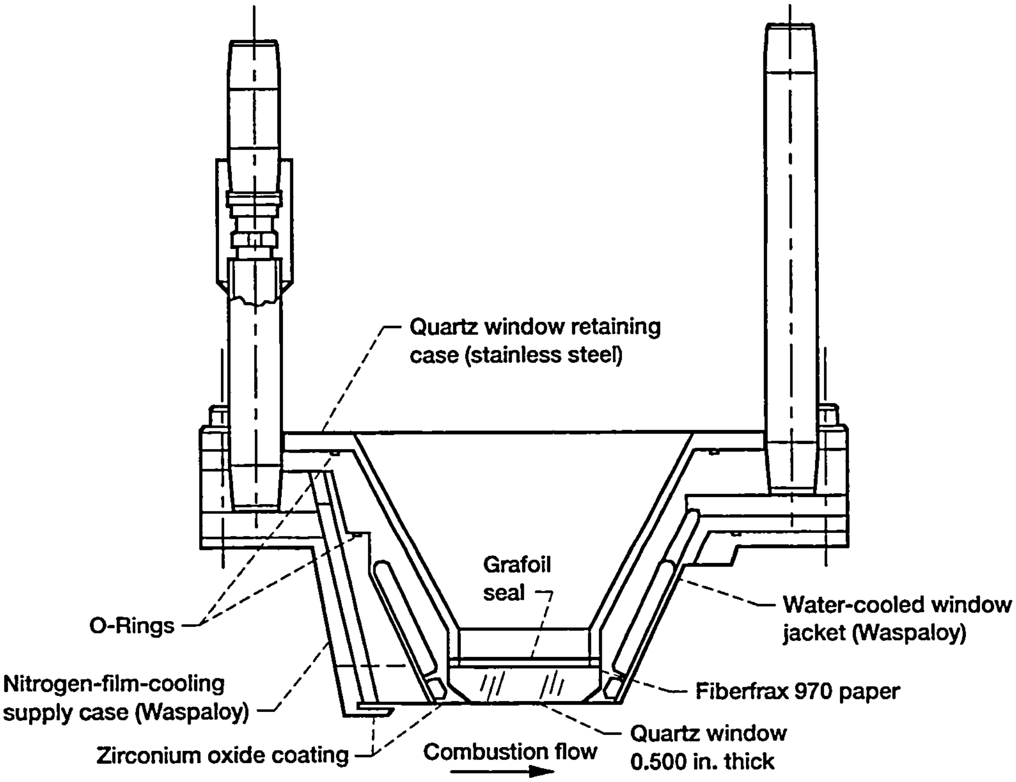

Figure 4.—Quartz window assembly.

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11. SUPPLEMENTARY NOTES

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