NOVEL CERAMIC RECEIVER FOR SOLAR BRAYTON SYSTEMS*

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ABSTRACT

Substantial progress is reported in the development of a high-temperature heated-air cavity receiver during the first six months of the DOE-sponsored advanced development program. Mechanical dome sealing methods are selected as the preferred sealing approach and a free-standing hemispherical dome contact-type seal and a clamped shallow dome seal are chosen for preliminary design, analysis, and fabrication. Analytical and experimental investigations establish the technological foundation of the seal concepts by demonstrating that ceramic domes can be designed to support the combined pressure, thermal stress, and temperature loads of a heated-air receiver, that a mechanical contact seal with a leak rate which is two orders less than the design goal leak rate is feasible, and that metalization of ceramics and the formation of an alternative brazed diaphragm seal are possible.

INTRODUCTION

Studies of advanced receivers for solar thermal heated-air Brayton power systems have been underway at MIT/Lincoln Laboratory since 1975 and have shown that the ceramic domed cavity receiver concept is a promising approach for central receiver systems. Development of the novel ceramic receiver concept, which heats pressurized gas to 1800°F (1000°C) for use with gas turbine units, has been proceeding under Department of Energy sponsorship since May 1978. An application of the concept is shown in Figure 1.

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FIGURE 1. CONCEPT FOR A 1-MW, SOLAR HEATED-AIR, CERAMIC-DOME, CAVITY RECEIVER.

Principal tasks to be accomplished during the year include (1) studies to establish the technical performance, economics, and scaling parameters of ceramic domes and heated-air receivers and (2) the development and experimental demonstration of receiver dome sealing methods.

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This paper summarized accomplishments during the first six months of the advanced development program to develop a high-temperature seal. Discussions are included on seal concepts, ceramic materials, ceramic dome stresses, metalization of ceramics, selection of a preferred sealing approach, and experimental leak tests of a mechanical contact seal.

Solar Heated-Air Cavity Receiver Concept

The essence of the heated-air ceramic domed receiver is shown in Figure 1 which illustrates the application of domed ceramic elements to form the walls of a 1 MW bench model-size receiver. Application of the ceramic dome concept to commercial-size central receivers and to dispersed dish/receiver systems are shown in Figures 2 and 3 respectively.

FIGURE 2. CONCEPT APPLIED TO A COMMERCIAL-SIZE CENTRAL RECEIVER.

FIGURE 3. POINT FOCUS CERAMIC DOME RECEIVER.

In this approach, the ceramic domes face convex-side outward from the cavity towards the pressure forces created by the airflow which is to be heated (see insert on Figure 1). The domes carry the pressure loads by going into overall compression; a preferred

condition for ceramic materials. The concave sides of the domes face toward the interior of the cavity and are heated by concentrated sunlight entering through the cavity aperture. Heat is conducted through the dome walls and is absorbed into the airflow through an impingement heat transfer scheme which utilizes numerous impinging air jets directed inward against the convex side of the domes. The heated air is then collected in manifolds located about the periphery of the dome and piped to the turbine where mechanical work is generated and electrical energy produced.

The advantages of the ceramic receiver approach include the ability to heat pressurized gases directly without the need for intermediate heat exchangers, the use of impingement heat transfer methods and the utilization of ceramics in compression to support the pressure loads.

High-Temperature Seals

Mechanical dome sealing methods were selected as the preferred sealing approach after a review of previous high-temperature seal studies, consideration of the progress made in the present program with respect to experimental leakage measurements on sub-scale mechanical seals and the development of techniques for metalization and brazing of ceramics, and appraisal of competing seal concepts such as direct bond and compliant ceramic-to-ceramic glass seals and direct bond and compliant ceramic-to-metal seals.

Mechanical seal approaches present undergoing detailed examination are shown in Figures 4 and 5, and consist of hemispherical dome forms with contact type or brazed diaphragm seals and shallow dome forms with clamp edges respectively. In the contact seal arrangement, a freely supported hemispherical silicon carbide dome is mounted on a ceramic insulating ring and the contact area between the dome and ring provides the primary high-temperature seal. A pressurized metal O-ring under the insulating ring provides a low-temperature seal between the ring and the metal support structure.

FIGURE 4. FREE HEMISPHERICAL DOME WITH CONTACT OR DIAPHRAGM SEAL

FIGURE 5. CLAMPED SHALLOW DOME SEAL

The freely supported dome may expand independently of the insulating ring as the receiver heats up thus allowing dissimilar ceramic materials to be used across the free-contact seal without the generation of temperature stresses. The pressure forces acting on the dome provide the contact seal seating loads and the leak rate through the annular contact area is controlled by selection of the surface finishes on the two ceramic surfaces which touch. The insulating ceramic ring drops the temperature from the operating dome temperature of 2000°-2200°F to the 1600°-1800°F temperature range required by the metal O-rings and the metal structure. The diaphragm seal is also being considered as a way to obtain the primary seal in the hemispherical dome geometry. Here, a seal is assured by brazing a metal diaphragm between the ceramic dome and the surrounding metal structure. The objective of the experimental program is to demonstrate a seal on a one-foot diameter dome under dome operating conditions of 1100°C temperature and 4 atmosphere pressure.

The analytical and experimental program undertaken at MIT/Lincoln Laboratory to develop the technological foundation for the seal concepts will now be reviewed. To date, we have been able to show that ceramic domes can be designed to support the combined pressure, thermal stress, and temperature loads expected in a heated-air receiver, a mechanical contact seal with a sufficiently low leak rate is feasible and metalization and brazing techniques required for the diaphragm seal are possible.

Ceramic Materials

Silicon carbide has been selected as the dome material while silicon carbide (SiC), aluminum oxide (Al_2O_3) and mullite are under consideration for the insulating ceramic ring. Two versions of SiC with high thermal conductivity and superior modulus of rupture at elevated temperature (Table I) are being used in the experimental program; one is a siliconized SiC which may be operated satisfactorily in air to a maximum temperature near 2400°F, and the other, a chemical vapor deposition (CVD) SiC which potentially can be operated to 3000°F. Aluminum oxide and mullite have superior insulating qualities than SiC with thermal conductivities near $K=8$ and $K=3$ Btu/ft² hr (°F/ft) respectively at 1200°C.

THERMAL CONDUCTIVITY AND MOR OF SiC MATERIALS (1200°C)

	NORTON NC-430	NORTON NC-435	MITC CVD SiC
K BTU/FT ² HR (°F/FT)	18	—	12
MODULUS OF RUPTURE (MOR) (KSI)	38-52 (3 POINT)	68 (4 POINT)	52-68*

* MATERIALS TECHNOLOGY CORPORATION

† ESTIMATE BASED ON GARRETT CORPORATION BURST TESTS OF CVD SiC TUBES

TABLE I

Ceramic Dome Stresses

Both analytical and finite element analyses were used to determine the stresses in dome units subjected to combined pressure, thermal stress and temperature stress loadings for a variety of dome edge conditions (Figure 6).

FIGURE 6. DOME EDGE CONDITIONS CONSIDERED

An example of the combined pressure and thermal stresses in a 1/8-inch thick, 12-inch hemispherical dome with free edges as predicted by the analytical methods is shown in Figure 7 with variations in dome compressive and tensile stresses illustrated as a function of polar angle θ . These calculations assume a 4-atmosphere pressure differential across the dome and a temperature gradient through the dome for conduction of heat of 400°C/inch. For this case, the maximum tensile stress in the dome is 9000 psi and occurs in the hoop direction on the outside of the dome at its edge; $(\sigma_{\theta})_{\theta=0}^{\text{top}} = 9000 \text{ psi}$.

$$\theta/\theta_{\text{max}} = 1$$

FIGURE 7. TOTAL PRESSURE AND THERMAL STRESSES IN A 12-INCH HEMISPHERICAL SiC DOME WITH FREE EDGES

The maximum stress levels in SiC hemispherical and shallow dome shapes with free and clamped edge conditions for three dome thicknesses, 1/16, 1/8 and 1/4 inch, and three dome spans, 6, 12, and 36 inch, are summarized in Table II. General trends observed in Table II for a free hemispherical dome seal configuration include a decrease in the total stress as the dome thickness is decreased or as the dome span is increased; the first effect is due to a lowering of the thermal stress and the second effect is due to an increase in the compressive pressure component of the total stress. Also, a clamped shallow dome is seen to have the lowest stress of all configurations examined.

SiC DOME STRESSES					
DOME THICKNESS (INCHES)	DOME SPAN (INCHES)	HEMISPHERICAL DOME		SHALLOW DOME $h/b \approx 0.2$	
		CLAMPED	FREE (TROLLEY)	CLAMPED	FREE (TROLLEY)
1/16	6	+2,400	+3,900	+1,950	+24,000
	12	+1,000	+2,500	- 100	+64,300
	36	-4,900	NC*	-8,800	NC*
1/8	6	+9,700	+10,000	+9,400	+15,500
	12	+6,500	+9,000	+5,950	+28,700
	36	+3,900	+5,800	+1,700	+118,000
1/4	6	+15,700	+20,500	+15,400	+20,000
	12	+14,600	+20,000	+14,300	+24,900
	36	+12,800	+19,000	+11,900	+54,500

* Ratio of dome mid-height to span.
* Not calculated.

Note: Plus sign (+) indicates tensile stress and minus sign (-) indicates compressive stress.

TABLE II

The free standing hemispherical dome seal and the clamped dome seal concepts, previously shown in Figures 4 and 5, were selected for design, fabrication and test after a review of the predicted stress levels summarized in Table II. The hemispherical dome unit which will be fabricated in a 12-inch diameter size and a 1/8 inch wall thickness should see in use a maximum stress of 9000 psi while the clamped shallow dome of similar size and wall thickness should see 5950 psi. Since maximum dome stresses are in the range from 6000 to 9000 psi while the modulus of rupture of the candidate SiC dome materials are in the range from 38,000 to 68,000 psi, satisfactory design margins of safety are guaranteed.

Mechanical Seal Leak Tests

Experimental leak rate measurements of a mechanical contact-type seal have been made using the high temperature leak test fixture shown in Figure 8; the design goal for the seal of the ceramic dome receiver being a leak rate of one percent (or less) of the total heat transfer airflow impinging on the dome. The 2-inch diameter free-contact seal hardware was utilized in the leak rate test fixture shown in Figures 8 and 9. Initially, the dome receiver/seal geometry was modeled by a ceramic disk supported on a short section of ceramic tube. Subsequently, the flat disk was replaced by shallow ($H/B = 0.20$) and hemispherical dome units (Figure 10). The leak rate through the annular contact seal between the disk and the tube was measured for different surface finishes on the ceramic parts and as a function of the air pressure which forces the disk against the annular seat. Measurements of the variation of leakage versus gas temperature were accomplished by placing the leak test fixture inside a radiant furnace unit.

FIGURE 8. HIGH TEMPERATURE LEAK TEST FIXTURE

FIGURE 9. CROSS-SECTION OF THE LEAK TEST FIXTURE

FIGURE 10. HEMISPHERICAL DOME/SEAL UNIT

The leakage rate formula for flat metal contact seals is given by:

$$Q_c \propto \frac{H^N D}{\mu L T S^{3/2}} \quad (1)$$

where Q_c = leakage rate
 H = surface roughness
 D = mean seat diameter
 μ = viscosity of the leakage gas
 L = radial seat land width
 T = gas temperature
 S = apparent seat stress
 N = exponent = 3.0 for metal seals
 = 1.6 (measured on ceramic seals)

This formula was validated experimentally for ceramic to ceramic contact seals by measuring the effects of surface roughness and gas temperature. The leak rate was found to vary with surface roughness as H^N where $N=1.6$ for ceramic seals and to vary with gas temperature as expected i.e. $Q_c \propto T^{-1.56} = (\mu T)^{-1}$ (Figure 11). Experiments are presently underway to validate the leakage formula for the effects of seat stress.

FIGURE 11. VARIATION OF LEAK DATA WITH TEMPERATURE AT 4 ATMOSPHERE PRESSURE - 2" OD SEAL

Experimental data taken on 1 7/8" OD ceramic contact seals have been extrapolated to 12" diameter domes operating at 1800°F gas temperature using Equation 1 and the results are shown in Figure 12. Two results are immediately evident in Figure 12. First the leakage on the smaller seals is already two orders of magnitude lower than the design goal and second, the expected leakage rate on 12" diameter contact seals is at least 3 orders of magnitude less than the goal.

FIGURE 12. HIGH TEMPERATURE SEAL LEAKAGE VERSUS DOME DIAMETER

Metalization of Ceramics

Experimental studies of the metalization of SiC, Al_2O_3 and mullite and the adherence of the metalized layer to the ceramic when raised to elevated temperature conditions are being carried out as part of the high-temperature seal program. Metalization of ceramics allows a number of design options to be realized including the brazed diaphragm seal. Vacuum sputtering has been used in the present investigation to coat the ceramic parts and the ceramic/metal combinations shown in Table III have been prepared and tested. Each metalized coupon is tested by heating it in a furnace to a maximum temperature which is raised incrementally between tests. The sample is inspected and photographed after each temperature cycle and microscope enlargements are taken of edge boundaries between the ceramic/metal and metal/metal coatings.

CERAMIC/METAL COMBINATIONS

CERAMIC MATERIAL	METAL COATING			
	TUNGSTEN	NIOBUM	NICKEL	RHODIUM
SiC	X X X		X X	X
Al_2O_3		X X	X X	
MULLITE	X X		X	

TABLE III

The main thrusts of the program have been to investigate metal/ceramic couples in which the coefficients of thermal expansions of the ceramics and metalization are nearly matched (e.g., tungsten on SiC and mullite or niobium on Al_2O_3) and to study the adherence of subsequent metal coatings added to improve oxidation protection (e.g., nickel or rhodium on tungsten) or to facilitate the use of conventional aerospace-type nickel-alloy-braze materials, (e.g., nickel on tungsten).

Metalization of SiC coupons with tungsten has been quite successful with good coating adherence at room temperature and continued adherence when heated in 200°C temperature increments from 600° to 1400°C (1100°-2500°F). The appearance of a 2-inch diameter tungsten-coated disk after the 1200°C temperature cycle is shown in Figure 13. An enlargement of a circular area of that disk is shown in Figure 14 and excellent adherence between the tungsten metal and the silicon carbide is noted. The adherence is displayed with particular clarity along the circular boundary of the tungsten coating.

FIGURE 13. TUNGSTEN COATED SiC DISK AFTER 1200°C (2200°F) CYCLE

FIGURE 14. ENLARGEMENT OF THE TUNGSTEN/SiC INTERFACE 1200°C (2200°F)

The initial metalization of tungsten on SiC has also been overcoated successfully with an oxidation protection metal coating which too has shown good adherence at room temperature and when heated incrementally to 1000°C (1800°F). Figure 15 is a photograph of 1/2-inch square tungsten and nickel/tungsten coated SiC coupons after the 1000°C furnace cycle. The nickel coating covers the right half of the sample and examination of the vertical nickel/tungsten boundary shows excellent coating adherence. SiC coupons with tungsten/nickel coatings have been successfully brazed together to form tensile test specimens with aerospace-type AMS-4783 braze at a brazing temperature of 2150°F (Figure 16). Braze remelt temperatures of such joints may be raised to 2400°F through the use of heat treatment techniques.

FIGURE 15. TUNGSTEN AND TUNGSTEN/NICKEL COATED SiC COUPONS AFTER THE 1000°C (1800°F) FURNACE CYCLE

FIGURE 16. BRAZED SiC JOINT

CONCLUSIONS

The technology required to implement high-temperature mechanical seal concepts for a solar heated-air receiver has been demonstrated through a combined analytical and experimental program. The stresses in the dome structures due to pressure and thermal stress have been shown to be low in comparison to the flexural strengths of the candidate SiC materials. Experimental leak rate tests on ceramic contact seals have found leak rates which are two to three orders of magnitude lower than the design goal leak rate; thus establishing the feasibility of that approach. Metalization and brazing of SiC has also been demonstrated and appears to be an attractive way of obtaining a zero leak rate, diaphragm type seal.