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SOLAR HEATED-AIR CAVITY RECEIVER DEVELOPMENT (SHARE)*+

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Abstract

Studies of advanced receivers for solar thermal heated-air Brayton power systems have been under way 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. The advanced development program is focused on the solution of technologically pacing items in the receiver; for instance, the development of a high-temperature seal between the pressurized air and high-temperature ceramic dome material. The paper discusses progress made on a number of elements in the development program including ceramic dome stress calculations, metalization of ceramics, selection of a preferred receiver/dome sealing approach, and mechanical seal leak measurements. The continuing experimental program to develop and demonstrate seals on ceramic domes to one-foot diameter is described.

Introduction

Since May 1978, MIT/Lincoln Laboratory has been developing a novel concept for a solar heated-air receiver for central receiver plants under DOE contract ET-78-S-02-4878.A000. Funding of $249,680 has been provided for the year ending 1 May 1979. Principal tasks to be accomplished during the year contract 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.

This paper summarizes 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, experimental leak tests of a mechanical seal, and the experimental program which is planned for the next six-month period.

Schedule

The solar heated-air receiver (SHARE) development program tasks and schedule are summarized in Table 1. Subtasks 1, 3, 4, and 5 entitled:

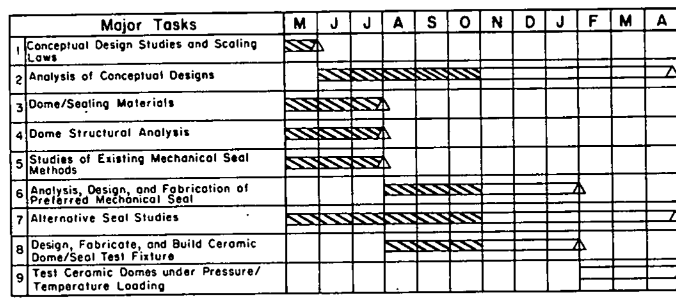
1. Conceptual Design Studies and Scaling Laws
3. Dome/Sealing Materials
4. Dome Structural Analysis
5. Studies of Existing Mechanical Seal Methods

have been completed. The program is on schedule with work continuing on subtasks 2, 6, 7, and 8:

2. Analysis of Conceptual Designs
6. Analysis Design and Fabrication of Preferred Mechanical Seals
7. Alternative Seal Studies
8. Design, Fabricate, and Build Ceramic Dome/Seal Test Fixture.

Table 1

Schedule and Major Tasks for Solar Heated-Air Cavity Receiver Development (SHARE)



Solar Heated-Air Cavity Receiver Concept

The essence of the heated-air ceramic domed receiver is shown in Fig. 1 which illustrates the application of domed ceramic elements to form the walls of a 1-MW$_t$ bench model-size 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 (insert, Fig. 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 (Fig. 1).

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

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DISCLAIMER

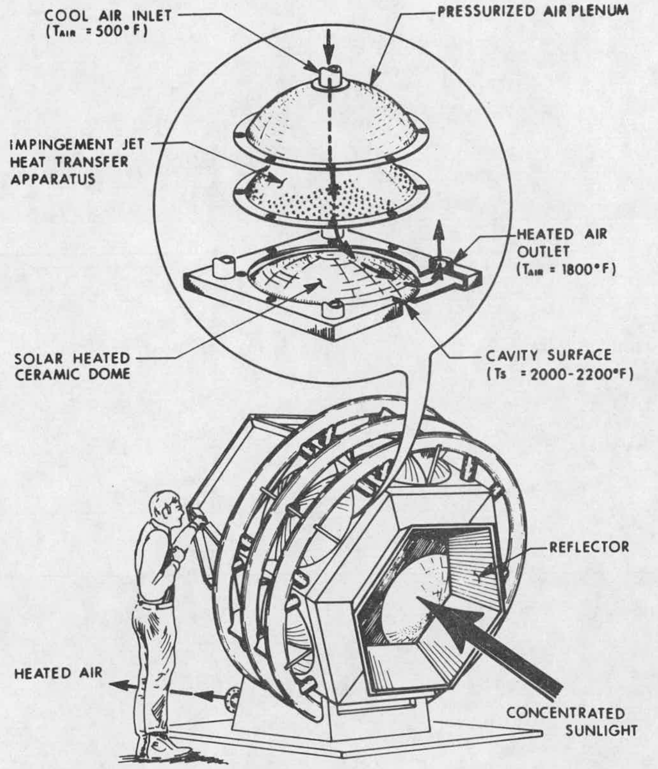

Fig. 1. A concept for a 1-MW_t, solar, heated-air, ceramic-domed, cavity receiver.

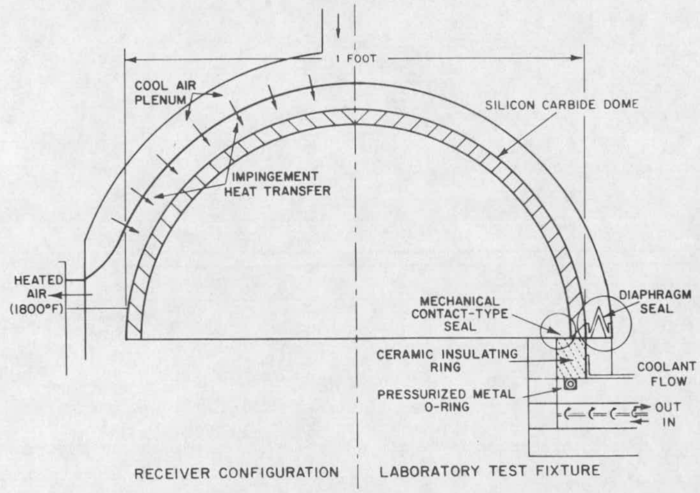

Fig. 2. Hemispherical dome contact seal.

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 which are 3 to 6 times more effective than other heat transfer approaches for the same pressure drop and the utilization of ceramics in compression rather than in tension to take advantage of a strength advantage of from 5 to 20 times (depending on the ceramic).

High-Temperature Seals

Mechanical dome sealing methods were selected as the preferred sealing approach after a review of previous high-temperature seal studies and consideration of the progress made in the present program with respect to stress analysis of a variety of dome shapes and configurations, experimental leakage measurements on subscale mechanical seals and techniques for metalization and brazing of ceramics. Competing seal concepts that were considered included direct bond and compliant ceramic-to-ceramic glass seals and direct bond and compliant ceramic-to-metal seals. The mechanical dome seal category selected also contained a number of possible options which ranged from ball and socket joints, to tapered joints, to the use of O-rings, diaphragms, etc.

One of the mechanical seal approaches presently undergoing detailed examination is shown in Fig. 2. In this design, 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.

The freely supported dome may expand independently of the insulating ring as the receiver heats up thus allowing similar or 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. This approach is also being studied for application to other dome shapes including shallow domes. A second method of obtaining the primary seal is also illustrated in Fig. 2. Here, a seal is assured by brazing a metal diaphragm between the ceramic dome and the surrounding metal structure. In addition to free-contact seals, a clamped contact seal (not shown) for shallow dome shapes is under study.

An analytical and experimental program has been undertaken at MIT/Lincoln Laboratory to develop the technological foundation for the design concepts offered in Fig. 2. 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 of ceramic/ceramic or ceramic/metal couples is possible. Discussions of these topics follow.

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. Silicon carbide is preferred for the dome because it has superior properties such as thermal conductivity, strength, and thermal shock resistance at elevated temperatures. Two versions of SiC are being used in this program; one 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. Values of thermal conductivity and modulus of rupture (MOR) at 2200°F (1200°C) for two Norton siliconized SiC materials and MTC CVD SiC are listed in Table 2. NC-435 siliconized SiC is a smaller grain, higher-strength version of NC-430 with a more limited shape-forming capability. Experimental burst tests by Garrett Corporation of NC-430 and MTC CVD SiC tubes have shown that CVD SiC is 30 percent stronger than NC-430.

Table 2

Thermal Conductivity and MOR of SiC Materials (1200°C)

	NC-430	NC-435	MTC* CVD SiC
K Btu/ft^2 hr (°F/ft)	18	—	12
Modulus of Rupture (psi)	38-52000 (3 point)	68000 (4 point)	52-68000$^+$

* Materials Technology Corporation.

\+ Estimate based on Garrett Corporation burst tests of CVD SiC tubes.

Aluminum oxide and mullite have thermal conductivities at 1200°C which are a factor of 2 and a factor of 5 to 8 less (depending on the type of mullite), respectively, than SiC and their MORs are substantially less than SiC with mullite being the weaker of the two materials.

NC-435 SiC, Al_2O_3, and mullite ceramic materials have been put to use in the experimental program in a variety of shapes as shown in Fig. 3. SiC has been used in the form of plates, disks, test coupons and domes (not shown); Al_2O_3 as disks, test coupons, domes and insulating rings; and mullite as test coupons and insulating rings. Dome sizes presently being handled range from 2 to 6 inches in diameter. Ceramic hardware at the 2-inch size was utilized in the mechanical-joint, contact-seal leak tests. Ceramic test coupons were used in the ceramic metalization and brazing portion of the investigation. After metalization, the ceramic/metal couples were heated in a furnace to expected operating temperature levels to test the adhesion qualities of the ceramic-to-metal bond. The metalized coupons were also brazed to each other to form tensile test specimens for brazed-joint strength tests.

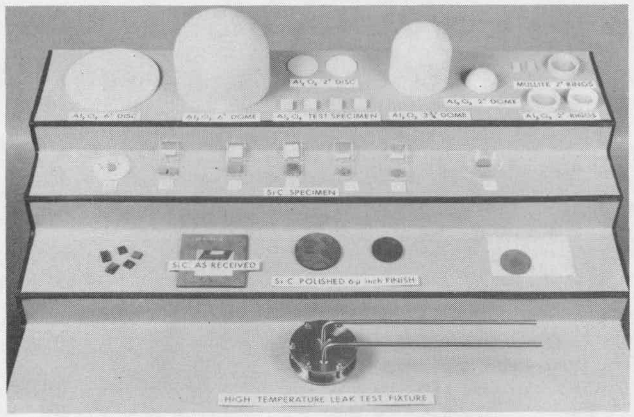

Fig. 3. Ceramic parts and the leak test fixture.

Ceramic Dome Stresses

Methods were developed for the preliminary design analysis of stresses in a variety of ceramic dome/seal configurations including the free-standing hemispherical dome contact seal and the clamped shallow dome seal. Both analytical and finite element analyses were used to determine the response of ceramic spherical dome segment heat exchanger units to combined pressure, thermal stress, and temperature stress loadings. The thermal stress in the dome is due to the required temperature gradients through the thickness of the dome for conduction of heat while temperature stress loadings are due to the relative expansions of ceramic and metal parts during transient or steady-state receiver operation. Dome stresses were calculated for a 4-atmosphere pressure differential across the dome and a maximum temperature gradient through the dome of 400°C/inch. This assumed value of pressure ratio is consistent with the operating pressure level of a heated-air receiver for a regenerative open-cycle Brayton system while the assumed temperature gradient is the maximum value required to transfer heat in a cavity receiver at the highest incident flux levels now available for receiver testing.

The analytical methods are based on Timoshenko's treatment of plates and shells and apply to thin spherical dome segments of finite angular span. The analytical dome structural analysis techniques were coded for machine calculation, validated by reproducing example cases, and used to obtain an exact description of the tensile and compressive stress distributions over entire spherical shell segments. Stresses were calculated for domes with free, clamped, and stiffened edge conditions and for dome shapes which varied from hemispherical-to-shallow dome form. Calculations were performed for dome thicknesses in the range from 1/16 to 1/4 inch and dome spans from 6 to 36 inches using material properties representative of Norton NC-435 SiC material. The complementary finite element computer analyses utilized an MIT/Lincoln Laboratory version of STRUDL* to evaluate the effects on dome stress levels of (1) variable dome thickness and/or temperature distribution over the dome, (2) the use of domes with small angular span, and (3) the attachment of the dome segment to the surrounding structure; items not easily handled by the analytical methods.

* Structural design language, a large, general-purpose structural analysis program developed by MIT Civil Engineering Laboratory and Lincoln Laboratory. Used by about 1000 organizations in 40 countries.

An example of the combined pressure and thermal stresses in a 1/8-in.-thick, 12-in. hemispherical SiC dome with free edges as predicted by the analytical treatment is shown in Fig. 4. Variations in dome compressive and tensile stresses as a function of polar angle, ϕ, are illustrated and show that a maximum hoop stress of $\sigma_{\theta_{top}}$ = 9000 psi occurs in this example on the outside of the dome at its edge, ϕ/ϕ_{max} = 1. Table 3 lists the maximum combined pressure and thermal stresses on the dome, as derived from angular distributions similar to Fig. 4, for SiC hemispherical and shallow dome segments with clamped or free trolley edge conditions for three dome thicknesses, 1/16, 1/8, and 1/4 in., and three dome spans, 6, 12, and 36 in. General trends observed in Table 3 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. A clamped shallow dome configuration is seen to have the lowest stress of all the configurations examined with a maximum stress of only 5950 psi on a 12-in.-dia. dome.

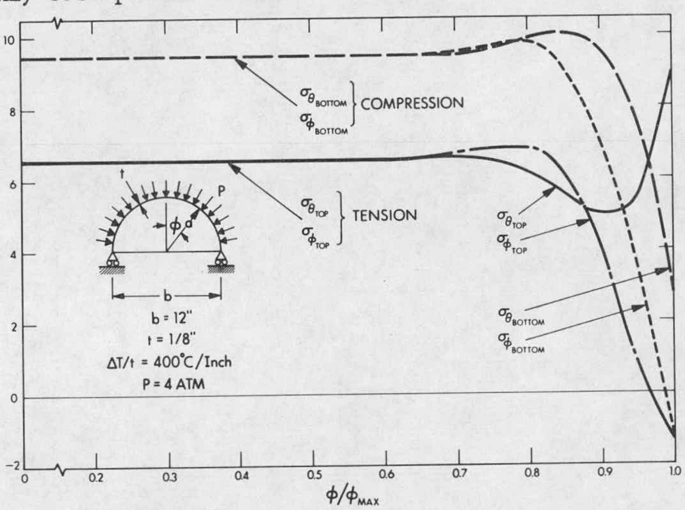

Fig. 4. Pressure and thermal stresses in a 12-in. hemispherical SiC dome with free edges.

Table 3
SiC DOME STRESSES

		HEMISPHERICAL DOME		SHALLOW DOME H/B*= 0.2	
DOME THICKNESS (INCHES)	DOME SPAN (INCHES)	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 signs (+) indicate tensile stress and minus signs (-) indicate compressive stress.

A comparison is made in Fig. 5 of the maximum dome stresses for free or clamped 12-in.-dia. domes and the flexural strength of three types of SiC; Norton NC-430, Norton NC-435, and MTC CVD SiC. This figure shows that the calculated stress levels are substantially below the published strengths (MOR) of the SiC dome materials. The calculations that have been performed show that hemispherical domes with clamped, stiffened or free edges are feasible design concepts as are clamped or stiffened shallow domes over the range of dome thicknesses and spans considered.

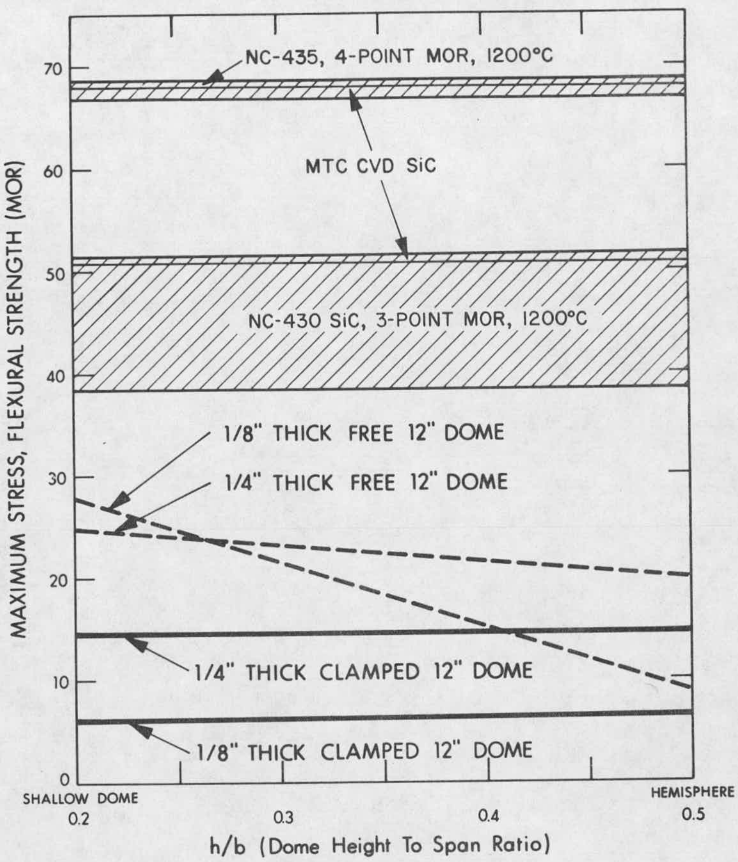

Fig. 5. Comparison of maximum dome stresses with SiC flexural strength.

The free-standing hemispherical dome seal and the clamped dome seal concepts were selected for preliminary design and analysis after consultations with industrial ceramic manufacturers established that foot-diameter domes could be fabricated with wall thicknesses in the range from 3/32 to 1/8 in. which allowed satisfactory design margins of safety to be realized.

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 diaghragm seal (Fig. 6).

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 kovar).

A unique metalization technique known as vacuum sputtering has been used in the present investigation to coat the ceramic parts and the ceramic/metal combinations shown in Table 4 have been prepared and are being tested. Test coupons have been prepared

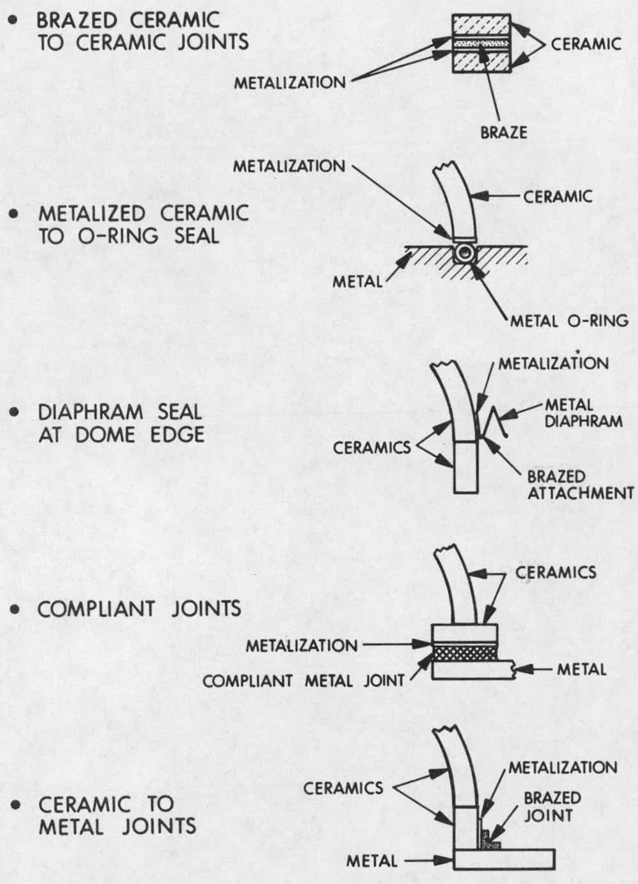

Fig. 6. Potential applications for metalization techniques.

with different metalization layer thicknesses in the range from 0.5 to 5 microns (0.02 to 0.2 mils) to determine the effects of metalization layer thickness. Each metalized coupon is heated in a furnace to a maximum temperature which is raised incrementally between furnace cycles. The sample is inspected and photographed after each temperature cycle with photographs of the entire sample being taken as well as microscope enlargements of edge boundaries between the ceramic/metal and metal/metal coatings.

Table 4

Ceramic/Metal Combinations

Ceramic Material	Metal Coating			
	Tungsten	Niobium	Nickel	Rhodium
SiC	X			
	X		X	
	X		X	X
Al_2O_3		X		
		X	X	
			X	
Mullite	X			
	X		X	

Metalization of Norton NC-435 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 1200°C (1100°–2200°F). The appearance of a 2-in.-dia. tungsten-coated disk after the 1200°C temperature cycle is shown in Fig. 7. The dark circular area in the center of the SiC disk is uncoated SiC while the light surrounding area is the coating of tungsten metal. Excellent adherence of the metal and SiC is observed along the circular boundary. Temperature heating tests of tungsten/SiC couples to 1600°C are under way.

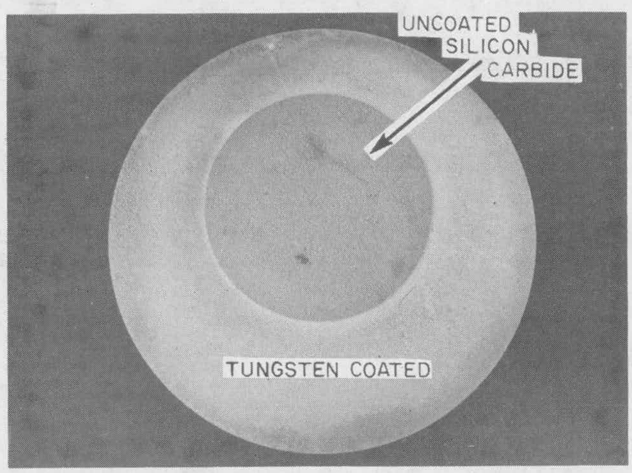

Fig. 7. Tungsten-coated SiC disk, 1200°C (2200°F).

The initial metalization of tungsten on SiC has also been overcoated successfully with an oxidation protective metal coating which too has shown good adherence at room temperature and when heated incrementally to 1000°C (1800°F). Figure 8 is a photograph of 1/2-in.-sq. 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. Temperature tests of Ni with SiC couples to 1400°C are continuing.

SiC coupons with tungsten/nickel coatings have been successfully brazed together to form tensile

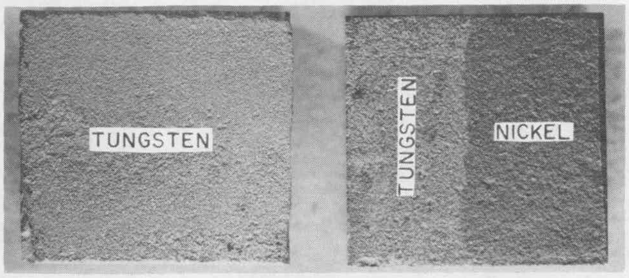

Fig. 8. Tungsten and tungsten/nickel coated SiC samples, 1000°C (1800°F).

test specimens (not shown) with aerospace-type AMS-4783 braze at a brazing temperature of 2150°F. The potential operating temperature of these brazed joints is much higher than 2150°F, however. Heat-treatment techniques have been developed for this type of braze by aircraft-engine manufacturers that may be used to raise the maximum use temperature of such joints to the 2400°F level. Other promising work in the SHARE program includes direct brazing of tungsten metalized SiC coupons and CVD deposition of the tungsten layer.

Mechanical Seal Leak Tests

Experimental leak rate measurements of a mechanical contact-type seal have been made; 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 leak measurements were performed on a 2-in.-dia. free-contact seal utilizing the leak rate test fixture shown in Figs. 3 and 9. Initially, the dome receiver/seal geometry was modeled by a ceramic disk supported on a short section of ceramic tube (Fig. 9). Subsequently, the flat disk was replaced by shallow (H/B = 0.20) and hemispherical dome units.

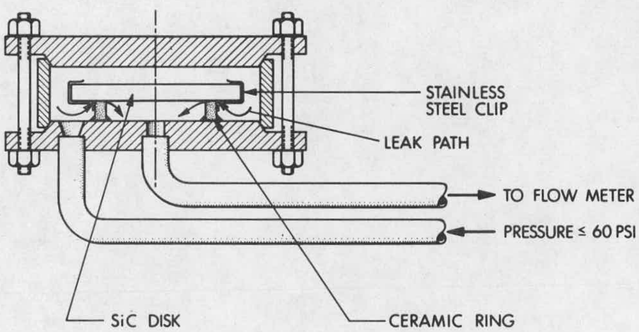

Fig. 9. Temperature leak rate test fixture.

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. Room temperature leakage measurements for a SiC disk on an alumina tube are shown in Fig. 10 for two different combinations of surface finishes on the ceramic parts; a 6 μ-in. Al_2O_3 ring in combination with a 6 μ-in. or 15 μ-in. SiC disk. The 15 μ-in. finish on the SiC disk and the 6 μ-in. finish on the Al_2O_3 ring are representative of as-received, surface-ground finishes from ceramic manufacturers.

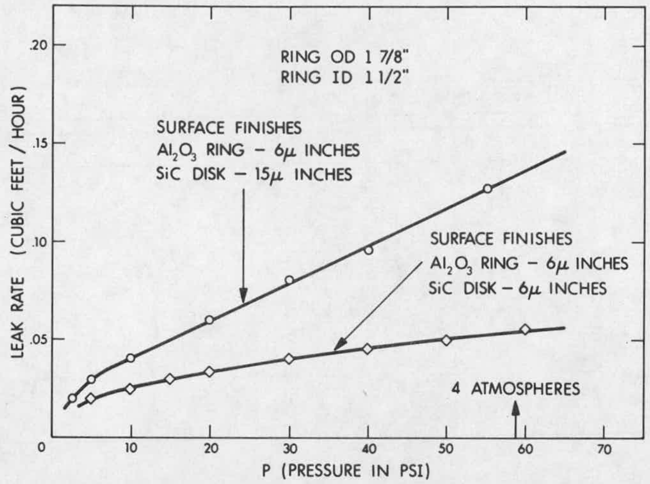

Fig. 10. Room temperature leakage measurements for SiC disk on alumina ring.

The room temperature measurements were then scaled to larger dome sizes and higher temperature air conditions using a leakage rate formula available in the literature for flat metal contact seals.

$$Q_c \; \alpha \; \frac{H^N D}{\mu \; L \; T \; S^{3/2}}$$

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)

A comparison of predicted high-temperature air leakage vs. design goal leakage ratio is offered in Fig. 11 where the extrapolations either neglect or include seat stress effects and are based on the highest room temperature leakage data shown in Fig. 10. This comparison shows that the expected leakage rate on a 12-in.-dia. dome at 1800°F will be more than two orders lower than the design goal if seat stress effects can be neglected in ceramic seals and more than four orders lower if they cannot.

Leak rate measurements at elevated temperatures are presently under way at MIT/Lincoln Laboratory to validate the extrapolations offered in Fig. 11. In these tests, the high-temperature leak test fixture is heated to the desired temperature by placing it in a radiant furnace (Fig. 12).

Future Program

The applied technology program which includes metalization of coupons, fabrication and testing of brazed joints, and subscale leak measurements of contact, diaghragm, and clamped seals at temperature

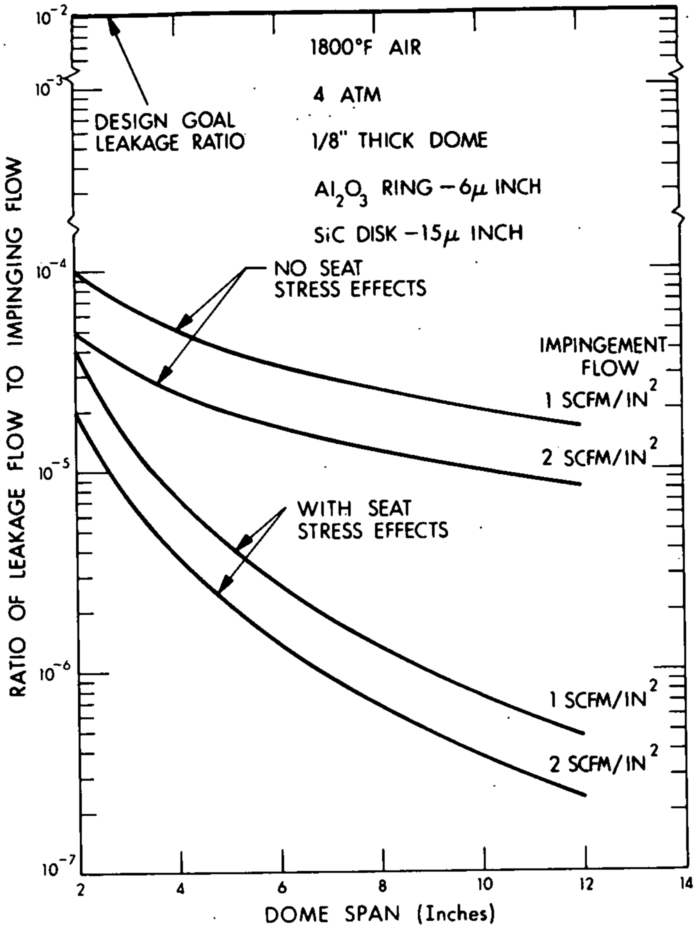

Fig. 11. High-temperature air leakage vs. dome diameter.

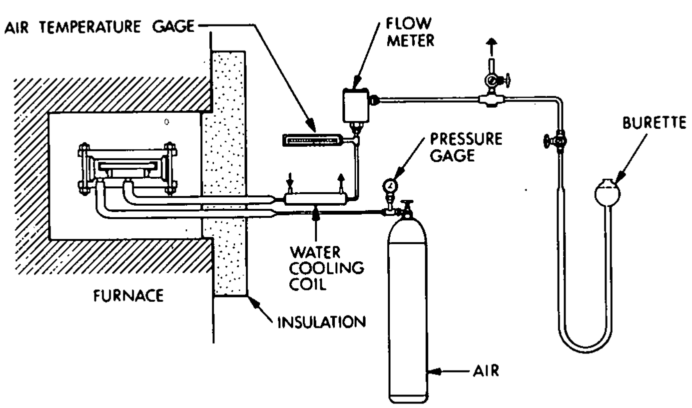

Fig. 12. High-temperature leak rate test setup.

will continue during the next six-month period. Demonstration of a high-temperature seal on a 1-ft-dia. dome during this same period will be a key objective. A dome test fixture will be constructed which mates with a large, existing high-temperature furnace and seal tests will be performed at receiver design operating temperatures and pressures, but without simulation of the heat transfer through the dome.

Conclusions

Substantial progress has been made in the development of a high-temperature seal for a solar heated-air cavity receiver during the first six months of the advanced development program. Mechanical dome sealing methods were selected as the preferred sealing approach. A free-standing hemispherical dome contact-type seal and a clamped shallow dome seal were chosen for preliminary design, analysis, and fabrication. Analytical and experimental investigations established 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.

Acknowledgments

The contributions of MIT/Lincoln Laboratory staff members Anthony Leyenaar and Dr. Frank Bachner in the areas of seal leak tests and ceramic metalization, respectively, are appreciated.