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CERAMIC SOLAR RECEIVERS†

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ABSTRACT

The application of ceramic materials to high temperature solar receivers for advanced Brayton and advanced Stirling thermal electric systems is discussed. Conceptual designs for ceramic cavity receivers employing impingement jet-cooled, dome-shaped silicon carbide heat exchanger modules are offered. Optical, mechanical, heat transfer and structural analyses of this novel receiver approach are presented.

DEVELOPMENT OF ADVANCED RECEIVER SYSTEMS for the conversion of focused solar energy to heat or electrical energy is underway in the U.S. Ceramic receiver systems look particularly promising for use with advanced Stirling and advanced Brayton systems requiring heated gas working fluids with gas temperatures in the 1800-2400°F range, such temperatures precluding the use of metal receivers. A novel ceramic receiver concept is being developed by MIT/Lincoln Laboratory, under U.S. Department of Energy sponsorship, which employs a cavity receiver geometry and utilizes an impingement jet-cooled, dome-shaped silicon carbide heat exchanger module(s) to form a portion(s) of the cavity wall(s) and to transfer the heat to the working fluid.

In dispersed/dish systems the receiver is placed at the focal point of the concentrator and may be coupled directly to a Stirling engine as shown in Figure 1, or take the form shown in Figure 2 for a Brayton unit. During operation of the Brayton receiver, cool air from a recuperated Brayton engine typically at 1000°F temperature and four atmospheres pressure enters into the cold air plenum, passes through a perforated impingement jet plate and strikes against the hot ceramic dome where the gas temperature is increased to the desired level (Figure 2). The receiver unit is equipped with an entrance reflector to direct the incident flux through a small entrance aperture, a small aperture being required to reduce radiation losses from the high temperature cavity.

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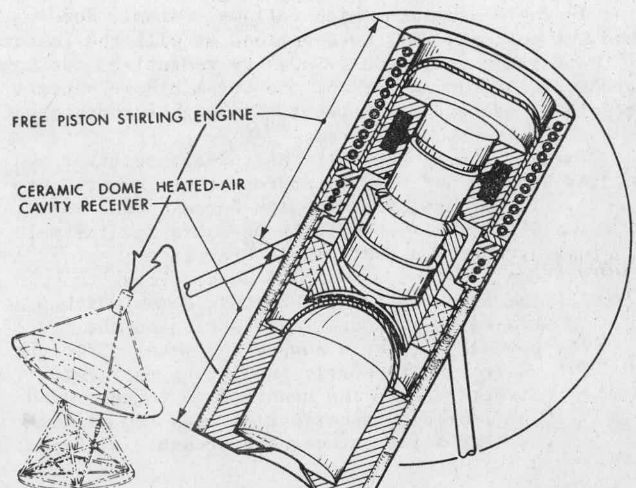

Fig. 1 - Ceramic Dome Receivers for dispersed-dish applications

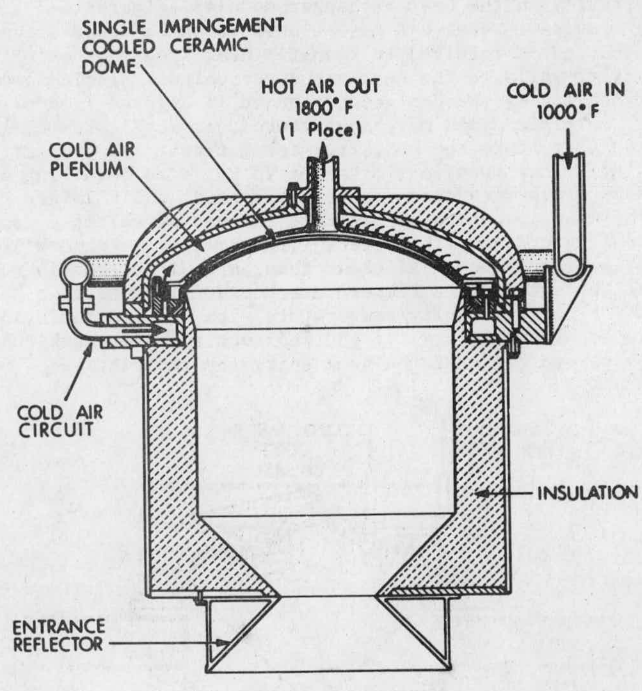

Fig. 2 - Point-focus ceramic cavity receiver for Brayton systems

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DISCLAIMER

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The dome units are subject to stresses arising from the action of pressure forces on the dome and from the thermal gradient through the dome thickness required for heat transfer. The ceramic dome receiver approach offers a number of design advantages which include the ability to heat a pressurized gas stream, the use of impingement jet heat transfer methods which are highly effective, the utilization of ceramic dome materials in compression (ceramic materials are substantially stronger when used in compression rather than tension) to support the pressure forces and a maximum material operating temperature as high as 3000°F.

In the discussion which follows, ceramic dome receiver concepts will be described as will the features of the ceramic dome module. Cavity radiation modeling, structural design aspects of the ceramic dome/support structure, and the development of a high temperature seal will also be considered.

The purpose of the solar heated-air receiver studies to date has been to address these questions:

1. Is is possible to design ceramic dome units which will support the pressure and thermal stresses encountered in operation?
2. Can a method of support be developed to hold the high temperature ceramic domes which transmits pressure loads acting on the ceramic dome to a supporting metal structure while simultaneously insulating that metal structure from the severe dome temperatures and providing an effective high temperature seal at a four atmosphere pressure differential?

RECEIVER CONCEPTS

The receiver designer can choose from a number of possible options when considering receiver geometry and the placement and number of ceramic dome heat exchanger units. Direct receiver configurations can be selected in which the incident solar flux impinges directly on the heat exchanger modules (Figures 1-3), or indirect receivers may be used in which reradiation exchange is required to transfer heat from the hot cavity walls to the heat exchanger units. Single dome receivers may be designed as shown in Figures 1 and 2, or multiple domes may be clustered, as in Figures 3 and 4, to form the heat transfer surface. At present, single dome receivers of about 75 kW_t size requiring a dome of 24-inch span can be fabricated, while larger thermal capacities necessitate the use of multiple dome configurations. The direct type receiver is generally a few points more efficient than an indirect receiver at the same outlet temperature because it runs at a lower average cavity temperature with reduced radiation losses from the cavity; the indirect receiver must run hotter to transfer the heat energy by reradiation.

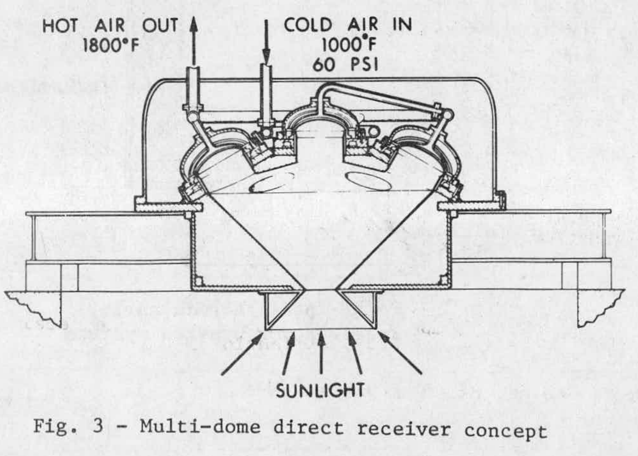


Fig. 3 - Multi-dome direct receiver concept

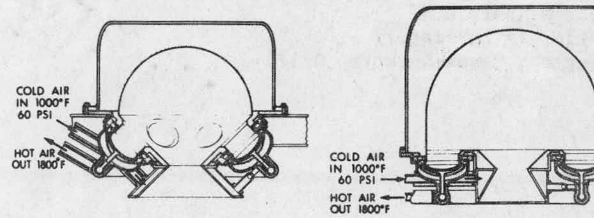


Fig. 4 - Multi-dome indirect receiver concepts

CERAMIC DOME MODULE

Ceramic dome modules with shallow dome forms, Figure 5, and hemispherical dome forms (not shown) are being fabricated and tested during the present investigation. The hot air may exit from the ceramic dome module at its center as shown in Figure 5, or may exit around the periphery of the dome, depending on the application. One method of supporting the dome while insulating it from the metal structure is shown in the enlargement, Figure 6. In this approach, the silicon carbide dome is supported at its edge by a ceramic insulating ring which provides a temperature drop between the dome and the metal structure. The primary pressure seal is achieved by a mechanical contact seal at the dome/ring interface with a secondary seal provided at the foot of the ring with a pressurized metal o-ring. The leak rate through the high-temperature mechanical seal is controlled by selection of the surface finishes on the ceramic parts in the contact area.

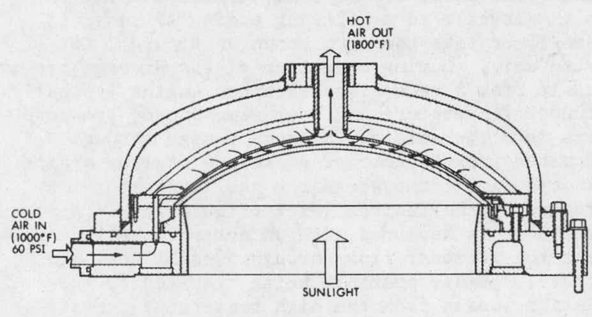


Fig. 5 - Shallow ceramic dome module

Silicon carbide is being used for the impingement-cooled dome structure because of its high thermal conductivity and high strength while alumina (Al_2O_3) and mullite are being used for the insulating ring. Designs have been prepared in which the silicon carbide dome is free to expand relative to the insulating ring during heating or cooling. Potential temperature stresses which might be produced by the differing coefficients of thermal expansion of the dome and insulating ring ceramics are avoided by allowing relative motion to occur between the ceramic parts.

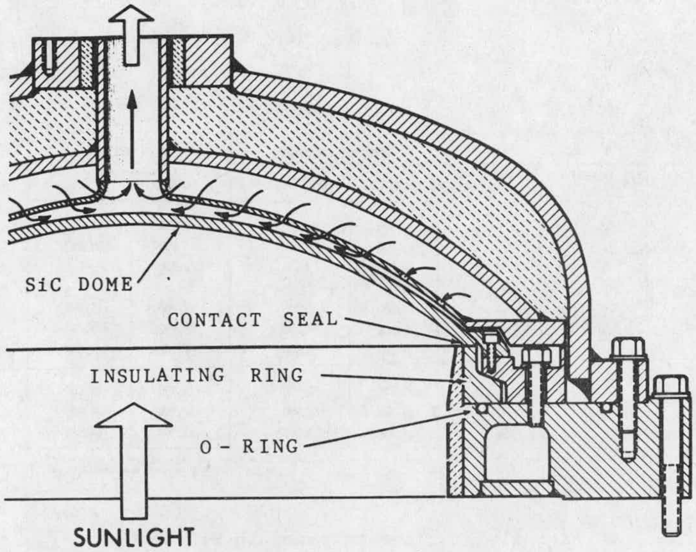


Fig. 6 - Details of support/seal system

CAVITY RADIATION MODELING

As part of this investigation, analytical methods (1)* have been developed to describe the incident solar flux distributions in cavity receivers heated by parabolic concentrators. Cavity reradiation exchange and the resulting cavity temperature and flux distributions have also been modeled analytically by dividing the interior of the cavity surface into a number of subelements, determining the radiation exchange view factors between each of the elemental surfaces, writing a set of simultaneous equations which express the radiation interchange between surfaces and solving these equations using the Gauss-Seidel iteration technique until radiation equilibrium is established within the cavity. Results will now be shown for a hemispherical dome-capped cylindrical cavity receiver geometry, Figure 7, a geometry applicable to the Stirling engine coupled receiver (Figure 1).

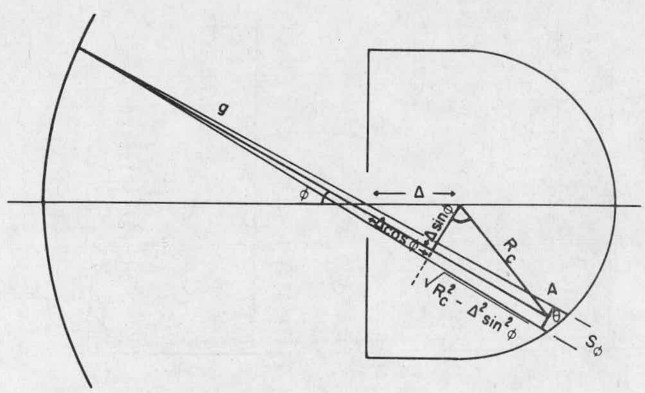


Fig. 7 - Dome-capped cylindrical cavity receiver geometry

The incident flux distributions on the walls of a 14-inch-diameter cavity placed at the focal point of a 30-foot-diameter, 45-deg rim angle, parabolic dish are shown in Figure 8 for a dish with perfect optics. The flux impinging on the hemispherical dome heat exchanger unit is essentially constant, while flux peaks occur on the cavity walls near the rim angle of the concentrator. The resulting temperature distribution within the cavity, after reradiation exchange, is displayed in Figure 9. This example assumes that heat extraction from the cavity is occurring through the hemispherical dome which is operating at a dome temperature of 1800°F. For the case shown, the equilibrium temperatures on the forward bulkhead which encircles the entrance aperture and on the cavity wall forward of the radiation peak are 2400°F. The maximum cavity temperature of 2800°F occurs in the vicinity of the peak flux on the wall.

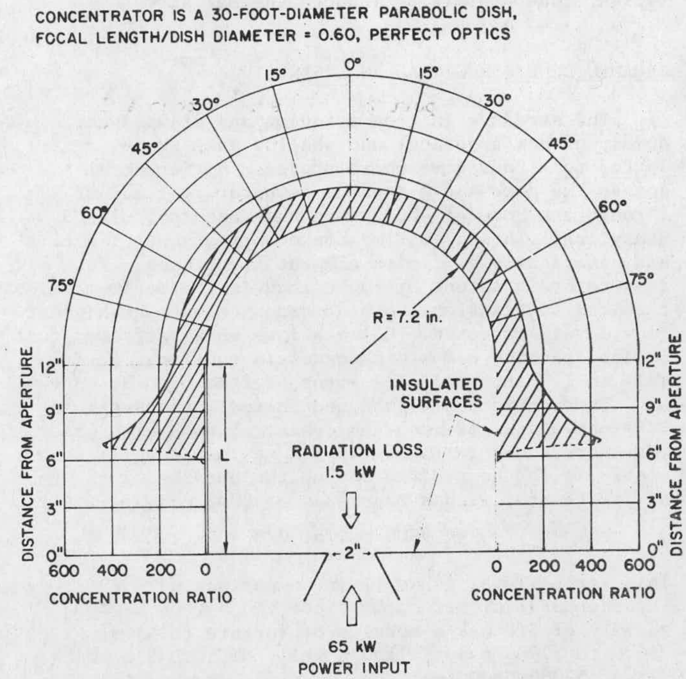


Fig. 8 - Incident flux distribution in the receiver

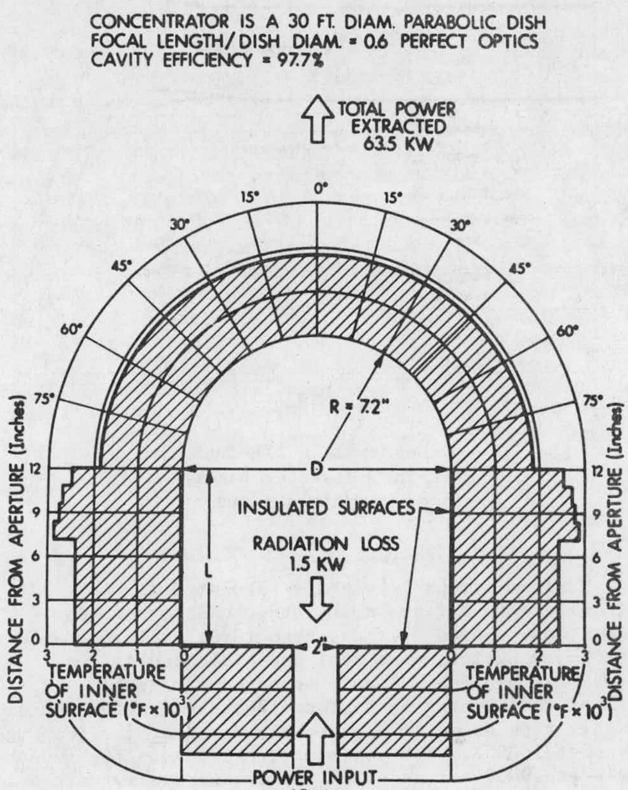


Fig. 9 - Temperature distribution in the receiver

*Numbers in parentheses designate References at end of paper.

Analytical methods have also been developed which treat cavities in which the cavity wall or end shapes may be part hemispherical, hemispherical, spherical or elliptical. Application of these techniques has shown that a cavity geometry and form may be chosen which assures that the ceramic dome heat exchanger units will receive uniform incident solar and reradiated cavity fluxes, thus minimizing induced thermal stresses.

CERAMIC DOME STRUCTURAL ANALYSIS

The stresses in free standing and clamped ceramic domes, of hemispherical and shallow dome shape, subjected to a four atmosphere pressure differential across the dome and a maximum temperature gradient through the dome of 400°C/inch have been calculated analytically based on Timoshenko's treatment of shells and numerically by finite element techniques. The temperature gradient of 400°C/inch is the maximum value required to transfer the heat deposited at the highest flux levels expected. Calculations were performed for silicon carbide dome thicknesses in the range of from 1/16 to 1/4 inch and dome spans of from 6 to 36 inches.

The combined pressure and thermal stresses in a 1/8-inch-thick, 12-inch-hemispherical dome with free edges are shown in Figure 10. A maximum tensile stress occurs in the hoop direction on the outside of the dome at its equator with a magnitude of 9000 psi;

eg. $\sigma_{\theta\,top}$ = 9000 psi at ϕ/ϕ_{max} = 1.0

This stress level is small in comparison with silicon carbide material strengths since the Norton NC-430 variety of SiC has a modulus of rupture (MOR) of 38000 to 52000 psi at 1200°C while MTC CVD SiC has a MOR of 52000-68000 psi.

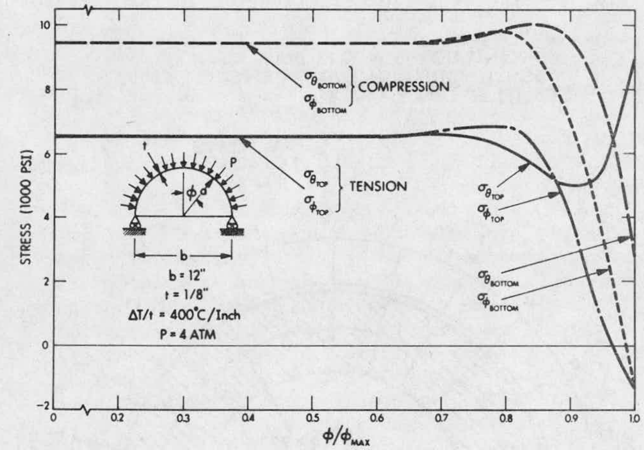


Fig. 10 - Stresses in a 1/8-inch-thick, 12-inch-diameter hemispherical dome with free edges

Maximum stress levels are tabulated in Figure 11 for domes with various spans, thicknesses and edge conditions. Based on these structural analyses, a free hemispherical dome seal and a clamped shallow dome seal (h/b = 0.20) were selected for test. A goal of the program is to test 12-inch-diameter seals of this type using 1/8-inch-thick domes at gas temperatures of 1800°F. The maximum stress levels for these seals are 9000 psi and 5950 psi respectively, values low in comparison to SiC material strengths.

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

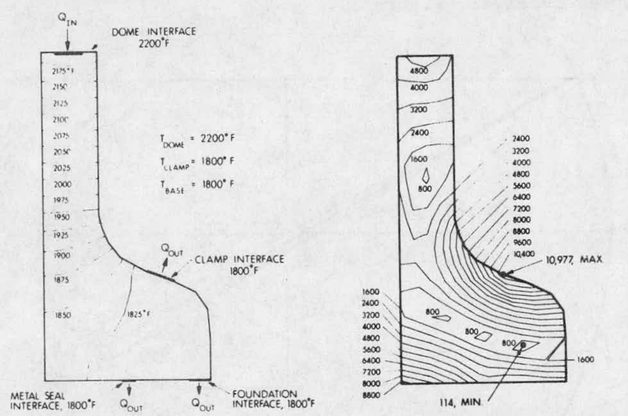
* Ratio of dome mid-height to span.
* Not calculated.

Note: Plus signs (+) indicate tensile stress and minus signs (-) indicate compressive stress.

Fig. 11 - Maximum stresses in SiC domes

INSULATING RING STRUCTURAL ANALYSES

A finite element analysis of the stresses in the insulating ring was carried out. Temperature and stress contours are shown in Figure 12 for a clamped 12-inch-diameter SiC ring subject to a temperature difference of 400°F between the dome interface and the ring foundation and a 4 atm pressure load along the dome interface. A maximum stress intensity of 11,000 psi occurs at the clamp interface. An alumina ring (not shown) experiences a maximum stress intensity of 13,000 psi under the same loading conditions. In both cases, the stresses produced by the combined loadings are low in comparison with the ceramic material strengths, thus substantiating the design.



temperature contours   stress intensity contours

Fig. 12 - Temperature and stress contours in a clamped 12-inch-diameter insulating ring

MECHANICAL CONTACT SEAL LEAKAGE TESTS

Leakage through a mechanical contact seal of the ceramic dome/ring type (Figure 13) was measured to ascertain the usefulness of that approach. Leakage was measured as a function of the surface finish on the ceramic parts (Figure 14) and as a function of gas temperature (Figure 15) to validate for ceramic seals a leakage formula which had previously been developed for metal to metal contact seals. Experimental measurements were initially carried out on 2-inch-diameter ceramic seals to validate the metal contact seal leakage formula:

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

where Q_L = leakage rate
- H = surface roughness
- D = mean seat diameter
- μ = viscosity of leakage gas
- L = radial seal landwidth
- T = gas temperature
- S = apparent seat stress
- N = exponent

The room temperature leakage measurements (Figure 14) validated that leakage varied with surface finish as H^N where N=1.6, while the temperature tests (Figure 15) validated that leakage varies inversely as the product of viscosity and temperature i.e.,

$$Q_L \,\alpha\, \mu^{-1} T^{-1}.$$

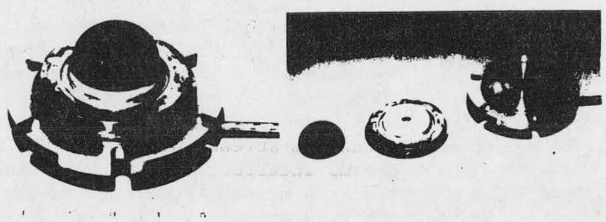


Fig. 13 - Mechanical contact seal test unit

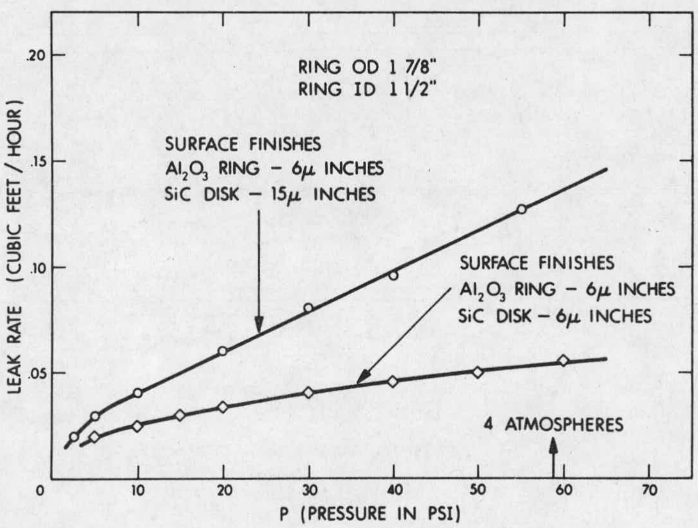


Fig. 14 - Seal leakage variation with surface finish

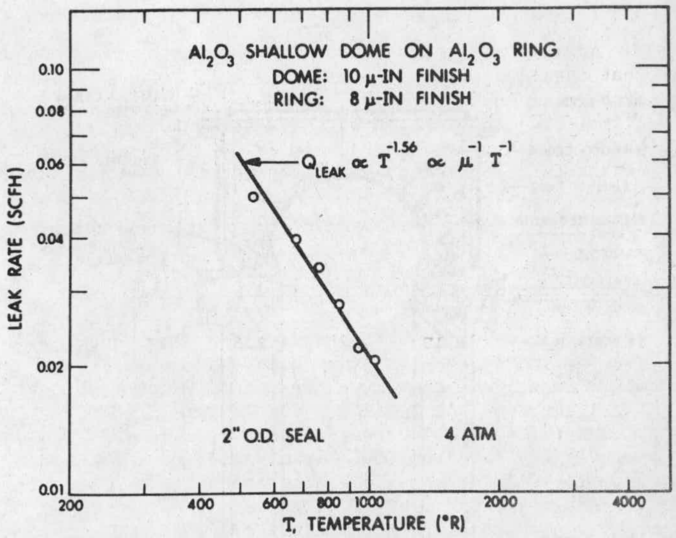


Fig. 15 - Seal leakage variation with gas temperature

The design goal of the seal tests is to demonstrate a seal leakage at a gas temperature of 1800°F and a pressure of 4 atmospheres of one percent (or less) of the total flow impinging on the dome. For a hemispherical dome seal this corresponds to an allowable leak of 2.0 SCFH on a 2-inch diameter seal at the nominal impingement flow rate of 30 SCFH/inch^2 (.5 SCFM/inch^2) and of 68 SCFH on a 12-inch-diameter seal. Two facts are evident immediately from the experimental data displayed in Figures 14 and 15. First, the measured leakage at room temperature on a 2-inch-diameter seal is more than one order of magnitude less than the 1% leakage goal. Second, the effect of increased temperature is a substantial reduction in leakage. Extrapolation of the two-inch seal test results to 1800°F gas temperature and a 12-inch-diameter seal have been made which predict a leakage rate which is three orders of magnitude less than the design goal using surfaces which have normal diamond ground finishes. Therefore, the mechanical contact seal is an attractive method for achieving the desired leakage goal.

Tests are presently underway at MIT/Lincoln Laboratory on 12-inch ceramic hardware to confirm the leakage predictions for this size mechanical contact seal. An experimental test fixture has been built which houses the dome and dome support ring and this fixture has been mounted on an existing cylindrical vacuum furnace as depicted in Figure 16. Seal tests are being conducted at the correct seal pressure differential and temperature, but without impingement cooling and heat transfer through the dome.

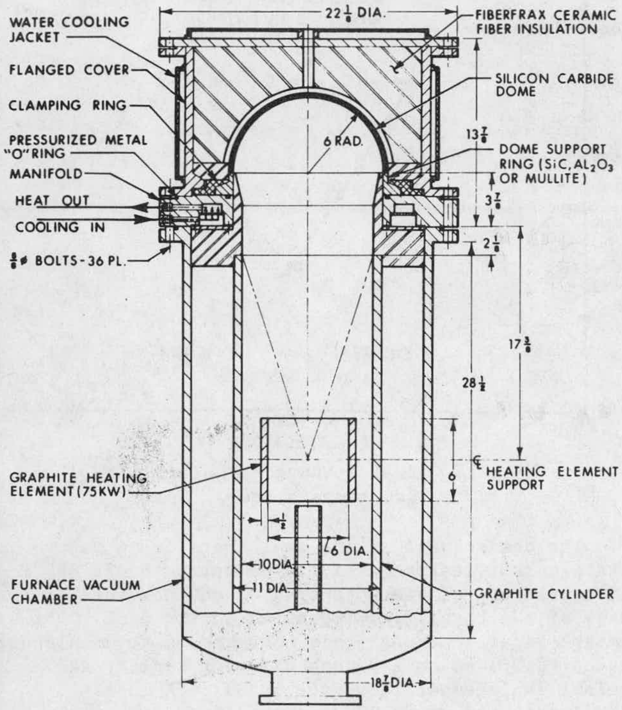


Fig. 16 - 12-inch-diameter seal test apparatus

ALTERNATIVE SEAL DESIGNS

The development of an alternative brazed leak tight seal between the SiC dome and surrounding metal structure has also been pursued under the present program. Methods of metalizing the SiC and forming the brazed joints have been demonstrated. This brazed joint option appears attractive for applications requiring zero leakage. Also, based on our experiences, a number of design simplifications appear possible in the mechanical contact seal system reported here; this avenue is also being investigated. In some ceramic dome module configurations, it appears possible to eliminate the insulating ring and achieve the desired temperature drop directly in the ceramic dome itself. This requires that a dome of extended span be used and that the proper cooling airflow and radiative heat input distribution to the periphery of the dome be selected. In this design, a single metal o-ring at the periphery of the dome would provide the pressure seal.

CONCLUSIONS

Cavity receivers employing impingement jet cool silicon carbide ceramic dome heat transfer modules have been studied both analytically and experimentally for use with advanced Stirling and advanced Brayton systems requiring gas temperatures in the 1800-2400°F temperature range and the results are quite promising. Uniform incident solar flux and reradiated flux distributions over the ceramic heat exchanger units may be achieved through the proper selection of cavity geometry and placement of the ceramic modules within the cavity. Methods which provide structural support and high temperature sealing of the ceramic domes have been tested. Leak rates substantially lower than the one percent design goal have been achieved with mechanical contact seals.

REFERENCE

1. Hamilton, N.I., and Jarvinen, P.O., "Conceptual Design of a Solar Heated-Air Receiver Coupled to a Brayton or Stirling Engine," 1979 International Solar Energy Society Congress, Georgia World Congress Center, Atlanta, Georgia, 28 May-1 June 1979.