

HIGH-TEMPERATURE CERAMIC RECEIVERS^{†*}

PHILIP O. JARVINEN

CONF-800639--1

MASTER

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
 LINCOLN LABORATORY
 LEXINGTON, MASSACHUSETTS USA 02173

Abstract

An advanced ceramic dome cavity receiver is discussed which heats pressurized gas to temperatures above 1800°F (1000°C) for use in solar Brayton power systems of the dispersed receiver/dish or central receiver type. Optical, heat transfer, structural, and ceramic material design aspects of the receiver are reported and the development and experimental demonstration of a high-temperature seal between the pressurized gas and the high-temperature silicon carbide dome material is described.

There is no objection from the patent point of view to the publication or dissemination of the document(s) listed in this letter.

BROOKHAVEN PATENT GROUP

6/16 1980 By *CPH*

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Introduction

This paper discusses a program underway at MIT/Lincoln Laboratory to develop a ceramic heated-air receiver for advanced Brayton central tower and dispersed-dish solar-thermal-electric applications. The ceramic receiver converts solar energy to high-temperature heat and the heated airstream from the receiver is used to drive a gas turbine/generator unit to produce electrical energy. A ceramic receiver is

[†]This work was sponsored by the U.S. Department of Energy.

^{*}Presented at the International Symposium on Solar Thermal Power and Energy Systems, Marseilles, France, 15-20 June 1980.

required to heat the pressurized air to the desired temperature of 1800°F to 2400°F since such temperatures preclude the use of metal receivers. The receiver concept which is being developed uses impingement-jet-cooled, silicon carbide ceramic dome heat exchanger unit(s) located on the interior surface(s) of a cavity receiver to transfer the solar-generated heat to the heat-transfer fluid and an example of a dish receiver concept is offered in Fig. 1. The dispersed-dish/receiver concept (Fig. 1) is shown with a single, hemispherical dome at the rear section of a cylindrical cavity to accomplish the transfer of heat. Ceramic modules with shallow dome shapes (Fig. 2) are also viable alternatives for this (and other) applications.

Pl

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

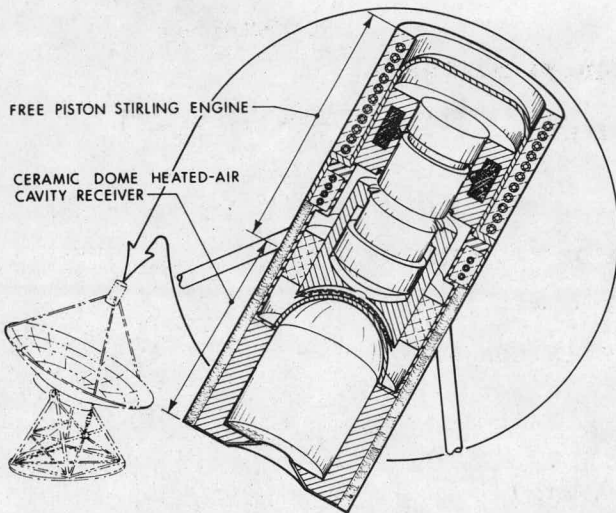


Fig. 1. CERAMIC DOME RECEIVER FOR DISPERSED-DISH APPLICATIONS

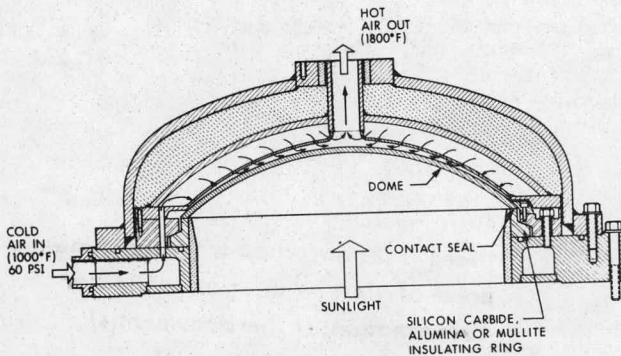


FIG. 2 CERAMIC, IMPINGEMENT-COOLED SHALLOW DOME MODULE

Operation of an impingement-cooled ceramic dome module is illustrated in Fig. 2. Cool air from a regenerative Brayton engine, typically at 1000°F temperature and four-atmospheres pressure, passes into the air plenum of the module. Subsequently the airflow passes through the perforated impingement-jet heat-transfer dome and strikes against the hot ceramic dome where it is heated to 1800°F temperature (or higher). Then the heated air is collected in a manifold and is directed to the gas turbine. The ceramic dome receiver approach offers a number of design advantages including a non-windowed cavity design, the use of impingement-jet heat-transfer methods which are 3 to 6 times more effective for the same pressure drop than alternative heat-transfer methods, the utilization of ceramic dome materials in compression (rather than tension) to support the pressure forces, and a maximum operating temperature limit as high as 3000°F.

The solar heated-air receiver studies have addressed the following questions:

1. Is it possible to develop a cavity receiver of the ceramic dome type which operates at high conversion efficiency while producing heated air at 1800°F?

2. Can ceramic dome units be designed which will support the pressure and thermal stresses encountered in operation?

3. Can the ceramic dome heat exchanger modules be so positioned in the receiver to receive nearly uniform incident solar and reradiated cavity fluxes to minimize induced thermal stresses?

4. 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?

The design objective for the support/seal system was a leak rate through the high-temperature seal of one percent (or less) of the total flow impinging on the dome. A program goal was the experimental demonstration of the high-temperature seal on ceramic hardware of physically meaningful size; in this case a one-foot-diameter dome unit.

The paper which follows first reports on analytical methods which describe the incident flux distributions inside cavities heated by parabolic concentrators and presents results which show that the required degree of flux uniformity in the cavity can be controlled by selecting the proper cavity dimensions and form. Radiative exchange within the cavity and radiative losses through the cavity aperture are then considered. Finally, the development and experimental demonstration of a suitable dome/support/seal system is reported. The thermal barrier between the ceramic dome and metal support structure in the chosen approach is achieved by mounting the silicon carbide dome on an insulating ceramic ring and the primary high-temperature pressure seal is achieved at the dome/ring interface by controlling the selection of the surface finishes on the two ceramic pieces which touch along an annular contact area (Fig. 2).

Solar Radiation Flux Distributions in Cavity Receivers

Analytical methods¹ were developed to describe the incident solar flux distributions in cavity receivers heated by parabolic concentrators. These methods will now be used to describe the incident flux in an example receiver, the hemispherical dome-capped cylindrical receiver being considered as a candidate for a dispersed-dish system (Fig. 1). In this configuration, heat is removed from the cavity via the impingement-cooled hemispherical dome cap.

Incident flux distributions on the walls of 12-inch-diameter cavity with a length-to-diameter ratio of unity placed at the focal

point of a 30-foot-diameter 45° rim-angle, parabolic dish are shown in Fig. 3. The flux impinging on the hemispherical dome is constant over the dome, with flux peaks occurring on the walls of the cylinder. The uniform nature of the incident flux on the dome guarantees that very low thermal stresses are generated in the dome from the incident flux field.

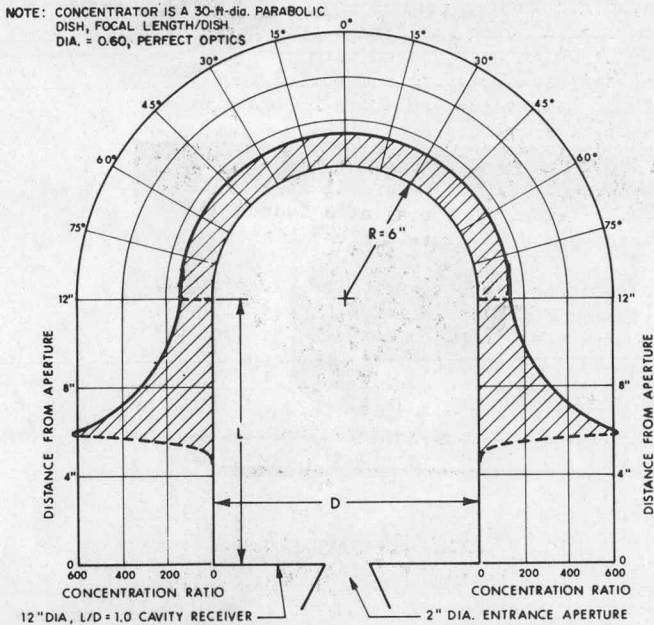


FIG. 3 INCIDENT SOLAR FLUX DISTRIBUTION IN DOME-CAPPED CYLINDRICAL RECEIVER

Cavity Reradiation Exchange

The temperature and final flux distributions on the walls of the dome/cylinder cavity receiver were calculated¹ by dividing the interior surface of the cavity into a number of sub-elements, determining the radiation exchange view factors between each of the elemental surfaces and all other elemental surfaces, writing a set of simultaneous equations and solving these equations using a Gauss-Seidel iteration technique until radiation equilibrium is established within the cavity.

For the case shown in Fig. 3, the equilibrium temperatures on the forward bulkhead which encircles the entrance aperture and on the cavity wall forward of the radiation peak were found to be 2400°F and a maximum cavity temperature of 2800°F was found to occur in the vicinity of the peak flux on the wall. Radiation exchange within the cavity receiver was found to be an excellent means of transferring energy from the regions of high peak flux on the walls of the cavity to the ceramic-dome heat exchanger module.

The operating efficiencies of direct (incident radiation falls directly on the dome heat exchanger units) receivers and indirect receivers (Fig. 4), were evaluated

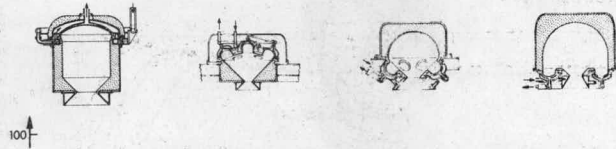


FIG. 4 DIRECT AND INDIRECT RECEIVER CONFIGURATION

using the analysis methods of Reference 1, and receiver collection efficiencies of 90 percent appear achievable. These studies showed that the direct receiver operates at an efficiency higher, by five points or more, than the indirect type since its lower operating temperature reduces its reradiation losses.

Ceramic Dome and Insulating Ring Structural Analysis

Methods were developed² for the analysis of stresses in a variety of ceramic dome/seal configurations including free-standing and clamped hemispherical and shallow-dome seals. Both analytical and finite-element analyses were used to determine the combined pressure and thermal stresses in spherical-dome-segment heat-exchanger units. Thermal stresses in the dome arise from the temperature gradient through the thickness of the dome for the conduction of heat.

Dome stresses were calculated for a four-atmosphere pressure differential across the dome and a maximum temperature gradient through the dome of 400°C/inch. 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 silicon carbide (SiC) material.

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. 5. 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, $\phi/\phi_{max} = 1$.

Maximum stress levels have been determined, from stress profiles of the type shown in Fig. 5, for free and clamped domes with shapes that vary from hemispherical to shallow forms and the results are summarized in Fig. 6. Based on these structural analyses, the free hemispherical dome seal and the clamped shallow dome ($h/b=0.20$) seal were selected for design, fabrication and test. The maximum stress levels for these configurations are 9000 and 5950 psi, respectively, and these stresses are small in comparison with the strengths of the silicon carbide material. The two types of SiC being used in the project are Norton NC-430 SiC and these materials have moduli of rupture at 2200°F (1200°C) temperature of 38,000 to

52,000 psi and 52,000 to 68,000 psi, respectively.

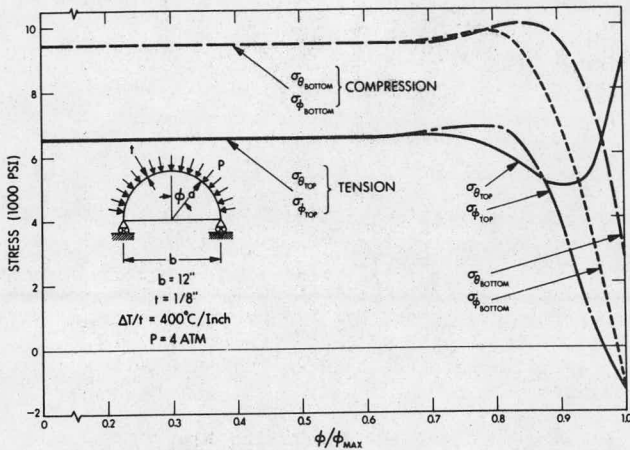


FIG. 5 COMBINED PRESSURE AND THERMAL STRESSES IN A 12-IN. HEMI-SPHERICAL DOME

SiC DOME STRESSES

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

FIG. 6 VARIATION OF MAXIMUM DOME STRESSES WITH DOME SPAN AND WALL THICKNESS

The stresses in the clamped insulating ring which support the ceramic dome and provides the thermal barrier between the hot dome and the cooler metal support structure were calculated² for a variety of ceramic materials by finite-element techniques. The stress produced by the combined pressure/thermal loadings was again found to be low in comparison with SiC ceramic material strengths, thus substantiating the design approach.

High-Temperature Seals

At the beginning of the program, three different methods for obtaining a high-temperature seal were successfully implemented in subscale hardware; a glass seal, a brazed seal and a mechanical contact seal. Based on these investigations, the mechanical contact seal approach was chosen as the preferred method for demonstration on one-foot-diameter ceramic dome hardware.

The glass seal approach was successfully demonstrated by forming glass bonds between silicon carbide and mullite ceramic pieces at a temperature of 2200°F (1200°C). An example

of the versatility of approach is shown in Fig. 7 where glass has been used to bond two 2"-diameter disks of silicon carbide together and in turn used to bond the silicon carbide unit to a mullite insulating ring (light cylinder). In the brazed seal approach, the ceramic dome is metalized about its equator and a circumferential metal diaphragm is brazed on (Fig. 8). An example of the brazed joint technology required to implement the brazed diaphragm seal is shown in Fig. 9. This brazed joint was formed from three SiC coupons which were coated with tungsten/nickel layers and brazed together with an aerospace-type AMS-4783 braze at a brazing temperature of 2150°F.

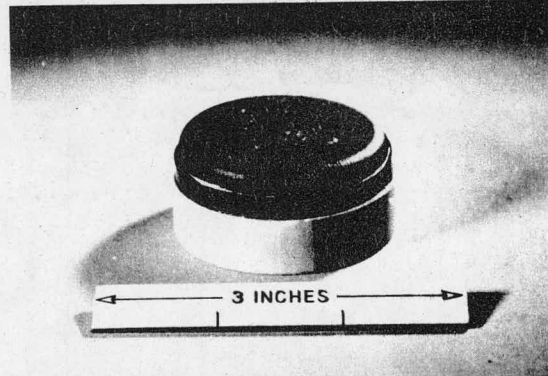


FIG. 7 HIGH-TEMPERATURE GLASS SEALS - 2" DIAMETER

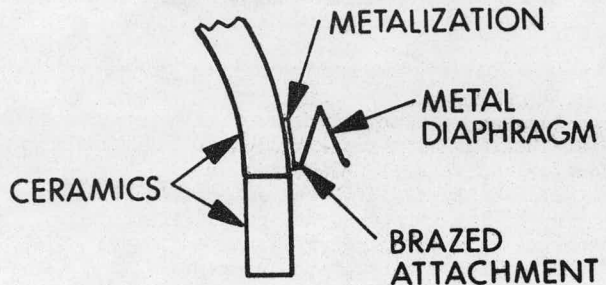


FIG. 8 BRAZED CERAMIC/METAL SEAL CONCEPT

A series of tests³ were conducted on subscale ceramic-to-ceramic mechanical contact seals (Fig. 10) and a seal scaling law which included the effects of surface roughness, gas temperature, seal width and seating pressure. Extrapolations of the 2-inch-diameter mechanical contact seal test results to seals of 12-inch diameter, operating at expected receiver temperatures, predicted a seal leakage rate which was more than three orders of magnitude less than the one-percent leakage design goal.

Based on considerations of ease of implementation, potential cost, and the promise of the approach, the mechanical contact seal was selected for further demonstration at the 12-inch-diameter size.

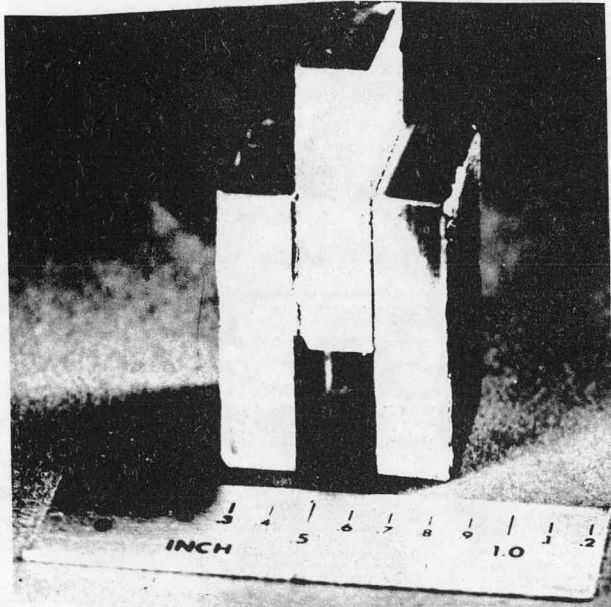


FIG. 9 BRAZED CERAMIC-TO-CERAMIC TEST JOINT

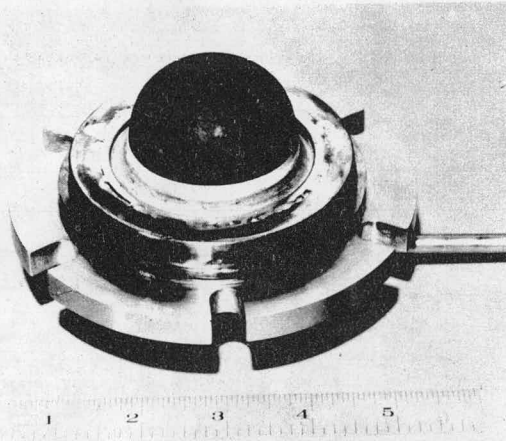


FIG. 10 MECHANICAL CONTACT SEAL - 2-INCH DIAMETER

Experimental Apparatus

The twelve-inch-diameter ceramic-to-ceramic contact seal tests were performed by constructing a dome seal test unit, Fig. 11, and mounting it on the top of an existing cylindrically shaped, electrically heated radiant furnace as shown in Fig. 12. The dome test fixture houses the dome, dome-insulating support ring and metal support structure. The space above the dome could be pressurized and the dome was radiantly heated to the desired temperature from below by the radiant furnace. Seal tests were conducted at the correct seal pressure differential and temperature but without impingement cooling and heat transfer through the dome. Leakage measurements are reported below for two cases; a hemispherical dome freely supported on an insulating ring which in turn sits freely on a secondary seal. Tests on shallow dome configurations provided similar results to those for the hemispherical dome and therefore are not reported here.

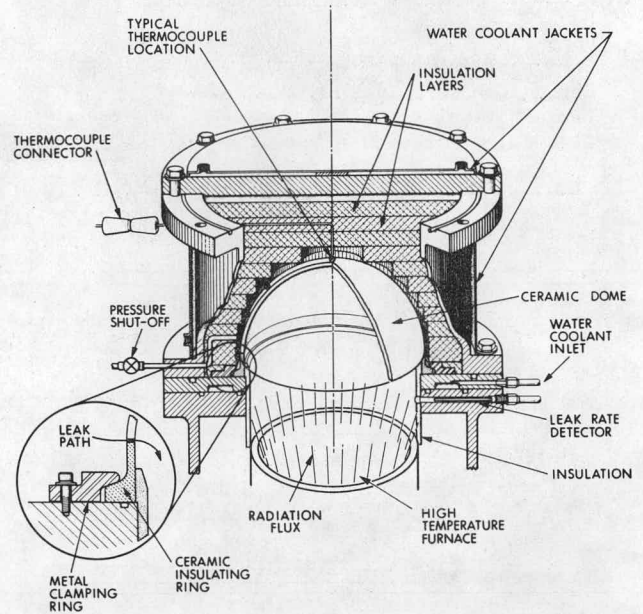


FIG. 11 HIGH-TEMPERATURE SEAL TEST UNIT

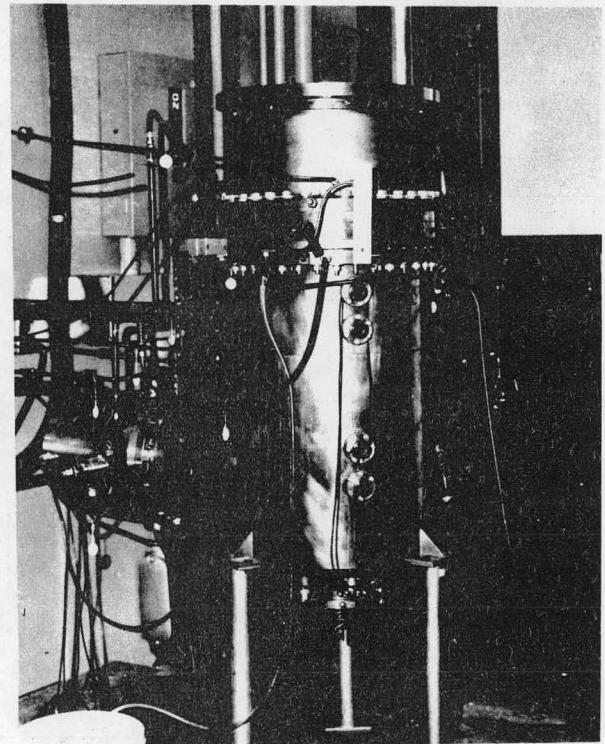


FIG. 12 SEAL TEST UNIT MOUNTED ON RADIANT FURNACE

Industrial ceramic manufacturers manufactured the ceramic hardware required for the seal tests. One-foot-diameter silicon carbide (SiC) insulating rings (Fig. 13), were delivered by Materials Technology Corporation (MTC) Dallas, Texas and by Norton Company, Worcester, Massachusetts. The MTC insulating rings were constructed by CVD deposition of a layer of silicon carbide on a graphite mandrel while those from Norton were solid SiC, prepared by a process which employs slip casting, firing and siliconization; designated as Norton

NC-430 SiC. One-foot span NC-430 SiC shallow domes and one-foot-diameter NC-430 SiC hemispherical domes were also delivered by Norton Company (Fig. 14). An assembled hemispherical dome seal test unit is shown in Fig. 15.

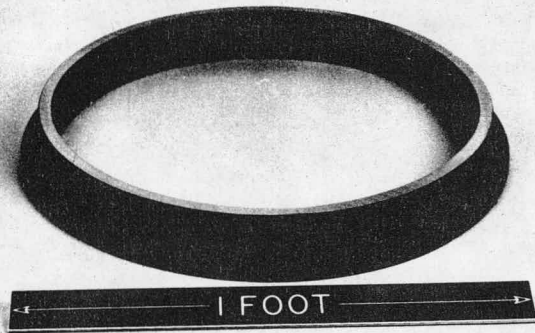


FIG. 13 TYPICAL ONE-FOOT-DIAMETER SILICON CARBIDE INSULATING RING

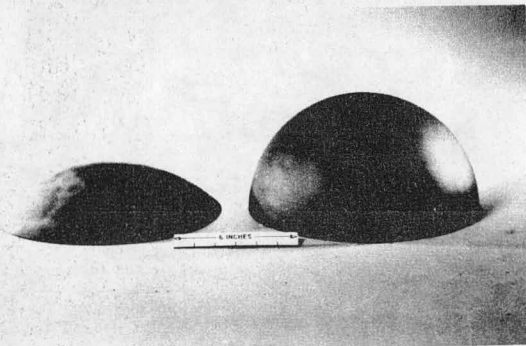


FIG. 14 ONE-FOOT-DIAMETER SHALLOW AND HEMISPHERICAL DOMES

Seal Leakage Measurements

Leakage tests were performed on a number of candidate seal configurations with the baseline seal configuration consisting of a hemispherical dome sitting freely on a clamped insulating ring, with a clean copper gasket for the secondary seal (Fig. 16). The clamping system for the insulating ring was designed to have translational freedom in the vertical direction in order to avoid any buildup of temperature stresses related to differential thermal expansion between the ceramic and metal support units. Gas leakage through the dome seal system into the furnace space was measured by flow meters connected to the furnace space.

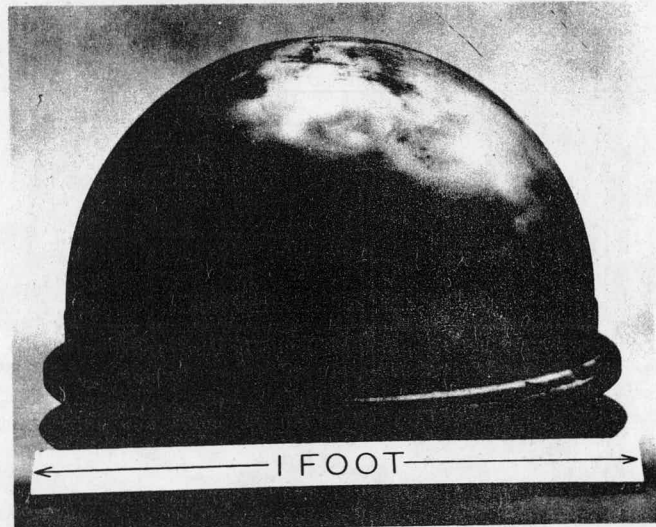


FIG. 15 HEMISPHERICAL SiC DOME SEAL TEST UNIT

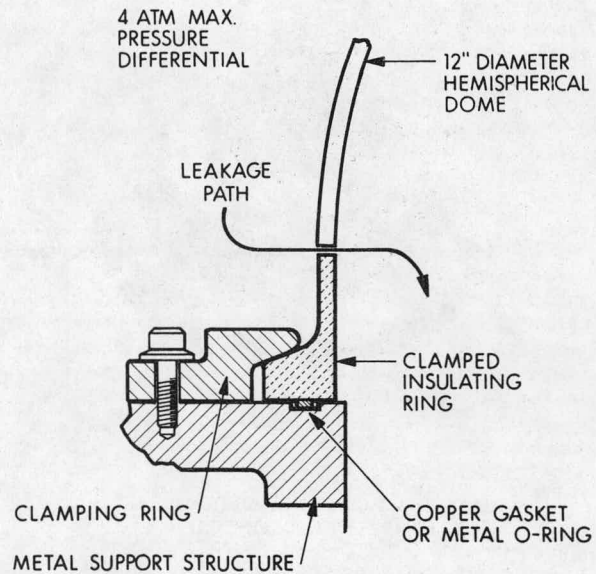


FIG. 16 BASELINE SEAL GEOMETRY

Baseline Seal

Experimental seal leakage rates for a one-foot-diameter baseline ceramic dome seal are illustrated in Fig. 17. The seal leak rate was found to decrease rapidly with temperature (also observed in the earlier test series using two-inch-diameter ceramic hardware) and essentially zero leak rate ($<.004$ SCFH) was measured for seal temperatures above 1000°F . The rapid decrease in leakage rate with increasing temperature is due to the increase in viscosity of gases. The surface finishes on the dome and ring were 10 inches and 6 inches, respectively, and were prepared by a local ceramic grinding house using standard diamond-grinding techniques. Diamond-ground surfaces were more than adequate for the tests and smoother lapped surfaces were not

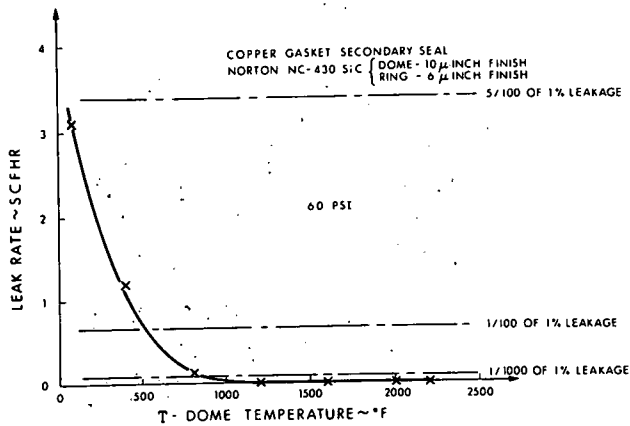


FIG. 17 BASELINE SEAL LEAK RATE VARIATION WITH TEMPERATURE 12-INCH-DIAMETER HEMISPHERICAL DOME ON CLAMPED INSULATING RING

needed. Constant leak rate levels as a fraction of the 1% leakage goal are superimposed on Fig. 10 and a comparison of the experimental leak rate data with these values shows that the baseline seal leak rate at temperature is substantially below the 1% goal. For temperatures above 1000°F, the leak rate was always less than 1/1000 of the 1% goal.

Baseline Seal With Unclamped Insulating Ring

The exceptional performance of the baseline mechanical contact seal, as exemplified by its low leakage rate in comparison to the 1% leakage goal, raised the possibility that the seal design approach could be simplified while maintaining the leakage at or below the design goal. One approach that was investigated in the test series was the possible elimination of the metal clamping ring and bolt system.

Tests were run on the baseline seal configuration with an unclamped insulating ring to determine the leakage rate as a function of temperature and pressure. Leakage data at 2000°F and 2200°F are shown in Fig. 18 for pressures to 60 psi (4 atmospheres). At 2000°F, the seal leak rate is 1/10th of the goal while at 2200°F it is 1/100th of that goal.

Comparison of Seal Leak Data

The leak data measured on the baseline mechanical contact seal and baseline seal with unclamped insulating ring are compared with each other and to fractions of the leakage goal in Fig. 19. The baseline seal has a lower leak rate than the baseline seal with unclamped ring. However, both seal configurations have leak rates at all temperatures which are below the 1% leakage goal.

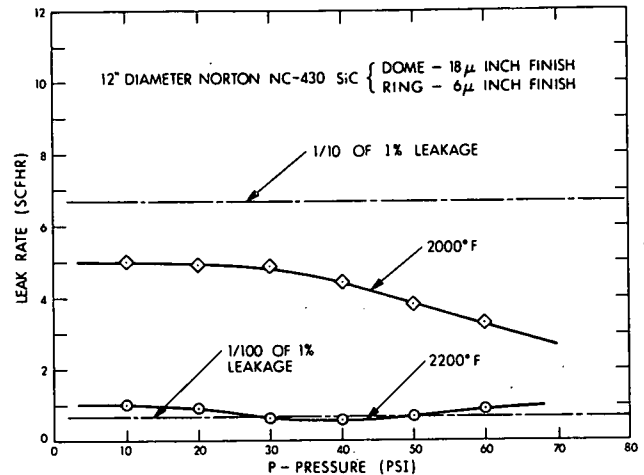


FIG. 18 LEAK RATE - 12-INCH-DIAMETER HEMISPHERICAL DOME ON UNCLAMPED RING

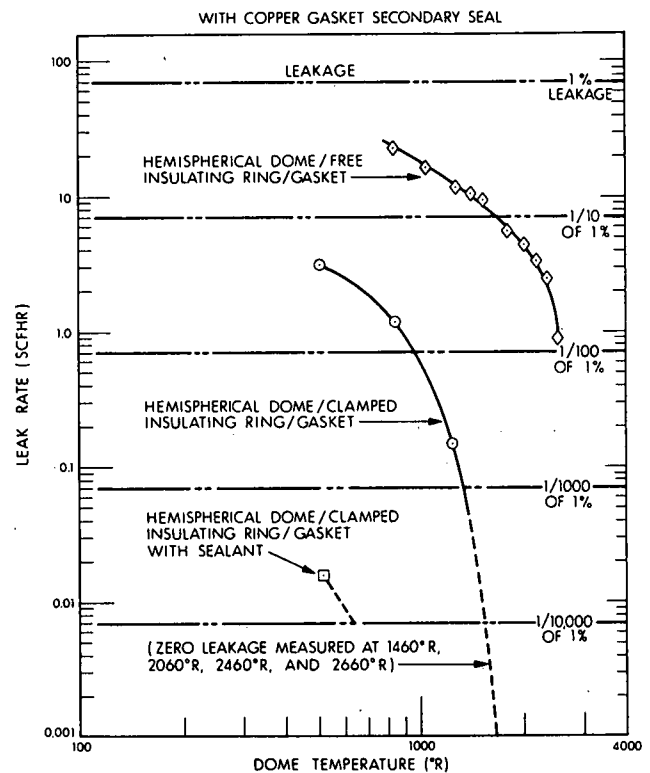


FIG. 19 COMPARISON OF THE LEAKAGE RATES OF VARIOUS CONFIGURATIONS

Ceramic Dome Combined-Cycle Solar Central Receiver Concept

Combined-cycle solar central receiver hybrid power systems have been studied and have been identified as having a number of advantages in comparison to other approaches. Receiver subsystem designs have been prepared⁴ for metallic and for tubular ceramic units. Fig. 20 shows an alternative ceramic receiver design for the receiver geometry of Reference 4. In this new approach, ceramic impingement-cooled dome heat exchangers are assembled together to

REFERENCES

1. Hamilton, N. I., and Jarvinen, P. O., "Solar Radiation Flux Distributions in Cavity Receivers", MIT Lincoln Laboratory Report C00-4878-9 (28 November 1979).
2. Sheldon, D. B., "Edge Stresses in Spherical-Shell Solar Receivers", MIT Lincoln Laboratory Report C00-4878-11 (18 January 1980).
3. Jarvinen, P. O. "Ceramic Receivers for Solar Power Conversion", AIAA Paper #79-1008, AIAA Terrestrial Energy Systems Conference, Orlando, Florida (June 4-6 1979).
4. "Combined Cycle Solar Central Receiver Hybrid Power Systems Study", Bechtel National, Inc., Report No. DOE/ET/21050-1 (November 1979).

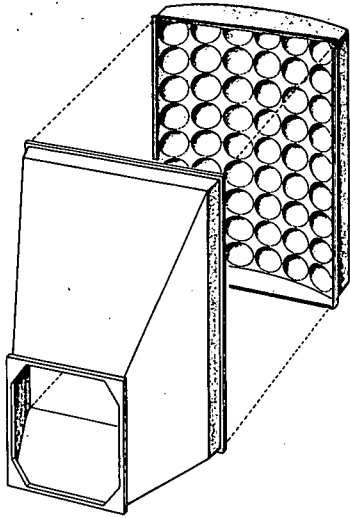


FIG. 20 CERAMIC DOME RECEIVER CONCEPT
FOR COMBINED-CYCLE SOLAR CENTRAL
RECEIVER HYBRID POWER SYSTEMS

form the rear wall of the receiver. The face of the wall is formed by vertical columns of domes, with individual domes cantilevered from vertical support pipes through which the incoming cool air supply and outgoing heated-air streams flow.

Conclusions

A mechanical contact seal has been successfully demonstrated on one-foot-diameter silicon-carbide ceramic-dome hardware at pressure differentials to four (4) atmospheres and at temperatures to 2200°F. Experimental measurements of the leakage of such seals have been carried out and the results compared with the goal of developing a seal with a leakage which is 1% (or less) of the heat-transfer airflow impinging on the dome. For all seal configurations tested and for all test temperatures between room temperature and 2200°F, the experiment leak data demonstrated that the contact seal approach easily bettered the 1% leakage goal. In fact the baseline seal arrangement demonstrated leakage which was but a fraction of the goal: a leak rate less than 1/10000th of the goal at typical seal-operating temperatures. Measured leakage rates on the baseline seal were so low that the metal clamping ring and bolt system could be eliminated from the baseline design with the measured leakage still remaining below the desired level. The mechanical contact seal which has been tested and proven provides a solution to the high-temperature seal question which was felt to be the technologically pacing element in the development of the Solar Heated-Air Ceramic Dome Cavity Receiver (SHARE) concept. A number of receiver configurations appear to be likely candidates for application of the developed dome heat exchanger technology.