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ADVANCED SOLAR RECEIVER DEVELOPMENT*+

MASTER

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ABSTRACT

Ceramic receivers for advanced solar Brayton and advanced solar Stirling thermal power systems are considered which utilize impingement jet cooled silicon carbide ceramic dome heat exchanger modules in conjunction with a cavity receiver geometry to heat a pressurized gaseous heat transfer fluid to temperatures in the range from 1800 to 2400°F. Conceptual designs of single and multiple-dome ceramic cavity receivers are presented and analyzed and a combined analytical and experimental program to develop a high temperature seal for the ceramic dome module is reported.

1. INTRODUCTION

The paper first describes potential applications for the ceramic receiver technology, namely central tower and dispersed dish solar thermal electric systems. Single and multiple dome conceptual receiver designs are offered for the parabolic dish/receiver application. Incident flux distributions in cavity receivers are presented along with the resulting temperature and flux distributions when cavity reradiation, radiation loss and heat transfer effects are modeled. It is shown that high cavity efficiencies are possible with careful design of the receiver geometry.

Next, a combined analytical and experimental program to develop a high temperature seal between the ceramic dome and receiver support structure is described. The seal is designed to have negligible leakage when supporting a pressure differential of four atmospheres and operating at 1800 to 2200°F. Ceramic dome stress calculations, selection of preferred receiver/dome sealing approaches, mechanical seal leak measurements and metalization of ceramics, in support of the high temperature seal development work, are discussed.

2. CERAMIC DOME RECEIVER APPLICATIONS

Ceramic dome cavity receivers are applicable, Figure 1, to large central tower systems, dispersed dish systems, or fuel/chemical systems (not shown) that require a pressurized working fluid, typically a gas, to be heated to temperatures above 1800°F; such high operating temperatures preclude the use of metal receivers.

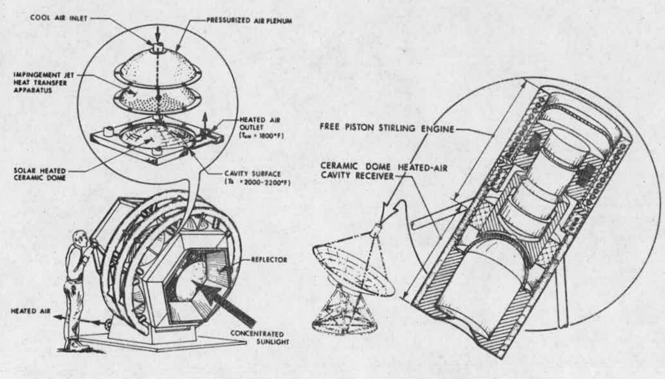

Fig. 1 Conceptual designs of a 1 MW_t central tower type and a point focus type ceramic dome heated air receiver

3. RECEIVER CONCEPTS FOR PARABOLIC DISH/ RECEIVER APPLICATIONS

The receiver unit may be constructed from multiple ceramic modules on which the incident solar flux impinges directly, Figure 2, or be of a design which depends on a process of absorption on the back wall of the receiver followed by reradiation of the heat to the ceramic heat transfer modules, Figure 3. Receivers with up to 75 kW_t capacity may be constructed from single domes at the present time. Receivers of higher thermal capacity require multiple dome configurations.

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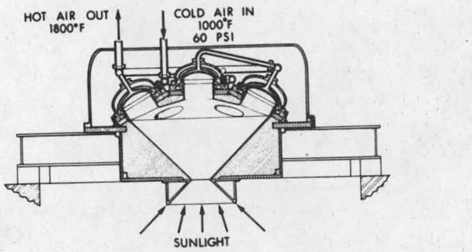

Fig. 2 Multi-dome direct receiver concept

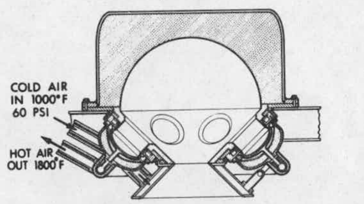

Fig. 3 Indirect multi-dome receiver concept

4. CERAMIC DOME MODULE

The ceramic dome module consists of a cool air entrance plenum, perforated impingement jet plate, silicon carbide dome and an insulating dome support ring (Figure 4). Impinging jets strike against the solar heated ceramic dome and remove heat into the airflow by jet action. Designs have been prepared and analyzed in which the ceramic dome is free to move on the insulating ring or in which the dome is clamped on the ring as shown in Figure 4. The insulating ring provides a temperature drop between the dome and the metal support structure. The design goal for the mechanical contact, high temperature seal at the dome/ring contact surface is a leak rate of one percent (or less) of the total flow impinging on the dome.

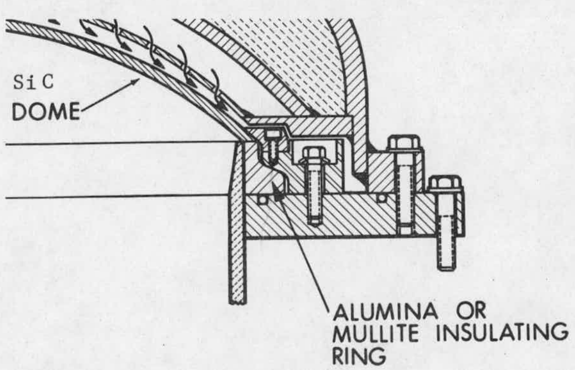

Fig. 4 Ceramic dome module

5. RECEIVER PERFORMANCE

Analytical techniques have been developed which provide incident flux distributions in cavity receivers heated by parabolic dishes (Figure 5) and which also provide the temperature distributions which result when reradiation heat transfer, power extraction and radiative heat loss processes are going on simultaneously in the cavity. These methods have been used to evaluate the operating efficiencies (ratio of the extracted energy to the energy entering the cavity) of direct and indirect receivers and it has been determined that direct receivers in which the incident solar energy impinges directly on the ceramic heat exchanger modules have efficiencies on the order of five points higher than indirect receivers. The efficiencies shown in Figure 6 are high since they assume a value of unity for the cavity absorptivity. Actual receivers would have lower absorptivities and thus lower operating efficiencies than this example. It is estimated that real life effects including reduced absorptivity and specular reflection would reduce these values by about 10 points (or less).

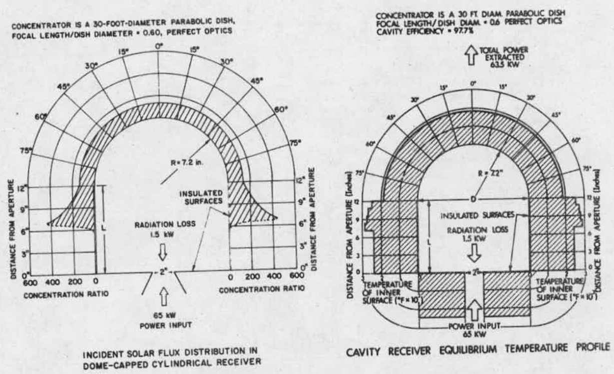

Fig. 5 Cavity receiver solar input and operating temperature distributions

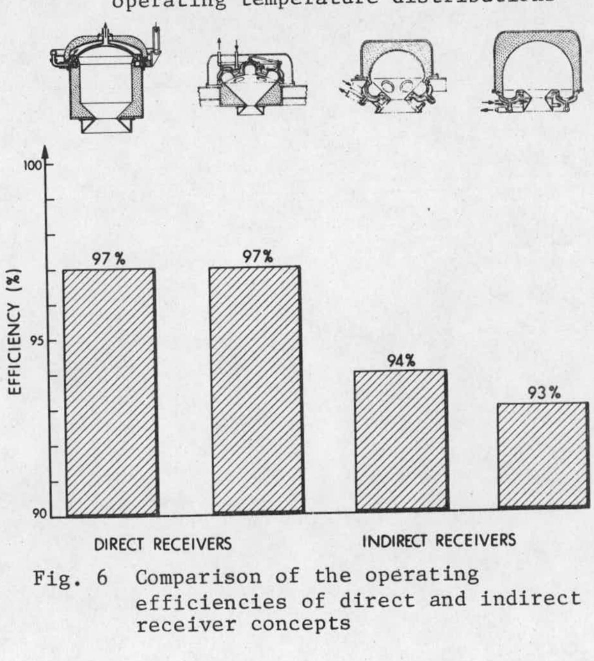

Fig. 6 Comparison of the operating efficiencies of direct and indirect receiver concepts

6. DOME STRESS ANALYSIS

Analytical methods based on Timoshenko's treatment of plates and shells have been used to evaluate the stresses in ceramic domes with free or clamped edge conditions subjected to a pressure differential of four atmospheres and thermal stresses arising from a 400°C/inch temperature gradient through the dome thickness. Resulting stresses in a 12-inch-diameter SiC dome with free edge conditions are shown in Figure 7. The maximum tensile stress of 9000 psi occurs on the outside of the dome at the equator for this example. Maximum stresses in domes of hemispherical and shallow shape with various dome thicknesses and spans are tabulated in Figure 8. Based on these analyses and an assessment of dome fabrication techniques, two support/seal configurations were selected; a free hemispherical dome and a clamped shallow dome each of 12" span and 1/8" thickness. The predicted stresses for these configurations of 9000 psi and 5950 psi respectively are low in comparison to silicon carbide material strengths which range from a low of 38000 psi to a high of 68000 psi, Figure 9.

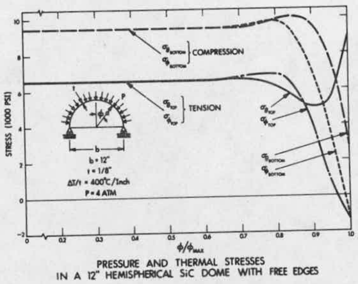

Fig. 7 Pressure and thermal stresses in a 12" hemispherical SiC dome with free edges

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. 8 Maximum stresses in SiC domes

	NORTON NC-430	NORTON NC-435	MTC* 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

Fig. 9 Moduli of rupture of representative SiC materials at 1200°C

7. INSULATING RING STRESSES

Stresses in the insulating ring which arise from the dome pressure loads on the dome/ring interface (200 pounds per linear inch), from a 400°F temperature difference across the ring and a clamping force of 150 lbs. per linear inch have been calculated by finite element methods and have been found low in comparison to ceramic material strengths. Results for a SiC insulating ring are shown in Figure 10.

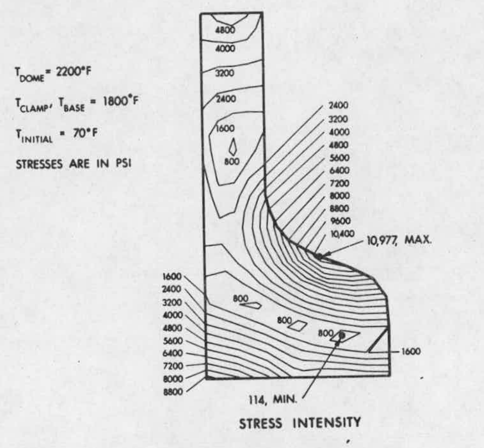

Fig. 10 Stresses in a 12" diameter SiC insulating ring

8. MECHANICAL SEAL LEAK TESTS

Mechanical contact seals in which a hemisperical dome or flat disk sits freely on a supporting alumina insulating ring, Figure 11, have been tested for leakage as a function of surface finish and gas temperature, Figure 12. Tests were carried out on 2-inch-diameter hardware by placing the seal within a pressurized vessel which itself was inside a laboratory furnace, Figure 13. The leakage through the seal was measured by a mass flowmeter attached to the interior space of the dome/ring unit. The leakage was found to be very low at room temperature and to decrease further as the temperature was raised.

Extrapolations of the data to 12-inch-diameter seals were made, Figure 14, and leakage flows which are two or more orders of magnitude less than the one percent design goal are predicted. Efforts are underway to confirm the extrapolations by testing 12-inch-diameter seals using a large radiant furnace on which the dome test unit is mounted on. A cross-sectional view of the 12-inch dome seal test setup is offered in Figure 15 along with a photograph of the actual equipment, Figure 16. Tests of the 12-inch-diameter ceramic ring/dome hardware shown in Figures 17 and 18 are now underway at MIT/Lincoln Laboratory.

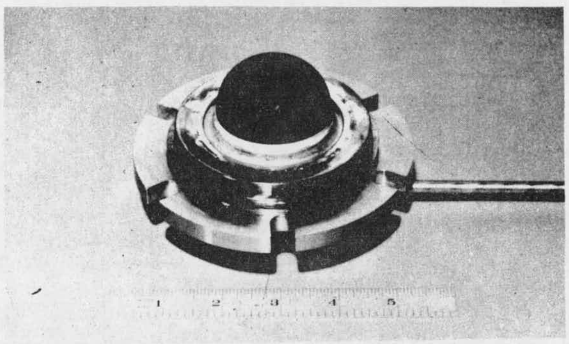

Fig. 11 Mechanical contact seal test unit

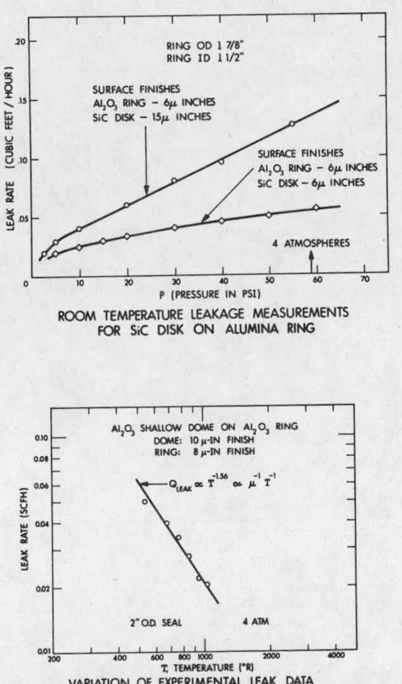

Fig. 12 Effects of surface finish and gas temperature on leakage through the mechanical seal

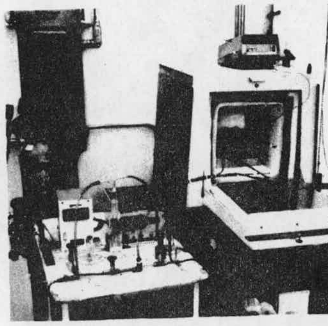

Fig. 13 2" diameter seal test setup

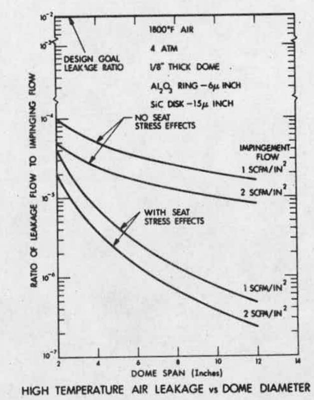

Fig. 14 Leakage predictions for larger diameter contact seals

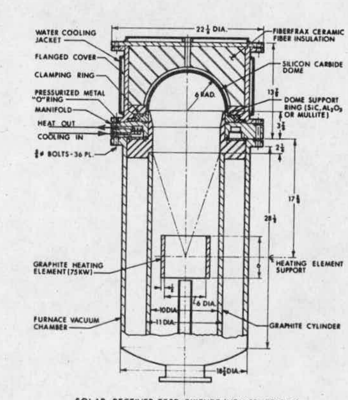

Fig. 15 Cross-sectional view of the seal test unit and radiant furnace

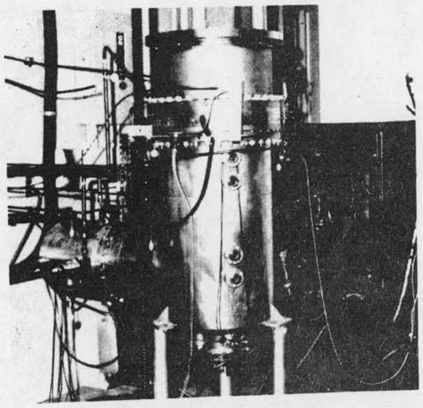

Fig. 16 12" dome seal test setup

Fig. 17 12" diameter SiC insulating ring

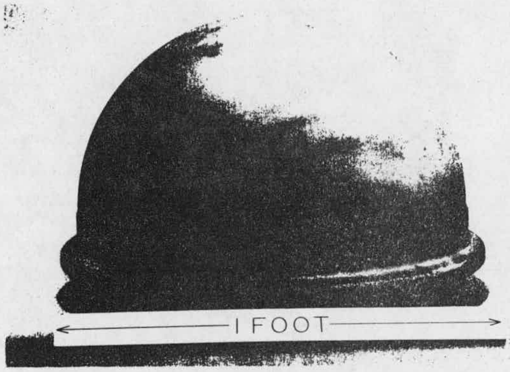

Fig. 18 12" diameter Norton NC-430 dome mounted on insulating ring

9. CERAMIC METALIZATION AND BRAZING

Methods have been developed during this program to metalize and braze silicon carbide ceramic pieces so that a leak tight diaphragm seal could be attached to the periphery of the silicon carbide dome, Figure 19, if desired. Ceramic/metal couples listed in Figure 20 were fabricated and cycled in a laboratory furnace to assess coating bonding and adhesion. Highly successful methods of vacuum sputtering the metal coatings to the ceramic samples and brazing the joints were developed. A ceramic joint consisting of three pieces of SiC which have been metalized with tungsten and nickel layers and brazed at 2150°F is shown in Figure 21.

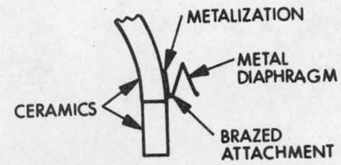

Fig. 19 Diaphragm seal at the dome edge

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	

Fig. 20 Ceramic/metal combinations tested for adherence qualities

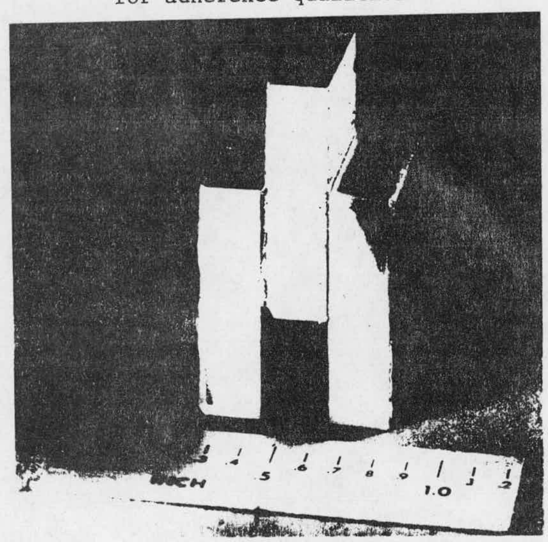

Fig. 21 Metalized and brazed SiC joint

10. CONCLUSIONS

Analytical and finite element structural analyses of ceramic dome units demonstrate that ceramic domes can be designed to support the pressure, thermal stress and temperature loads encountered. Experimental leak tests of mechanical contact seals at high temperatures establish the feasibility of that design approach. Ceramic metalization techniques for silicon carbide materials are reported which allow the fabrication of an alternative brazed diaphragm seal, if desired.