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THE DEVELOPMENT OF AN 85-kW (THERMAL) AIR BRAYTON SOLAR RECEIVER

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ABSTRACT

The AiResearch Manufacturing Company is under contact to the Jet Propulsion Laboratory (JPL) to manufacture prototype Brayton receivers for the Parabolic Dish Solar Thermal Power Systems Project. This paper summarizes the work accomplished in the program and describes the JPL testing of the receiver at the Parabolic Dish Test Site, Edwards AFB, California.

INTRODUCTION

In June 1979, The AiResearch Manufacturing Company received a contract from the Jet Propulsion Laboratory (JPL) for the design and fabrication of two prototype air Brayton solar receivers (ABSR's) as part of the Parabolic Dish Solar Thermal Power Systems Project directed by JPL and sponsored by the Department of Energy. These prototypes are designed to receive 85-kW thermal insolation at the focal plane of a parabolic dish concentrator and transfer that energy into the fluid stream of an open, regenerated, Brayton-cycle system. Initial receiver evaluation testing is now being conducted by JPL, utilizing the test bed concentrator developed for this type of activity at the Parabolic Dish Test Site. Following that evaluation, the prototypes will be available for incorporation into a demonstration of the Brayton cycle.

This paper describes the results of the program from its inception through December 1980. The first section will briefly describe the design requirements, concept, and significant analysis upon which the receiver is based. Section two will describe the fabrication processes that have been utilized in the construction of the prototype receivers now at the test station. Section three, the concluding section, describes the test and evaluation phase underway at the Parabolic Dish Test Site.

DESIGN REQUIREMENTS, CONCEPT, AND ANALYSIS

The design requirements for the ABSR were prepared by JPL, based upon its application as the heat source in a gas turbine engine system. The system schematic is shown in Figure 1. The solar input is 85 kW. The energy is concentrated at the receiver aperture by an 11-m parabolic dish that has a focal length of 6.6 m and an assumed slope error of between 1 and 2 milliradians. This energy is used to heat the air of the recuperated open-cycle gas turbine engine from 565° to 816°C (1049° to 1500°F). The operating air pressure is 225.5 kPa (36.75 psia) and the pressure drop of the receiver is 2.5 percent

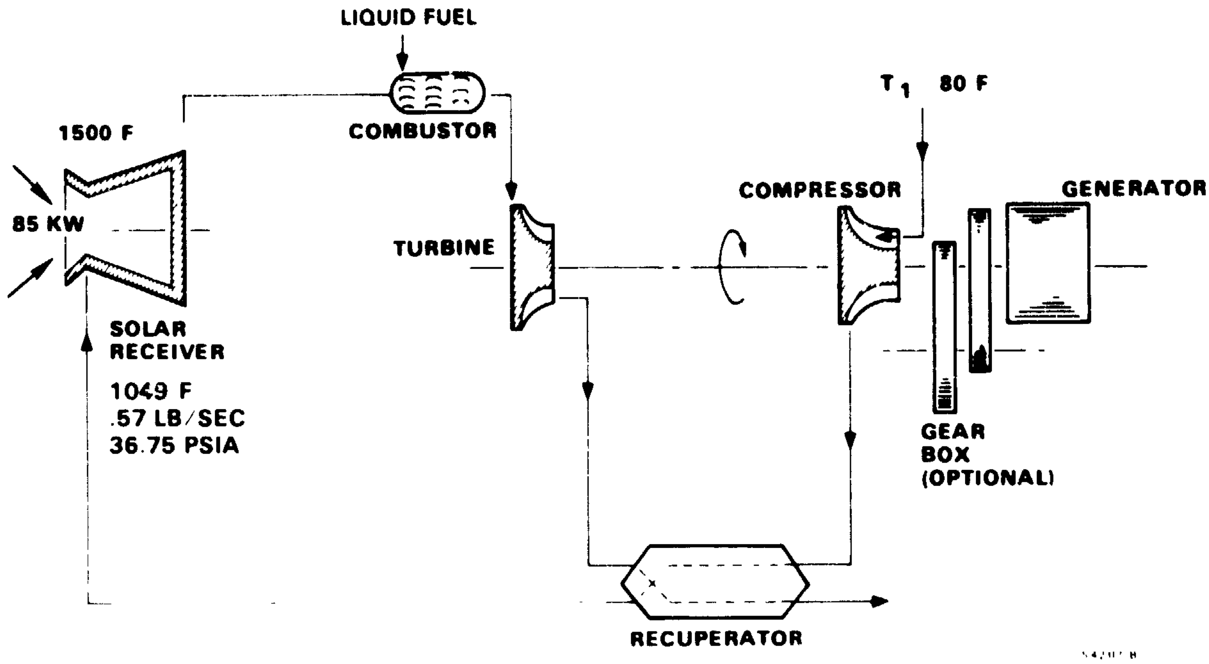

FIGURE 1. BRAYTON SYSTEM SCHEMATIC

$\Delta P/P$. Transient and off-design conditions are consistent with gas turbine operation. The unit will be mounted at the focal point of the concentrator and will be exposed to the ambient at the test site. As a consequence, the specified environmental conditions are for a high-desert environment, including ambient temperatures between -18° and 51.7°C (0° and 125°F), and wind gusts to 58 km/h (36 mph) with sand and dust.

The ABSR concept developed for this application uses direct air heating. Solar flux passes through an aperture located on the concentrator focal plane and falls upon the interior surfaces of a closed cylinder whose axis is located on the concentrator center line. The cylinder contains axial flow passages that bring the air discharging from the recuperator into contact with solar-heated surfaces. Heat transfer in the flow passages is enhanced by the use of an extended-fin surface. Neither the closed nor aperture ends of the receiver have airflow. These surfaces reradiate the impinging energy to the cooled heat-transfer cylinder.

Design optimization was based on thermal analysis performed by a finite element computer code developed by AiResearch. This optimization led to the ABSR design shown in Figure 2. The single sandwich cylindrical panel with an offset fin matrix of 4.72 fins/cm (12 fins/in.) has a 1.27-cm (1/2-in.) high-flow passage. The heat exchanger is supported by a series of slotted tubes and is insulated from the outer case. The heat exchanger is a brazed and welded structure

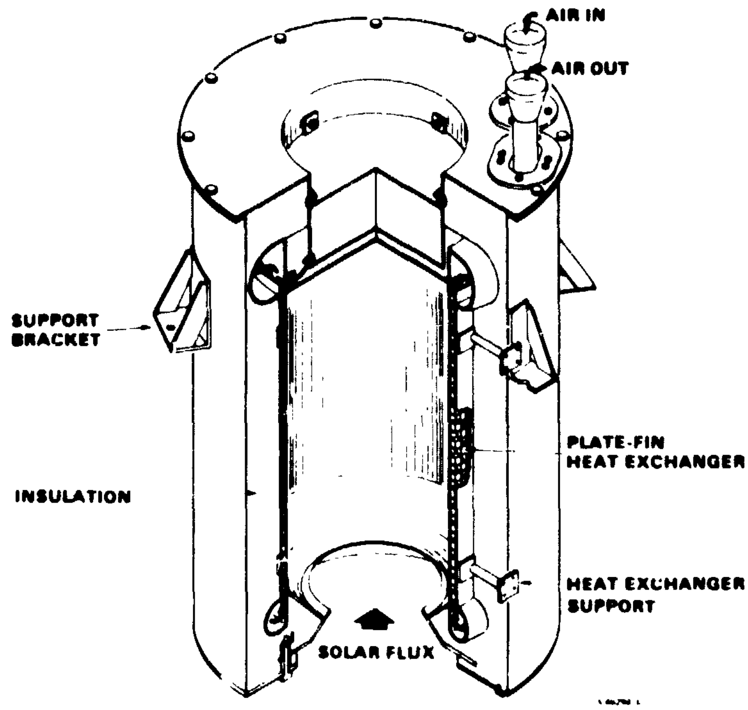

FIGURE 2. PROTOTYPE AIR BRAYTON RECEIVER

fabricated from Inconel 625. The stainless steel mount system allows for both axial and radial expansion of the heat exchanger with respect to the external mild steel case. The uncooled aperture and closed end are fabricated from silicon carbide. Both the circular closed end plate and the aperture assembly are mounted to minimize heat loss to the relatively cold receiver case. The physical characteristics of the design are shown in Table 1. The method followed in optical and thermal design has previously been reported and will not be repeated here.* The results of the thermal design indicate that the ABSR will perform with an overall efficiency of more than 90 percent.

A detailed structural analysis was undertaken to verify the adequacy of this design. The combined thermal and pressure-induced stresses were calculated for critical design elements. In the initial phases of this analysis, it became apparent that a continuous inner and outer shell would not be successful. This conclusion was based on the thermal gradient that is calculated to exist between the inner and outer shell (see in Figure 3). The peak heat input to this cylinder occurs approximately 1/3 of the distance toward the closed end. At that point, a 110°C (230°F) thermal gradient exists between the two surfaces. The thermally created stress, which develops as the result of the differential expansion of the two continuous cylinders, significantly exceeds the material strength limits.

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*M. Greeven, M. Coombs, and J. Eastwood, The Design of a Solar Receiver for a 25-kW(e) Gas Turbine Engine, paper presented at the Gas Turbine Division Conference of the American Society of Mechanical Engineers, March 1980.

TABLE 1

PHYSICAL CHARACTERISTICS OF THE ABSR

Materials		
Heat exchanger	Inconel 625	
Insulation	Cerablanket	
Case	Mild steel	
Aperture	Silicon carbide	
Receiver		
Weight, kg (lb)	203	(447)
Length, cm (in.)	116.1	(45.7)
Diameter, cm (in.)	76.2	(30.0)
Heat exchanger		
Length, cm (in.)	80.3	(31.6)
Diameter, cm (in.)	50.8	(20.0)
Skin thickness, cm (in.)	0.02	(0.008)
Fin thickness, cm (in.)	0.01	(0.004)
Aperture		
Diameter, cm (in.)	25.4	(10)
Conical height, cm (in.)	8.6	(3.4)

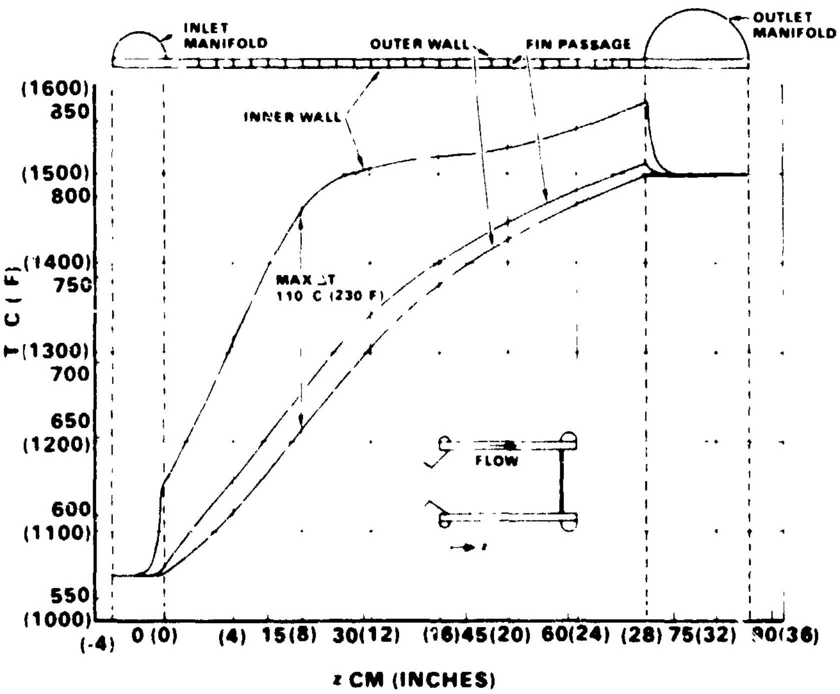

FIGURE 3. RECEIVER THERMAL GRADIENTS

The thermal gradient could be decreased by increasing the performance and conductive cross section of the fin; however, the air pressure drop limitation of 2.5 percent $\Delta P/P$ total is not consistent with this approach.

As a consequence, it was decided to segment the inner surface, and based on the results obtained by analysis, 36 segments were selected. The stress values of various critical design elements are shown in Table 2. These stresses were obtained by developing a structural model of a segment and applying the previously calculated temperatures as well as operating pressures. The analysis revealed that the unit was cycle-life limited as compared to operating-time limited. The inner surface of the unit at the point of maximum thermal gradient could be expected to withstand 6,000 full start/stop excursions prior to initial fracture. This is an acceptable value for a prototype configuration. The structural adequacy of the remaining design components, including the receiver mounting, heat exchanger supports, and manifolds, was verified. None of these elements are stressed to a limiting degree. This completed the analysis, and the design was released for fabrication.

TABLE 2

ABSR OPERATING STRESSES

Location	Temperature, °C (°F)	Stress, MPa (kpsi)
Inner skin	795 (1463)	187.1 (27.12)
Outer skin	666 (1230)	195.3 (28.31)
Fin	730 (1346)	85.1 (12.33)

RECEIVER FABRICATION

The critical fabrication processes for the ABSR are these: forming the offset heat transfer fin, joining of the heat exchanger into a continuous structure, and manufacture of the silicon carbide components.

Fin fabrication requires complex form tooling. The large available inventory of these tools permits selection from a number of different fin geometries. During fin fabrication, the formed fin was reduced from the 12.7-mm (0.5-in.) height selected in design to 6.35 mm (0.25 in.) and then contoured to the cylindrical surface. The lower fin height was selected for the fabrication because it allowed the best match with the desired fin contour, given existing fin tooling. The flow passage height was maintained at 12.7 mm (0.5 in.) by using two fin segments stacked one on top of the other. The principal detail parts of the heat exchanger assembly are shown in Figure 4.

The heat exchanger was initially brazed in three equal 120-deg full-length segments, utilizing an atmosphere furnace. The segments were assembled, tack welded, and then rebrazed for a continuous structure. The two-stage braze procedure also allowed for the braze attachment of the mounting rings and the manifold structure (see Figure 5 for a photograph of the completed heat exchanger assembly prior to manifold attachment). Following final braze, the inlet and outlet manifolds and ducting were welded to the heat exchanger to form the complete heat exchanger assembly.

Each assembly was subjected to both a pressure test and a verification of the predicted pressure drop prior to final assembly into the housing. The pressure test, which was conducted at 446 kPa (64.7 psia) and at room temperature, was based upon an ASME pressure vessel code type requirement; however, code certification was not obtained, because the number of units and their usage did not warrant this activity.

The aperture and reflecting plate were manufactured by the Norton Company, a leading manufacturer of silicon carbide components. The 3-ft and 2-ft diameter of these parts represented a significant fabrication task, but Norton met the challenge. These parts were slip-cast to their finished dimensions.

The first completed ABSR (shown in Figure 6) was delivered to JPL in September 1980; the second, in November. Unit testing is discussed in the following section.

RECEIVER TEST AND EVALUATION

The ABSR was designed to meet several requirements. Primarily conceived as part of a distributed electrical power generation module, it will also be used to heat gases for a variety of other purposes, such as heating process gas streams, preheating combustion gases, and providing heat flows for industrial processes that for economic or safety reasons do not use liquids. Thus the testing program was designed to include a wide range of conditions to demonstrate the versatility of the ABSR in many applications.

Initial tests on each ABSR were performed at AiResearch; these consisted of leakage, proof pressure, and flow continuity tests to ensure basic mechanical integrity. All tests were conducted at essentially ambient temperatures. Performance testing will be conducted at JPL's Parabolic Dish Test Site (see Figure 7). There, two 11-m-dia test bed concentrators have been installed. On a clear day each can concentrate about 82 kW(th) into a 20.3-cm (8-in.) dia focal spot. In addition, an expert test staff and all necessary support equipment, including instrumentation, a computerized data acquisition system, and shops, are available.

Airflow is provided by a 750-cfm diesel-powered air compressor. The air passes through an aftercooler, oil separator, dryer, and filter to ensure flow with only about 0.05-ppm contaminants. Flow rates between 0 and 0.43 kg/sec (0.93 lb/sec) can be produced, which brackets the 0.23 to 0.27 kg/sec (0.5 to 0.6

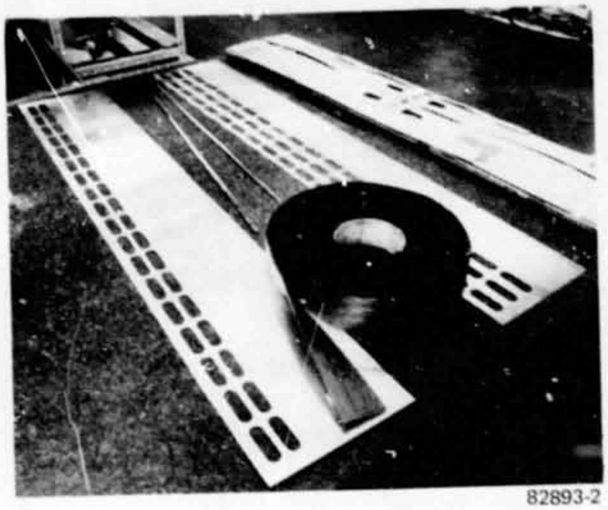
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FIGURE 4. HEAT EXCHANGER DETAIL PARTS

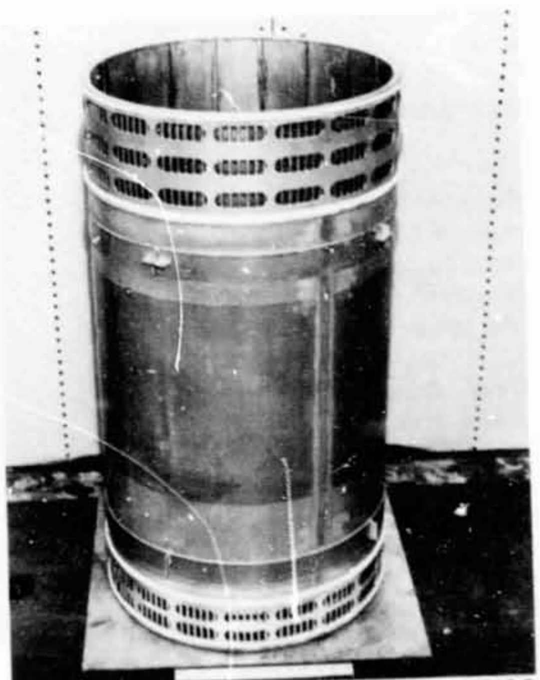
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FIGURE 5. COMPLETED BRAZE ASSEMBLY

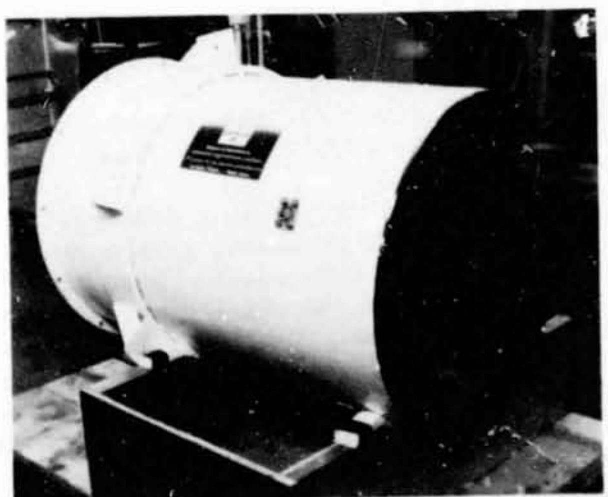
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FIGURE 6. COMPLETED BRAYTON RECEIVER

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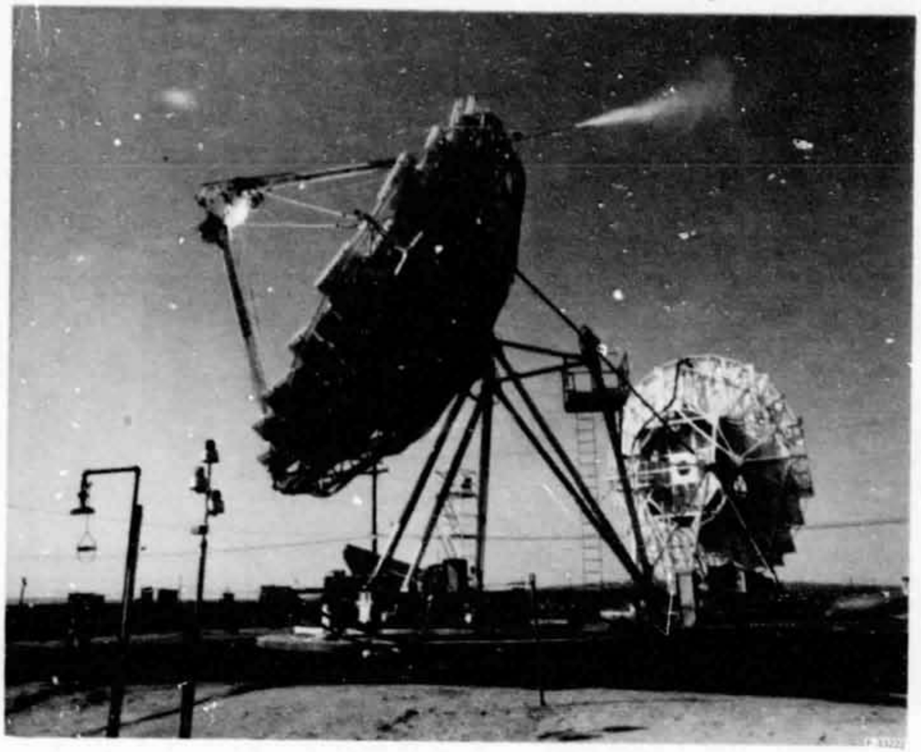

FIGURE 7. PARABOLIC DISH TEST SITE

lb/sec) design flow of the ABSR. Inlet pressures to the receiver will be in the 138 to 276 kPa (20 to 40 psia) range. Flow is controlled by a series of automatic valves; pressure in the ABSR is maintained by a ceramic orifice plate in the outlet piping.

The outlet temperature of the receiver is automatically maintained by the control system. Temperatures will range from about 260°C (500°F) up to the design maximum of 816°C (1500°F). Inlet temperatures range from ambient to about 700°C (1300°F), the maximum-design inlet temperature. In the 200° to 700°C (400° to 1300°F) range, heat is supplied by a propane-fired preheater.

The test matrix proper is a combination of three dynamic variables: mass flow, temperature, and pressure, plus a range of power inputs at 25, 50 and 75 percent as well as full power. Less than full power runs are made by masking off individual mirror facets in patterns devised to maintain the proper overall flux distribution. Testing will begin with the lowest temperatures and power levels and will be increased in steps until full power at maximum temperature is attained. Extensive thermal instrumentation, about 50 channels, as well as a full array of pressures and flows, is automatically monitored by a computerized control and data acquisition system during each test run. Both real time and posttest computational ability is available.

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This series of tests is designed primarily to assess the efficiency and dynamic response of the ABSR. Life and fatigue tests will be conducted later as resources permit.

Testing is scheduled to begin in mid-January 1981, with initial data to be available within a month. Variable winter weather is a problem on the high desert, but a maximum effort is being made to hold to this schedule.