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THE DEVELOPMENT OF AN 85-kW (THERMAL) STEAM RANKINE SOLAR RECEIVER

C. C. Wright
AiResearch Manufacturing Company of California
Torrance, California
H. Bank
Jet Propulsion Laboratory
Pasadena, California

ABSTRACT

The AiResearch Manufacturing Company of California is under contract to the Jet Propulsion Laboratory (JPL) to manufacture a prototype Steam Rankine Solar Receiver (SRSR) for the Parabolic Dish Solar Thermal Power Systems Project. This paper summarizes the work accomplished in this program and describes the JPL testing of the receiver at the Parabolic Dish Test Site, Edwards AFB. The receiver is a once-through monotube boiler designed for steam/electric and process steam applications at pressures up to 17.24 MPa (2500 psia) and temperatures up to 704°C (1300°F). The unit is 76.2 cm (30.0 in.) in diameter and 95.8 cm (37.7 in.) in length; it weighs 220 kg (485 lb). Its heat transfer surface, which is 45.7 cm (18 in.) in diameter by 57 cm (22.4 in.) long, is an Inconel 625, cylindrical, tube-coil assembly composed of primary and reheat sections. A test unit has been successfully operated at up to 6.9 MPa (1000 psia) and 704°C (1300°F) with solar input from a 11-m-dia parabolic dish concentrator.

INTRODUCTION

The participation of AiResearch in the Solar Thermal Power Systems Project at JPL began with a Phase I conceptual design study of a Steam Rankine Solar Receiver (SRSR) in July 1978. The final report on this study was completed in January 1979. On the basis of the Phase I study, final design conditions were formulated by JPL, and in June 1979 a Phase II contract was awarded to AiResearch for the final design and fabrication of an 85-kW (thermal) SRSR. A final design review was held in October 1979, and the first test unit was shipped to JPL in June 1980. A final report on the design and fabrication of the receiver described herein is in preparation. Testing by JPL at the Parabolic Dish Test Site commenced in September 1980.

The purpose of this paper is to (1) summarize the final design goals and conditions, (2) describe the construction details of the receiver, (3) present the estimated performance for a steam/electric application, (4) discuss methods of adapting the SRSR to industrial process steam applications, and (5) present preliminary test results.

DESIGN REQUIREMENTS AND CONDITIONS

The final design requirements are that the SRSR be sized for a steam/electric application with provisions for dual-mode operation (with or without reheat) and that the SRSR be adaptable to industrial process steam applications. The design life is to be 10,000 hours, with 1500 cycles of operation. Weight and size are to be minimal.

The design conditions for both applications are summarized in Table 1. The diurnal solar input is from an 11-m-dia parabolic dish concentrator on an average sunny spring day. The peak input is 85 kW, and the receiver must accept irregularities in solar flux input caused by mirror slope errors, reduced power (10 percent) from one-half of the mirror, and an asymmetric flux profile resulting from a ±2.54-cm (1.0-in.) offset of the receiver axis from the optical axis.

TABLE 1

SRSR DESIGN CONDITIONS

Solar energy source: 11-meter concentrator
Peak power input: 85kW

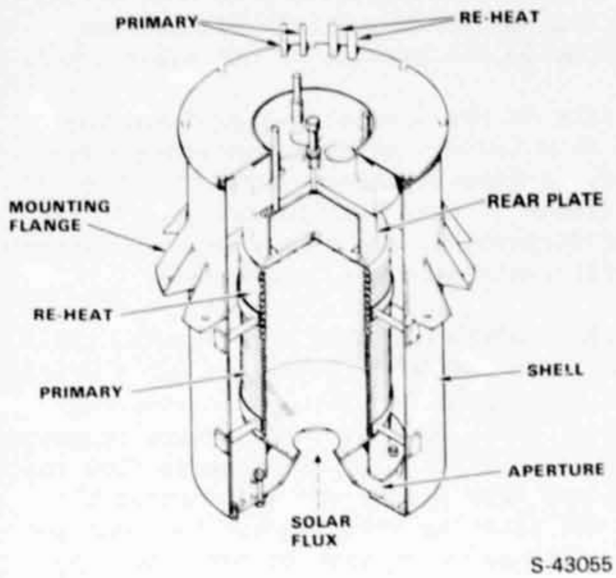
	Process Steam (up to)	Steam/ Electric
Primary section		
Inlet feedwater temperature, °C (°F)	149 (300)	93 to 149 (200 to 300)
Outlet steam		
Temperature, °C (°F)	704 (1300)	704 (1300)
Pressure, MPa (psia)	17.24 (2500)	17.24 (2500)
Reheat section		
Outlet steam temperature, °C (°F)	704 (1300)	704 (1300)
Inlet steam		
Temperature, °C (°F)	704 (1300)	343 (650)
Pressure, MPa (psia)	17.24 (2500)	1.21 (175)

Flow rate: Determine from energy balance; same in both sections
Pressure drop: $\Delta P/P$ = 10 percent

DESCRIPTION OF THE SRSR

A cutaway drawing of the SRSR is shown in Figure 1. The SRSR is a once-through monotube boiler that uses concentrated solar energy as a heat source to produce high-pressure, high-temperature steam at the conditions listed in Table 1. The major components are the outer shell assembly, 15.2 cm (6 in.) of Cerablanket insulation, an Inconel 625 tube-coil heat exchanger assembly, a rear plate that can be moved axially 7.6 cm (3 in.), and an aperture assembly that can be adjusted from 20.3 to 25.4 cm (8 to 10 in.). The rear plate and aperture assembly were made of NC405 silicon carbide, but, as a result of test experience, change to a rear plate of chromium nickel steel (RA 330) and an aperture assembly of graphite is recommended.

The tube-coil heat exchanger assembly is shown in Figure 2. The active heat transfer portion consists of 34 turns of 11.11-mm OD by 1.728-mm wall (7/16 by 0.070 in.) primary section tubing and 10 turns of 19.05-mm OD by 3.05-mm wall



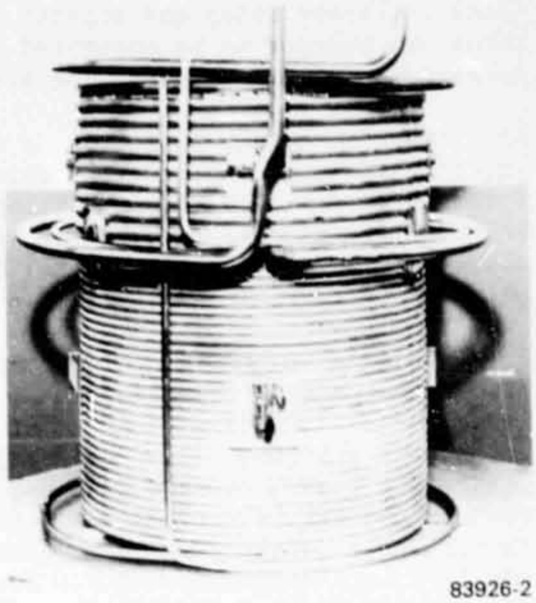


FIGURE 1. STEAM RANKINE SOLAR RECEIVER (CUTAWAY)

FIGURE 2. TUBE-COIL HEAT EXCHANGER ASSEMBLY

(3/4 by 0.120 in.) reheat section tubing. An additional turn of tubing at the ends of each section allows for thermal contraction and expansion of the assembly, and straight runs of tubing are used to route the water or steam to and from the coil. The inner surface of the coil is oxide-coated to produce a surface emissivity of about 0.8. Each section is a rigid, brazed unit, and the two sections are held together by three hinge-type joints. Eight radial post-type supports welded to the coil are used to attach the assembly to the outer case. These supports allow for radial and axial thermal expansion or contraction while preventing rigid body movement of the coil. The entire assembly is mounted to the concentrator boom structures so that the center of the receiver aperture is located at the focal point. The two coil sections can be connected in series for operation in primary mode only or in parallel for operation in the primary plus reheat mode. In the latter case, the primary and reheat outlets are adjacent to each other.

ESTIMATED PERFORMANCE

Method of Analysis

A finite element method of analysis was used to estimate the receiver performance. Incident solar flux on the inner surfaces of the receiver was computed by assuming parallel rays from the sun (point source) as being reflected from a perfect parabolic concentrator. The resulting flux profile was smoothed out and represented in a histogram input to a computer program for computation of the radiation interchange, fluid heat transfer, and pressure drop. This flux profile was the baseline for a sensitivity analysis of various possible incident flux profiles caused by concentrator irregularities.

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Radiation interchange computations were based on the assumption of flat surfaces, an equal solar absorptance and infrared emittance of 0.80, and diffuse radiation (both reflected solar and emitted infrared). Also, the heated surface of the tubes was assumed to be one-third (120 deg) of the total tube outside area. Aperture convection losses were assumed to be 2.5 percent of the solar input.

Heat transfer to the fluid inside the tube in the subcooled liquid and the superheated vapor regions was computed from Colburn modulus versus Reynolds number data for flow in round tubes (1). A tube-length-to-diameter ratio of L/D = 25 was used to account for the effects of tube coil curvature. In the boiling region up to a steam quality of 70 percent, the John Chen correlation was used (2). Vapor heat transfer coefficients were used thereafter.

Pressure drop in the liquid and vapor regions was computed from Fanning friction factor versus Reynolds number data for round tubes having an L/D = 25 (see Reference 1). Pressure drop in the boiling region resulting from momentum change and friction losses was computed with the Lockhart and Martinelli correlation for two-phase flow pressure drop (3). Stable and homogeneous flow was assumed. A stable match point for pump and flow system can be achieved by installing a suitably sized orifice in the plumbing line between the pump and receiver (see Reference 4 for a general discussion of methods for obtaining forced-flow boiling stability).

The thermodynamic process path in the receiver coil for the steam/electric plus reheat mode of operation consists of 28 percent liquid heating, 20 percent boiling, 32 percent superheating, and 20 percent reheating.

Heat Flux Distribution and Temperature Profiles

The solid-line curve in Figure 3 is a graph of the baseline incident heat flux distribution inside the receiver cavity. The absorbed flux for the primary plus reheat steam/electric design condition is represented by the dashed line. This occurs after radiation interchange and heat transfer to the fluid has taken place. The difference between the incident and absorbed flux is caused by radiation from the uncooled end plate and front cone, where very little heat flux is absorbed, and by the heat losses (radiation out of the aperture and convection from the receiver casing, especially the front end).

Figure 4 is a graph of the resulting tube-wall and fluid temperatures in the axial direction along the coil. Note that the primary and reheat fluid inlets are on opposite ends of the coil assembly and that the two outlets are adjacent to each other. This flow arrangement was selected to avoid a large temperature discontinuity at the junction of the two coils. Also, the lengths of the two coils were proportioned to obtain equal temperatures at the primary and reheat steam outlets. The temperature profiles in Figure 4 are valid only for the incident heat flux distribution displayed in Figure 3. If some other incident flux distribution occurs, then the positionable end plate must be moved either forward or backward to equalize the steam outlet temperatures and to prevent overheating of one of the coils at its outlet. For example, if the concentrator has a larger slope error than the baseline case or if there is haze in the atmosphere, the heat flux will be shifted towards the rear of the cavity. This will cause underheating of the primary steam and overheating of the reheat steam (and tubing near the outlet). Equalization of the steam outlet temperatures can be accomplished by moving the end plate forward.

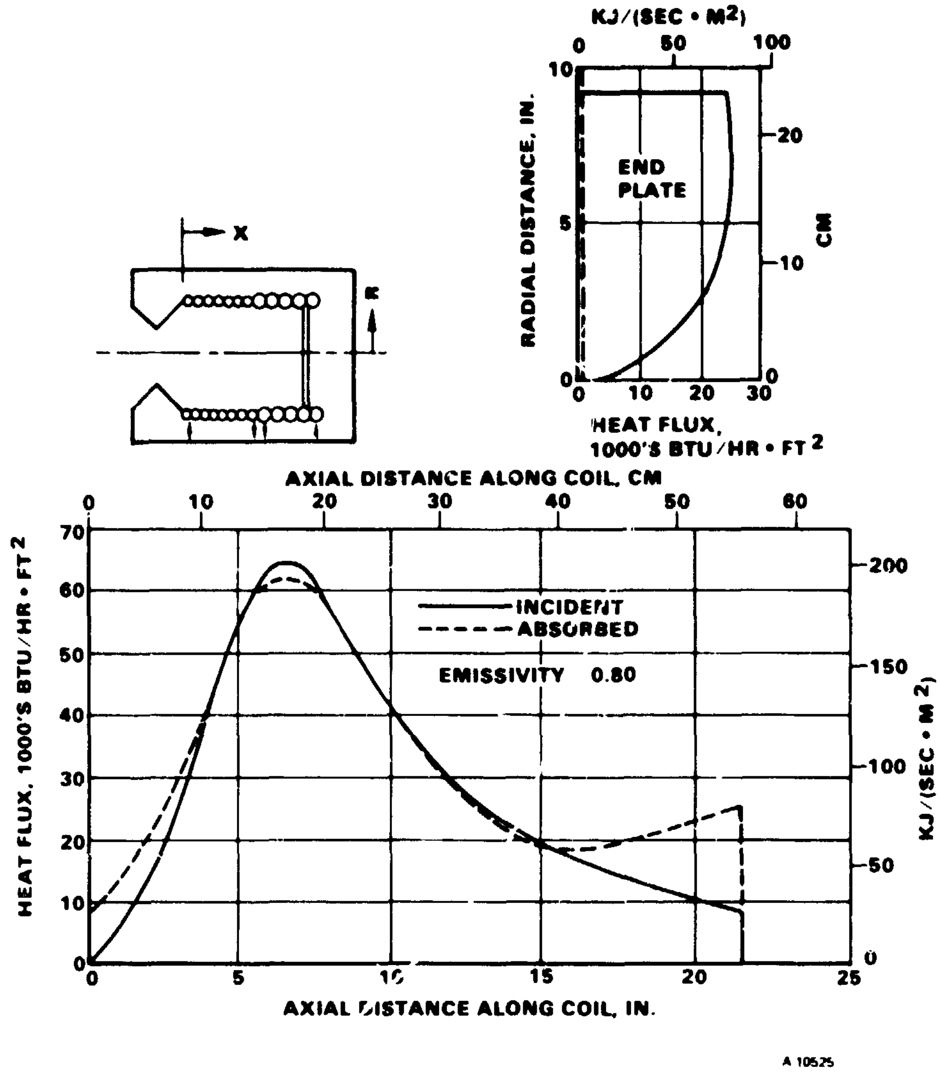

FIGURE 3. BASELINE HEAT FLUX DISTRIBUTION

In the primary mode only operation, during which the two coils are connected in series, the three zones (liquid heating, boiling, and superheating) will be extended over a greater axial distance, and the steam outlet will occur at the rear of the coil assembly. In this mode, the position of the end plate remains fixed at the rear for all incident heat flux distribution.

Summary of Estimated Performance

The estimated overall energy balance and pressure drop performance of the SRSR for the steam/electric application is presented in Table 2. Ninety-four percent of the 85-kW solar thermal input is absorbed by the working fluid (water) to produce primary steam at 17.24 MPa (2500 psia) and 704°C (1300°F) or both primary steam at the same conditions and reheat steam at 1.21 MPa (175 psia) and 704°C (1300°F).

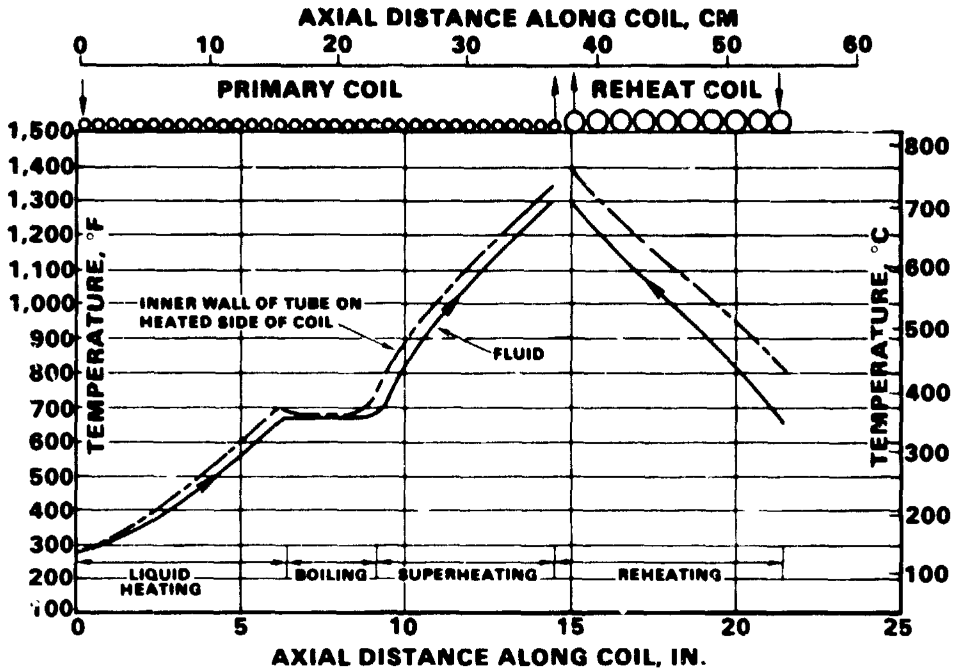

FIGURE 4. TUBE WALL AND FLUID TEMPERATURE PROFILES FOR BASELINE HEAT FLUX DISTRIBUTION

TABLE 2

SRSR ESTIMATED PERFORMANCE
STEAM/ELECTRIC APPLICATION

Parameter	Value
Solar input, kW(th)	85
Aperture (9-in. dia) radiation loss, kW(th)	1.3
Insulation loss, kW(th)	1.2
Assumed aperture convection loss, kW(th)	2.5
Thermal power to fluid, kW(th)	80
Receiver efficiency, percent	94
Flow rate, gm/sec (lb/hr)	19.81 (157.2)
Pressure drop, percent	
Primary	2
Reheat	10
Primary mode only	
Flow rate, gm/sec (lb/hr)	24.66 (195.7)
Pressure drop, percent	3

ADAPTATION TO PROCESS STEAM APPLICATIONS

Although the unit was designed as a steam Rankine solar receiver for a high-pressure, high-temperature steam/electric application, the receiver can be operated as a once-through boiler at higher flow rates to produce process steam at lower temperatures and lower pressures (down to about 3.45 MPa or 500 psia). Also, the receiver can be operated as a recirculation boiler or a high-pressure water receiver. Both of these adaptations require the use of external equipment to produce steam. The first procedure requires a liquid/vapor drum (or equivalent) type of separator and the second requires a steam generator. The pressurized water receiver concept requires the use of distilled, polished water in a closed-fluid circulating loop between the receiver and the steam generator.

TEST RESULTS AT PARABOLIC DISH TEST SITE

Preliminary testing was started at the Parabolic Dish Test Site in September 1980. The JPL concentrator contains 224 rectangular, separately focused mirrors approximately 57 by 61 cm (22.5 by 24 in.). The total solar power input capability was 80 kW for an insolation of 1000 W/m^2 (317 Btu/hr·ft^2).

Initial testing was done with water heating at 25- and 50-percent mirrors at low pressures (about 1.1 MPa or 160 psia) and low temperatures (about 150°C or 300°F). The second series of tests was conducted at medium pressures and temperatures (about 4.8 MPa or 700 psia and 288°C or 550°F) using 50-, 75-, and 100-percent mirrors. Exploratory high-temperature high-pressure tests have been started. In all runs, the primary and reheat sections of the coil were connected in series. Also, for procurement reasons, the material was changed to type 321 stainless steel, and the primary section tubing size was increased to 12.7-mm OD by 2.41-mm wall (1/2 by 0.095 in.), and the number of turns was reduced to 30

The tests of the receiver indicated good thermal and flow performance, with efficiencies in the range of 80 to 88 percent. No major instabilities were detected, but some modifications to the receiver were required. The ceramic end plate and aperture cone were severely damaged (shattered) by the solar heating during early tests. An end plate of RA 330 nickel chromium steel and a water-cooled aluminum aperture assembly were needed to continue the testing.

A typical test result obtained by JPL during the exploratory high-temperature testing on 17 October 1980 is shown in Figure 5. This is a graph of the back-side and heated-side tube-wall temperature versus axial distance along the coil. Also, the water inlet and steam outlet temperatures are identified. The back-side or unheated tube-wall temperature profile is as predicted, but the heated-side temperature profile shows a very high peak at the beginning of the boiling region. This may be due to a thermocouple error or to excessive local incident solar heat flux. Prior to further testing, JPL plans to install new thermocouples on the heated side of the tube coil (welded to the coil to ensure a good thermal bond) and to defocus the mirrors, which may reduce the peak incident heat flux.

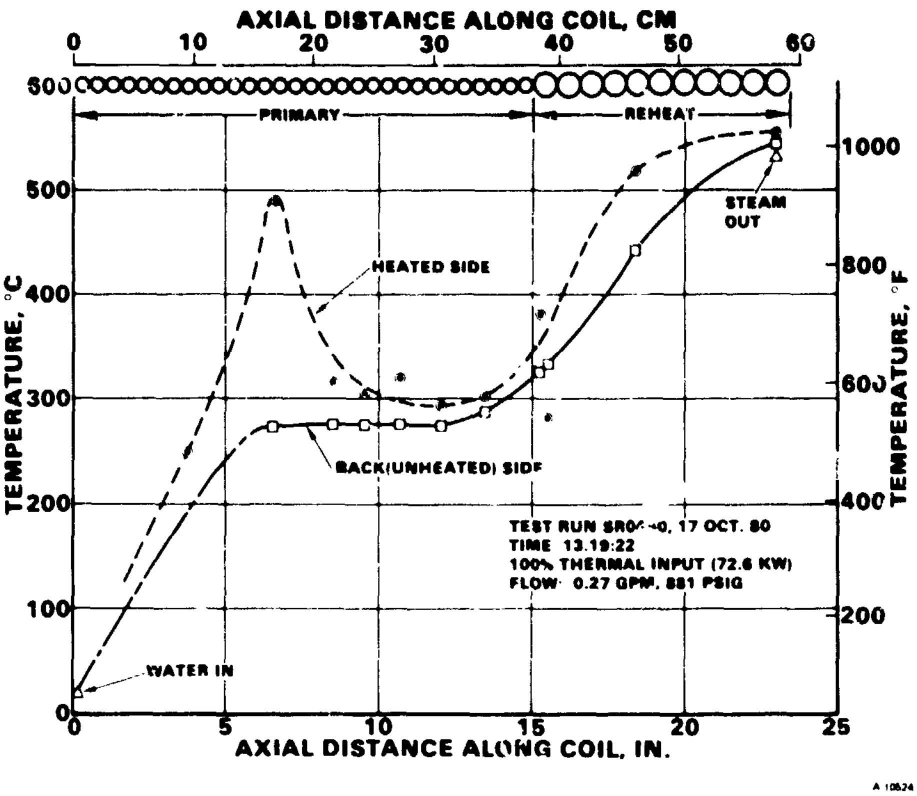

FIGURE 5. TYPICAL TEST RESULT, TUBE-WALL TEMPERATURE PROFILE

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