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ORGANIC RANKINE CYCLE RECEIVER DEVELOPMENT

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ABSTRACT

A solar receiver is being developed for use with an organic Rankine cycle (ORC) engine as part of the Small Community Solar Experiment (SCSE). The selected receiver concept is a direct-heated, once-through, monotube boiler operated at supercritical pressure. The cavity is formed by a cylindrical copper shell and backwall, with stainless steel tubing brazed to the outside surface. This core is surrounded by lightweight refractory insulation, load-bearing struts, and an outer case. The aperture plate is made of copper to provide long life by conduction and reradiation of heat away from the aperture lip. The receiver thermal efficiency is estimated to be 97 percent at rated conditions (energy transferred to toluene divided by energy incident on aperture opening). Development of the core manufacturing and corrosion protection methods is complete with development testing of the core to be completed in January 1981. A prototype receiver will be supplied in March 1981 for integration and test at the engine supplier's facility.

INTRODUCTION

The SCSE Phase II program in progress at Ford Aerospace & Communications Corporation (FACC) includes development of a prototype power conversion assembly (PCA). The PCA will be mounted at the focal point of a 12 meter parabolic dish and will output approximately 20 kW of 3 kHz ac power to a ground-mounted rectifier. The PCA includes a cavity receiver coupled to an ORC engine. The engine working fluid is toluene with a nominal bulk temperature limit of 399°C (750°F) at the receiver exit. The receiver design requirements include input thermal power up to 95 kW$_t$, toluene flow from 54 to 545 kg/h, operating pressure up to 5862 kPa (850 psia), and a nominal 30 year component life. The two principal constraints on the design are a weight limit of 272 kg (600 lbm) and a maximum toluene pressure loss of 448 kPa (65 psi). The performance goals of the receiver design are to maximize the thermal efficiency, and to maximize the heat capacity of the core. The latter goal is desired for stabilizing the PCA operation during intermittent cloud cover.

CONCEPT SELECTION

The original baseline receiver concept for the SCSE program was a pool-boiling configuration using a secondary fluid and separate toluene heat exchanger (1). A detailed evaluation of candidate secondary fluids led to the conclusion that

this concept was not practical for the ORC temperature of ~400°C. Alternate concepts were then considered including use of a pumped secondary liquid, use of a non-boiling sodium pool, and finally, a direct-heated copper shell with tubing brazed to the outside. After development of a feasible manufacturing process, the copper shell/brazed tubing concept was selected as the baseline receiver. This concept offers the maximum in serviceability in its fabrication, operation, and maintenance.

Several toluene boiler design options were also considered as part of the receiver concept evaluation. A once-through configuration was chosen over a recirculating boiler/superheater combination in order to minimize hardware complexity. A single tube, rather than multiple parallel tubes, was selected to help avoid flow instabilities. An important receiver/engine control decision was to throttle the toluene flow at the receiver exit (vapor phase) rather than at the inlet (liquid phase). The receiver then operates at an approximately constant toluene pressure over the full range of flows. This minimizes the risk of boiling instabilities and burnout occurring in the receiver tubing. A final boiler design trade-off was to select the toluene pressure level at the receiver. A minimum value of 4482 kPa (650 psia) is used (which is about 10 percent above the critical pressure of toluene) to further reduce the possibility of tube burnout.

In performing the receiver concept tradeoffs, it was found that the weight and complexity of an aperture door assembly could not be justified in comparison with the slight reduction in energy losses during transient cloud passages. In addition, the receiver performance was maximized by flowing the toluene from the front (aperture end) of the cavity to the rear, and by using a toluene-cooled backwall instead of an insulated backwall. The receiver transient performance was found to be best for a uniformly distributed heat capacity (uniform thickness) in the cavity wall.

DESIGN DESCRIPTION

The principal receiver components are the core assembly, core support structure, thermal insulation, outer case, and the aperture plate (see Figure 1).

The core consists of a barrel section and a flat plate backwall. These copper pieces have grooves machined in their outside surfaces to match a helical coil and a spiral coil of 347 stainless tubing. The tubing is mechanically held within the grooves and brazed to assure good thermal contact with the copper. The overall coppershell thickness is 1.71 cm (0.75 in.) with a nominal groove depth of 1.27 cm (0.5 in.). The cavity diameter and length are 0.61 m (24.0 in.) by 0.56 m (22.0 in.), respectively. The tubing outside diameter and wall thickness are 1.59 cm (0.625 in.) by 0.889 mm (0.035 in.), respectively, and the total tube length is 63.1 m (207 ft.). The core accounts for 147 kg (325 lbm.) of the total receiver weight of 271 kg (597 lbm).

The copper shell and tube/shell braze joint are protected from corrosion in air by an application of electroless nickel plating. The cavity interior is then given a coat of flat black high temperature paint to increase its surface solar absorptivity to about 0.95.
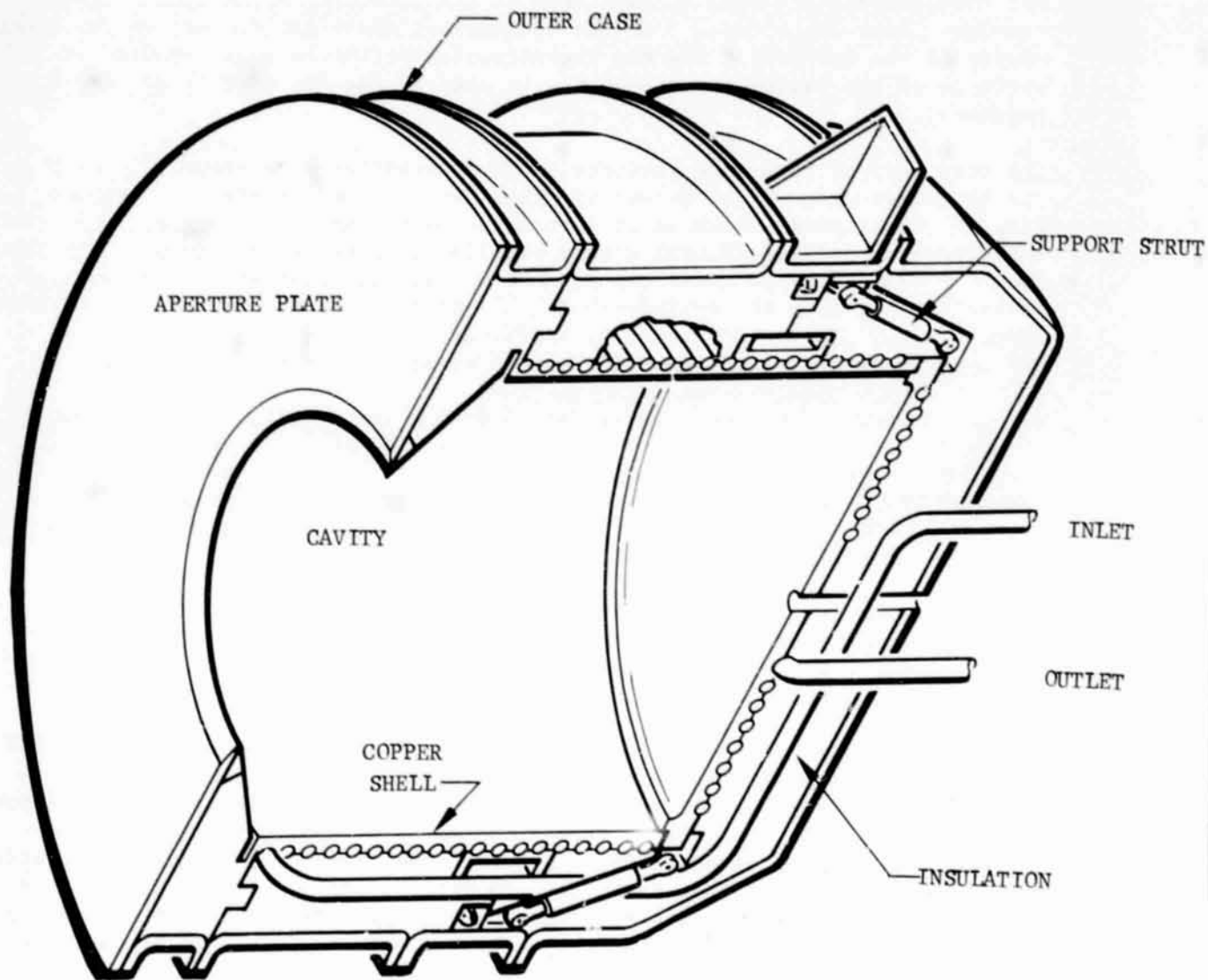
FIGURE 1. CUT-AWAY VIEW OF RECEIVER ASSEMBLY

The core temperature will be monitored at six locations using type K thermo-couples. Four locations are on the cylindrical shell and two are on the central region of the backwall. The two thermocouples on the backwall provide an estimate of the cavity flux which may be used in the PCA control system if necessary.

The core support structure features a circumferential band around the core at its center-of-mass. Four struts tie this "belly band" to the main support ring of the receiver which is in turn attached to the four mount rails of the PCA structure. These central struts provide complete lateral support for the core. Support against axial and pitch/yaw loads is provided by four additional struts running from the cylinder/backwall junction of the core out to the main support ring. The struts are length-adjustable and are pinned at each end to accommodate thermal expansion of the core relative to the support ring.

The insulation around the core is formed from a low density refractory wool. Insulation pieces are molded to the desired shape and set using a rigidizer compound. After forming, the pieces are given a water-resistant treatment. Although the insulation properties are unaffected by cyclic moisture absorption and dryout, the coating minimizes the risk of insulation damage from rapid heating while moisture is present.

The outer case forms a protective enclosure for the insulation against the external environment. It also serves to tie the aperture plate to the main support ring. The case segments are formed from aluminum sheet except for the forward segment and the support ring, which are stainless steel.

The aperture plate is made of 3.2 mm (0.125 in.) copper sheet, with a thicker copper ring welded to the sheet metal to form the aperture lip. The nominal aperture diameter is 37.95 cm (14.94 in.), providing a collector concentration ratio of 1000. The assembly is nickel plated to prevent oxidation and is painted with high temperature black paint on the exterior. In normal operation, the concentrated solar beam is subject to dynamic and static pointing errors which result in transient lip heating. Circumferential conduction in the lip ring helps average out this heating. Radial conduction from the lip into the face plate is a major factor in maintaining a low ($< 400^{\circ}C$) lip temperature. The heat conducted into the face plate is rejected to the environment by reradiation and free convection. This simple, passive approach provides for very long life for this important component. Normal sun acquisition and detrack maneuvers, performed at nominal rates of 2 degrees in each of two axes, result in a transient heat pulse for the face plate as the solar beam sweeps off the receiver axis. The heat capacity of the copper is sufficient to limit the transient temperature rise in the face plate to about $55^{\circ}C$ ($100^{\circ}F$).

PERFORMANCE

The receiver thermal efficiency is estimated to be better than 97 percent at rated conditions. These conditions include a direct, normal solar insolation on the concentrator of 1000 W/m^2, ambient temperature of $28^{\circ}C$ ($82^{\circ}F$), and the nominal concentrator parameters of 0.78 reflectivity, 0.95 dust factor,

ana 0.932 blockage factor. With the exception of a small reflection loss, the receiver thermal losses are independent of insolation and are typically 2 to 2.5 kW_t. This insensitivity of loss to solar input is due to the nearly constant receiver cavity temperature over the range of input thermal power. The average cavity surface temperature is 360°C (680°F).

The core heat capacity is approximately 13 Wh/°C (25 Btu/°F), which provides some transient operating capability for the engine during cloud passages. If the sun is suddenly obscured by a cloud, the engine can be run at rated power for about one minute or for about 2 1/2 minutes at 40 percent of rated power. During these periods, the toluene vapor temperature at the turbine inlet would be reduced about 55°C (100°F).

MANUFACTURING DEVELOPMENT

The feasibility of the copper shell/brazed tubing concept for the receiver core was initially established using small, flat braze samples. These samples verified the material selections for the brazing process and identified the level of manufacturing tolerances desired to obtain a low porosity joint. Cylindrical samples have now verified the method of assembling the tubing onto the shells, and the technique for retaining the tubing in intimate contact with the shell during the braze cycle. A complete development receiver core will be used to demonstrate the performance of the receiver concept. A complete prototype receiver will then be fabricated for use in the SCSE prototype power module.

The initial core development testing will be conducted at FACC using a toluene test loop to simulate the ORC engine, and using a ~100 kW radiant cavity heater to simulate the input solar beam. The tests will include static thermal performance measurements at several input power levels. Following these, the dynamic (open-loop) response of the receiver to step changes in input power and toluene flow will be measured. These data will permit optimization of the PCA control system to maintain stable operation of the engine at a nominally constant turbine inlet temperature. Thus, engine efficiency will be maximized over a wide range of input power.

The complete prototype receiver will be sent to the engine vendor's facility following initial proof testing and performance checks. There it will be integrated with the ORC engine for qualification testing of the complete PCA and control system.

The present SCSE program schedule calls for completion of the core development tests in January 1981 and shipment of the prototype receiver to the engine supplier in March 1981.

REFERENCE

1. Osborn, D. B., "An Organic Rankine Receiver for the SCSTPE Program", paper presented at the First Semi-Annual Distributed Receiver Systems Program Review, Lubbock, Texas, January 22-24, 1980.