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GROUND TEST PROGRAM FOR A FULL-SIZE SOLAR DYNAMIC HEAT RECEIVER

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ABSTRACT

Test hardware, facilities, and procedures were developed to conduct ground testing of a full-size, solar dynamic heat receiver in a partially simulated, low-Earth-orbit environment. The heat receiver was designed to supply 102 kW of thermal energy to a helium and xenon gas mixture continuously over a 94 minute orbit, including up to 36 minutes of eclipse. The purpose of the test program was to quantify the receiver thermodynamic performance, its operating temperatures, and thermal response to changes in environmental and power module interface boundary conditions. The heat receiver was tested in a vacuum chamber using liquid nitrogen cold shrouds and an aperture cold plate. Special test equipment were designed to provide the required ranges in interface boundary conditions that typify those expected or required for operation as part of the solar dynamic power module on the Space Station Freedom. The support hardware includes an infrared quartz lamp heater with 30 independently controllable zones and a closed-Brayton cycle engine simulator to circulate and condition the helium-xenon gas mixture. This paper describes the test article, test support hardware, facilities, and instrumentation developed to conduct the ground test program.

INTRODUCTION

Boeing Aerospace & Electronics (BA&E) designed and built a full-size solar dynamic heat receiver for NASA as part of the advanced development effort to support solar dynamic power module design for the Space Station Freedom [1,2,3]. A follow-on program [4] was also awarded to BA&E to test this heat receiver by operating it over the range of expected or required interfaces for space operation [5].

The success criteria for the test program were (1) the successful operation of the heat receiver and test support equipment with no hardware failures; (2) the collection and storage of all test instrumentation data; (3) measuring a baseline receiver thermal performance that compares with pre-test predictions; and (4) measured receiver temperatures remaining below maximum rated values. Three types of tests were conducted: verification tests, flux variation tests, and cold soak start up tests.

Verification Tests

Verification tests were conducted to establish the receiver performance envelope over the required range of environmental and operational boundary conditions including: (1) the seasonal solar intensity; (2) concentrator optical properties and flux characteristics; and (3) the closed-Brayton cycle (CBC) engine interface parameters of inlet gas temperature, inlet gas pressure, and gas flow rate.

Flux Variation Tests

The heat receiver was designed using the flux distribution from an on-axis, parabolic concentrator with no circumferential flux variation. Flux variation tests were conducted to quantify the potential changes in receiver performance and operating temperatures with variations in the axial and/or circumferential distribution of incident flux supplied by the quartz lamp heater.

Cold Soak Start Up Tests

Start up of the solar dynamic power module from a cold soak condition may be the most severe receiver operating mode. The rate of temperature rise of receiver components from a cold soak condition is rapid due to the large amount of energy delivered into the cavity by the concentrator upon acquisition of the sun. The resulting thermal stresses will exceed normal orbital values. Fortunately, the design allowables for receiver alloys are higher at lower operating temperatures and, therefore, receiver components should be capable of withstanding the higher loading. The cold soak start up test mode was conducted to show the length of time required to charge the receiver to a condition that will support engine operation, and to demonstrate the capability of the heat receiver to survive this highly transient condition. The cold soak shut down and subsequent start up test modes were conducted last because of the unanalyzed risk of damage.

FACILITIES

The thermal vacuum testing was conducted in a large vacuum chamber at the BA&E Tulalip hazardous test site, located in Marysville, WA. The vacuum chamber sits on a large concrete slab under a covered shelter but is otherwise exposed to the outside environment as shown in Figure 1. The concrete slab is ideal for supporting the weight of the CBC engine simulator (approximately 10,0000 lbs).

The vacuum chamber inside diameter is about 14 feet and it has an internal working length of approximately 18 feet. A 32-inch diffusion pump produces a vacuum in the low 10^{-6} torr range with the chamber at ambient temperature. Site power capacity was upgraded to 400 kW to support the test program.

TEST HARDWARE

Heat Receiver and Support Cart

The heat receiver was designed and built by BA&E and delivered to NASA for testing in June 1990 [3]. The receiver cavity has an inner, diameter of 70 inches and is 80 inches long. The outer diameter of the receiver is 86 inches and the total length is 110 inches. The test receiver weighs approximately 4,797 lbs. The heat exchange system is comprised of 24 parallel heat exchanger tubes, each surrounded by an annulus containing a salt/felt metal composite. The salt is a near-eutectic mixture of lithium fluoride and calcium difluoride and has a melt temperature of approximately 1420°F. The salt is capable of storing about 72 kw-hrs of energy during its change of phase from solid to liquid. Nickel felt metal is used to improve the heat conduction across the salt annulus and to prevent the gravity force from controlling the locations of voids that form in the salt when it solidifies.

The salt is contained around the heat exchanger tubes by an exterior bellows. The convolutions distribute the net thermal expansion of the TES containment tube and maintain peak stress at an acceptable level [3]. The 24 heat storage tubes are cantilevered from the front end of the receiver to minimize the constraint produced from the thermally induced axial growth during heat up of the receiver. A flow annulus, formed by inserting a smaller diameter tube (called the "spud") inside the heat exchanger tube, allows the internal convective heat transfer coefficient to be adjusted by changing the spud diameter. Gas flow is split between the 24 heat exchanger tubes and collected for transfer to the power cycle by cylindrical, domed plenums. The plenum design minimizes pressure drop across the receiver, reduces fabrication costs, and reduces the constraint of the gas loop piping system during high-temperature cycling.

The receiver was suspended in the vacuum chamber by a receiver support cart as shown in Figure 1. This structure also supported the back end of the quartz lamp array and the aperture cold plate. It was designed to roll in and out of the vacuum chamber on rails. A portable platform, also visible in Figure 1, mates up to the front of the vacuum chamber and allowed the installation of the quartz lamp array, cold shrouds, and receiver exterior instrumentation to be completed outside of the chamber. The cart was then rolled into the vacuum chamber for final assembly.

The rolling capability of the support cart inside the chamber also allowed the cart to roll forward to accommodate thermal growth of the gas piping at the back of the receiver. The cable supports of the receiver inside the cart structure also relieved stress induced from thermal growth. No problems were experienced with the support cart arrangement during the conduct of the testing.

CBC Engine Simulator

The CBC engine simulator circulates the working gas through the receiver, removes heat, and conditions the gas to achieve the desired temperature and pressure at the receiver inlet. A functional schematic of the CBC engine simulator is given in Figure 2. A photograph of the as-built hardware is shown in Figure 3.

A single-stage rotary lobe blower pressurizes and moves the working fluid through the piping network. The flow rate through the receiver is controlled manually using the blower by-pass valve. Hot helium-xenon gas returning from the receiver is cooled to an acceptable blower inlet temperature by first passing through a regenerative gas-to-gas heat exchanger and then through a water cooled heat exchanger. The water cooled heat exchanger drops the gas temperature to about 125°F prior to entering the blower. The hot water exiting the heat exchanger flows through a nozzle to produce a mist to cool it prior to its discharge into the environment. The gas is repressurized by the blower and heated above the desired receiver inlet temperature when it passes through the regenerative heat exchanger.

The temperature control of the gas at the receiver inlet is achieved by mixing this hot gas with cooler gas that bypasses the regenerative heat exchanger. A large, coarse control valve is set manually to obtain an inlet temperature close to the desired value. A low capacity, fine metering control valve has temperature controlled feedback and adjusts the gas flow through the bypass to achieve the desired inlet gas temperature. The temperature of the gas is measured just upstream of the receiver inlet plenum. The temperature control system worked very well during testing and easily controlled inlet gas temperature to within 5°F of the desired set point.

Inlet static pressure is controlled by the amount of helium-xenon gas inside of the piping loop. A gas reclamation system was provided to allow gas to be removed from the loop either for pressure control or to be reclaimed if the system required repair. A two-stage metal bellows pump is used to reclaim the gas mixture and is capable of producing 100 psig outlet pressure with a 7 psia inlet pressure. However, the system was never used during testing because pressure control was maintained without the need to remove mass from the system and no repairs of the simulator gas loop were required.

A Residual Gas Analyzer was connected to the CBC loop during testing to determine the mole fraction of helium in the helium-xenon gas mixture. However, the unit failed during test conduct and no concentration measurements were made. Samples of the gas from the loop were obtained after testing was completed to determine the change in gas composition.

Quartz Lamp Heater

The cavity of the receiver is heated with the infrared quartz lamp array that uses 456 quartz lamps as the heat source. The lamps are rated at 1000 watts each but are operated at a maximum of about half power during testing to increase lamp life. The lamp array is configured into 5 axial zones that are each comprised of 6 circumferential zones. The power supplied to the 30 zones is independently controllable.

The support structure for the lamp array consists of a single box beam. The beam is supported by a cable at the front (aperture) end and by a molybdemum rod at the back end of the receiver. The rear end attachment is mated to the receiver support cart and the front end is hung from the large structural ring on the receiver. Six bus plates hang from the box beam at eight axial locations and support the individual quartz lamps. The plates are electrically isolated from each other and from the box beam by ceramic insulators. Electrical bus rods attach to their required bus plate and extend out from the front of the receiver through the aperture plug assembly. Electrical connections are made to the ends of these rods outside the heated area of the receiver cavity. The box beam, bus plates, and bus rods are all fabricated from columbium and columbium alloys and are only elevated to high temperature in a vacuum. The lamp array is shown in Figure 4 prior to its installation into the receiver cavity.

The quartz lamp heater zones are powered by 6 phase-angle-firing, silicon controlled rectifier power controllers specially designed for corona environments. A total of 36 controllable channels or zones are available (6 spares) and each channel was capable of controlling from 0 to 26.6 kW in the range of 166 volts at 160 amps to 240 V at 111 amps. Each channel was independently controlled, single phase, and incorporated an instantaneous current trip circuit to sense an over-current condition, such as a corona discharge, and break the channel circuit. The power controllers automatically attempt to repower the affected heater zone 3 times before terminating operation.

Cold Shrouds and Aperture Cold Plate

A cold plate cooled with liquid nitrogen (LN_2) was used to absorb the heat lost through the receiver aperture and to collect off-gassing products liberated from within the receiver cavity during high-temperature operation. The cold plate was constructed from a single aluminum sheet with welded D-tubing LN_2 flow channels. It was suspended by turnbuckles from the receiver support cart and was installed just prior to closing the vacuum chamber door. It was supplied with LN_2 using a separate flow loop.

LN_2 cold shrouds surrounded the outer cylindrical section of the receiver and were primarily intended to cold soak the receiver for the start up test mode. However, they also provided a boundary condition for the receiver exterior that more closely simulates that for space. The cold shrouds were constructed from aluminum sheet with aluminum D-tubing welded to their surfaces. The shroud was comprised of four nearly identical sections that were installed directly onto the cylindrical cage of the receiver before the cart/receiver was rolled into the vacuum chamber. The shroud panels used two parallel LN_2 flow loops; each consisting of two panels flowing in series. Figure 5 shows the receiver just prior to installation of the cold plate and shows the configuration of the cold shroud panels on the receiver structure. The aperture plug assembly, electrical bus rods, and front support of the quartz lamp array can be seen in the figure.

Optical Borescope

Limited viewing of the inside of the receiver cavity during thermal vacuum testing was made possible using a high temperature borescope. The borescope has a 120° field of view and was mounted in a flange on the front door of the vacuum chamber. Its position was along the centerline axis of the receiver. The outside section provided a camera mount with an integral focusing ring. The final image size of about 1-inch diameter provided nearly full frame coverage on a 35 mm negative. The borescope was actively cooled with gaseous nitrogen permitting continuous operation at high temperature. It was originally intended to install the borescope with its tip inside the cavity but a last minute change in the lens o-ring material was required to obtain a helium leak tight seal. Therefore, the tip was pulled back out in front of the aperture hole because the new Viton o-ring material was rated at a temperature 100oF below that of the original material.

INSTRUMENTATION and DATA ACQUISITION

Test measurements included: (1) measurements to determine the temperature distributions within the receiver and support equipment; (2) temperature measurements to determine thermal energy storage subsystem performance; (3) temperature, pressure, and gas flow rate measurements to determine overall receiver thermodynamic performance; (4) electrical power measurements for each of the 30 heater zones; (5) vacuum chamber pressure; (6) ambient pressure and temperature; and (7) the molecular percentages of helium and xenon in the gas mixture. There were a total of 114 temperature measurements distributed as follows: 88 on the receiver, 10 on miscellaneous structure, the cold plate, and cold shroud panels, 9 in fluid lines associated with the CBC engine simulator, 3 on heater structure and components, 3 on the vacuum chamber facility, and 1 for ambient. Sheathed, grounded end, type K thermocouples were used throughout the receiver cavity.

Heat Storage Tube Instrumentation

Three of the 24 receiver heat storage tubes were instrumented with surface thermocouples installed on convolution peaks, 12 inches from each end-cap and at the middle of the tube. The thermocouples were attached every 90° around the tube. Nichrome wire was used to attach the thermocouples by preloading the tips against the surface of the tube. This method of thermocouple attachment was used during subscale canister tests and during molten salt filling of the heat storage tubes [3] and produced reasonable results. An alternative method of attaching the thermocouples using a ceramic adhesive was not used because it resulted in damage to the Inconel 617 during the subscale canister tests. The tubes were located at approximately 60°, 180°, and 270° clockwise from the top of the receiver as viewed from the aperture end.

Two of the instrumented heat storage tubes (at 180° and 270°) also had thermocouples internal to the TES annulus at both the inlet and exit ends installed during heat storage tube fabrication. The thermocouples extend into the TES annulus to a 12 inch depth and are sealed at the end-caps by a high-temperature braze [3].

Cavity wall temperatures were measured at 3 axial locations in the high-flux (inlet end), middle, and low-flux (exit end) of the cavity. Each axial location had 3 circumferential thermocouples, located at 60°, 180°, and 270°. Three thermocouples were attached to the back wall and on the aperture wall and are aligned with the cavity wall thermocouples. The sheathed thermocouples were attached to the cavity surfaces by stitching with quartz thread. The ends were then covered from a direct view of the quartz lamp array by a quartz cloth patch.

The exterior insulation on the cylindrical surface had 3 thermocouples attached at two axial locations, aligned with the internal cavity wall measurements in the high-flux (inlet end) and exit ends of the cavity. Three thermocouples each aligned with the 60°, 180°, and 270° locations were attached to the exterior front aperture face and aft-end of the receiver.

Data Acquisition and Control System (DACS)

All measured test data including temperatures, pressures, flow rates, and electrical lamp power were recorded by computer. Data sampling rates were variable and set by the test conductor based upon the rate of change in test conditions. A single Hewlett Packard 3852S data acquisition computer was used to scan, display, record, and process data. Software was customized to display key parameters in real time on various plot pages, including a page of heater power settings and another showing a complete schematic of the gas loop, receiver cavity, key structure, LN_2 loops, and environmental measurements. Data points for all key interfaces were displayed and updated at each scan. A total of 163 channels were used for the test and the data were recorded for post-processing.

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[5] NASA Document LeRC-SS-003, "Solar Dynamic Power Module System Part I Contract End Item Specification", 3 Feb 1987, NASA Lewis Research Center, Cleveland, Ohio.

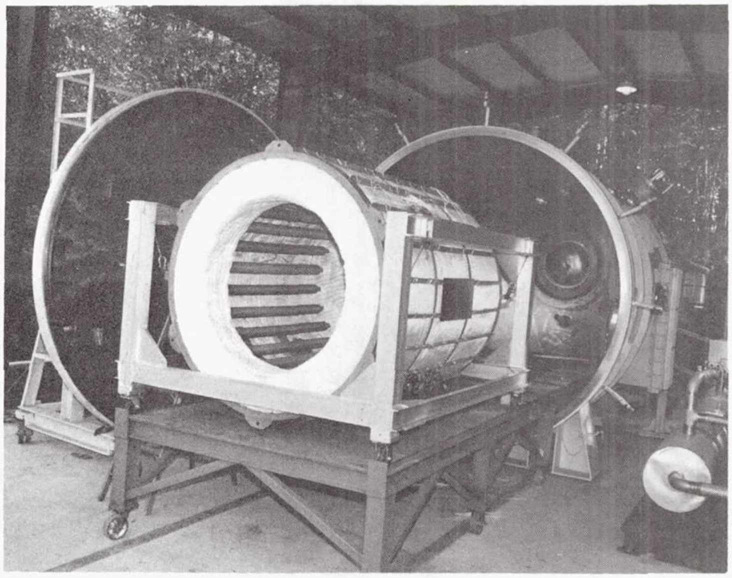

Figure 1: Vacuum Facility and Heat Receiver Mounted In Support Cart

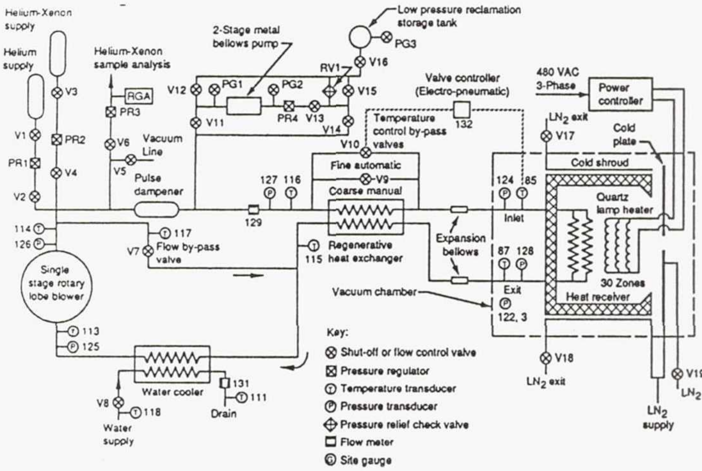

Figure 2: CBC Engine Simulator Schematic

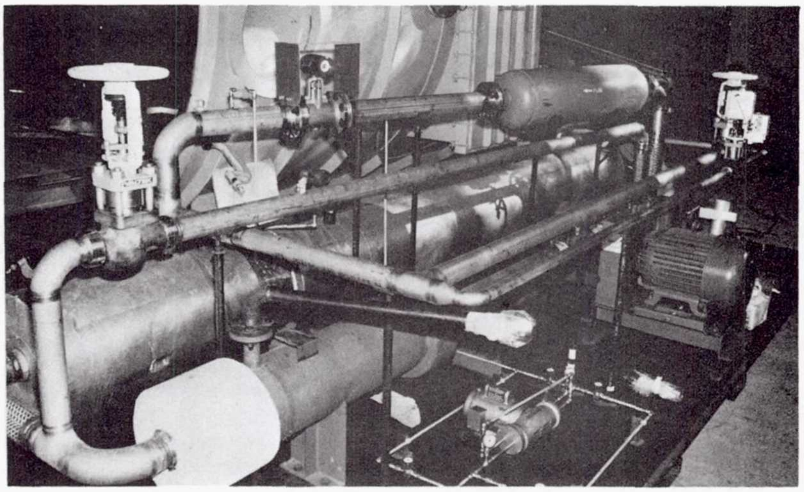

Figure 3: CBC Engine Simulator At Test Site

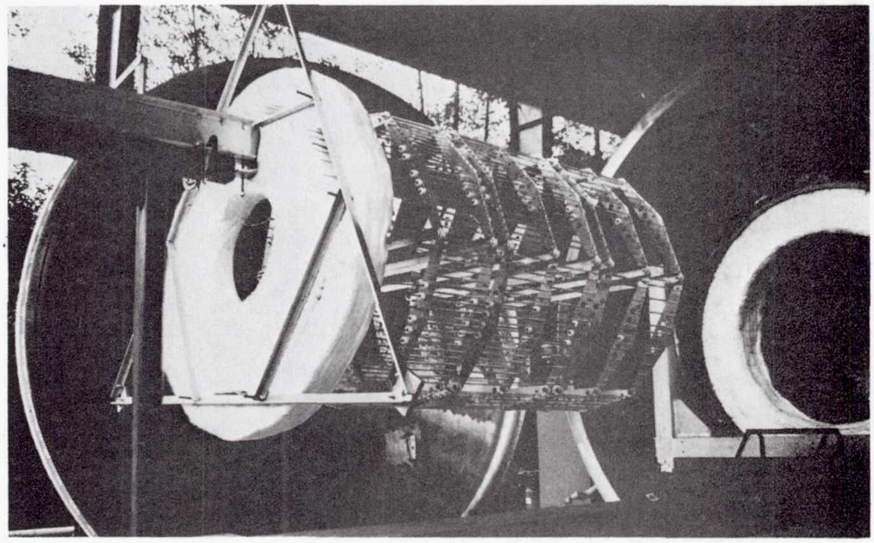

Figure 4: Quartz Lamp Heater Before Installation Into Cavity

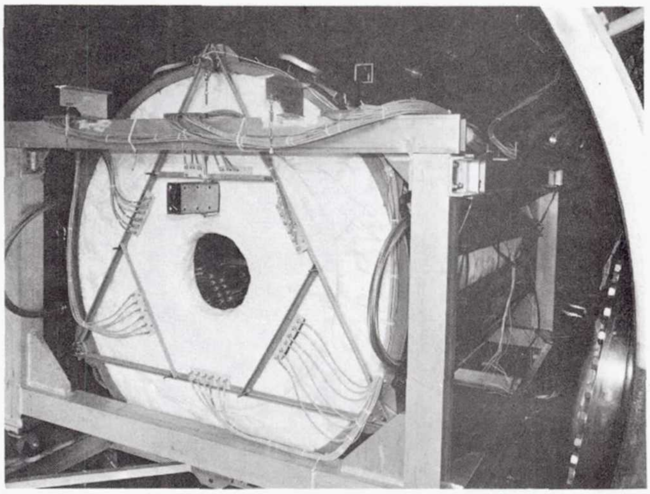

Figure 5: Receiver Inside Vacuum Chamber Prior To Testing

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16. Abstract
Test hardware, facilities, and procedures were developed to conduct ground testing of a full-size, solar dynamic heat receiver in a partially simulated, low-Earth-orbit environment. The heat receiver was designed to supply 102 kW of thermal energy to a helium and xenon gas mixture continuously over a 94 minute orbit, including up to 36 minutes of eclipse. The purpose of the test program was to quantify the receiver thermodynamic performance, its operating temperatures, and thermal response to changes in environmental and power module interface boundary conditions. The heat receiver was tested in a vacuum chamber using liquid nitrogen cold shrouds and an aperture cold plate. Special test equipment were designed to provide the required ranges in interface boundary conditions that typify those expected or required for operation as part of the solar dynamic power module on the Space Station Freedom. The support hardware includes an infrared quartz lamp heater with 30 independently controllable zones and a closed-Brayton cycle engine simulator to circulate and condition the helium-xenon gas mixture. This paper describes the test article, test support hardware, facilities, and instrumentation developed to conduct the ground test program.

17. Key Words (Suggested by Author(s))
Space stations; Solar dynamic power systems; Phase change materials; Heat storage; Brayton cycle; Solar collectors; Quartz lamps; Calcium fluorides; Lithium fluorides; Helium; Xenon; High-temperature; Vacuum; Performance tests; Test facilities

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