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Solar Thermal Vacuum Testing of an Integrated Membrane Concentrator System at the NASA GRC Tank 6

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Abstract. This paper reports the results of highly integrated thermal vacuum testing of key components of a membrane concentrator system that occurred during June 2001. The Dual Use Science and Technology (DUS&T) Electromagnetic Radiation Control Experiment (EMRCE) Team, including SRS Technologies, ATK Thiokol Propulsion, Boeing, Air Force Research Laboratory (AFRL), and National Aeronautics and Space Administration (NASA), is an industry and government partnership that is chartered to develop flight qualified membrane structures. Specifically, DUS&T EMRCE aims to complete development of membrane concentrator technologies to achieve flight experiment readiness in anticipation of a near term flight experiment opportunity. Potential flight experiments are in the areas of solar thermal propulsion, space power, and RF communications.

INTRODUCTION

From June 10-22, 2001, SRS Technologies, ATK Thiokol Propulsion, Boeing, Air Force Research Laboratory - (AFRLPR), NASA Glenn Research Center (GRC), of the Dual Use Science and Technology (DUS&T) Electromagnetic Electro-Radiation Control Experiment (EMRCE) Team, demonstrated critical components of a membrane concentrator system during solar thermal vacuum testing at the NASA GRC Tank 6 Solar Simulator facility. A representative orbit cycle was also simulated during the test. This highly integrated test combined SRS Technologies's membrane concentrators and photogrammetry system with ATK Thiokol Propulsion's hexapod focus control system and rigidized struts, AFRL's flux distribution camera, and NASA GRCs canister calorimeter. The test objectives were met via demonstration of:

- throughput efficiency of a membrane concentrator during solar thermal vacuum operation,
- thermal characterization of concentrator,
- hexapod focus control system,
- thermal characterization of membrane strut during test matrix, and
- photogrammetry shape measurement of the concentrator

This testing advanced Technology Readiness Levels (TRL) towards flight readiness by demonstrating the integration, operation, and performance of key components of a membrane concentrator flight experiment in an environment relevant to space. The benefits of this test include:

- advancement of technology towards flight readiness,
- collection of critical test data on components and system performance in a highly integrated flight-like test environment,
- coordinate government and industry interest and advocacy for a flight experiment opportunity, and
- increase technical credibility and recognition as the result of highly visible and technically significant testing in a world-class test facility.

Since the test, a number of government and commercial programs have begun to apply the test results. The Air Force's Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program is integrating the hardware and algorithms for pointing and control hardware and inflation control. As shown in Exhibit 1, the 2002 Air Force

Research Laboratory (AFRL) Solar Orbit Transfer Vehicle (SOTV) solar tracking test successfully integrated hardware, inflation control and algorithms for pointing and control. NASA GRC has proposed two similar test apparatuses using an optimized concentrator, a refractive secondary, and a rigidized torus for solar concentration testing and antenna assessment. A proposed Air Force PICOSAT flight experiment will deploy and conduct shape assessment of a 1-m class thin film concentrator in space.

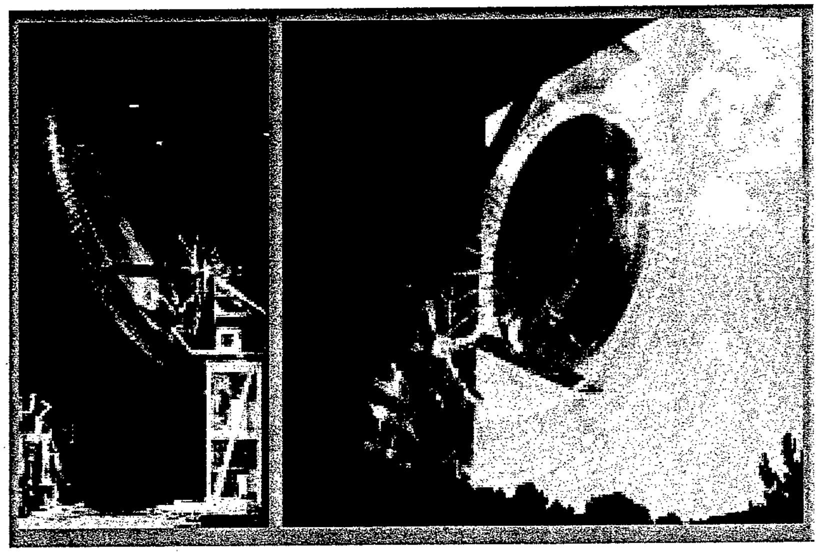


Exhibit 1 SOTV On-Sun Test

TEST FACILITY

The NASA Glenn Research Center Tank 6 Solar Simulator facility was the site of this test. This test chamber, depicted in Exhibit 2, is 68 ft. long and 25 feet in diameter. The solar simulator has nine 30 kW xenon lamps capable of providing up to 1.2 times the nominal solar intensity at approximately 50 feet from the source. The facility has 12 cryopumps that provide 10^{-6} torr level vacuum. Liquid nitrogen cold walls provide a simulated space thermal environment. Prior to the test, a "grafoil" shield was installed over the cold walls in support of non-related propulsion testing. This shield was designed to protect the cold walls but interfered with the cold soak capability by acting as an insulator.

TEST APPARATUS

Exhibit 3 shows the test apparatus as seen from the solar simulator. The membrane concentrator, catenary network, rigid support ring, support structures, hexapod, inflation control system, and canister calorimeter were integrated for the test. A glass strut and an iso-graphite strut were also included as test articles. A vacuum rated photogrammetry system was added to measure the concentrator shape and planarity and the AFRL flux distribution camera was added to characterize the focal spot and provide real-time alignment feedback. SRS designed and fabricated a 1-m class elliptical CP-1 membrane concentrator for NASA GRC as shown in Exhibit 4. The reflector film is aluminum coated. The films are joined along the edge with a space-rated adhesive. A ground test catenary network was used to integrate the concentrator with a rigid support ring. A rigid support ring was used in place of a flight design support structure and enables decoupled testing of the concentrator and catenary. Thermocouples were placed on the concentrator and catenaries, front and back, to collected temperature data during test-

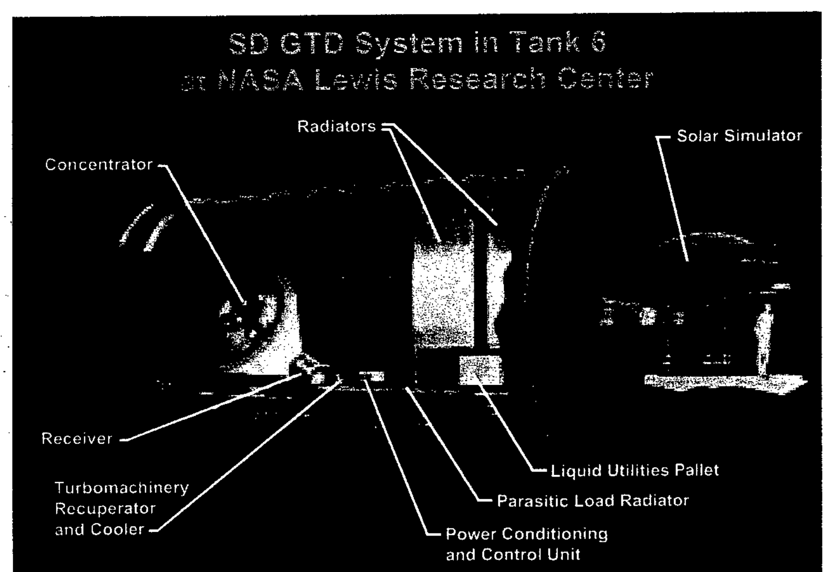


Exhibit 2 NASA Glenn Research Center Tank 6 Solar Simulator Facility

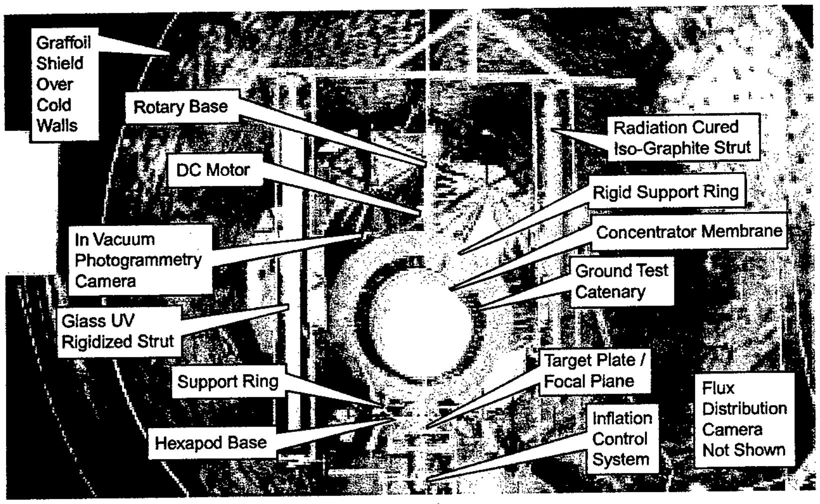


Exhibit 3 Test Apparatus

ing. The vacuum rated photogrammetry system was mounted to an I-beam on the facility ceiling and is remotely operated.

TEST HARDWARE SPECIFICATIONS

The hexapod fine focusing system is a 6-DOF table designed to keep the concentrator pointed towards the source to within +/- 0.1 degrees. The hexapod is actuator driven and is remotely controlled. The hexapod also includes a retractable target plate that covers the canister calorimeter entrance aperture while also enabling characterization of the focal spot. Though not integrated with the concentrator system, the rigidized strut testing was conducted to collect critical data on strut deflection as a function of thermal loading. The miniaturized vacuum rated inflation control system has an extensive and successful test background. Exhibit 5 shows the hexapod, struts, and inflation control system.

DATA ACQUISITION AND FACILITY OPERATIONS

As shown in Exhibit 6, each test participant was involved in the data acquisition process. NASA GRC also provided operation and control of the test facility.

TEST PLAN

The team developed and executed a test plan that included the following elements.

- Purpose
- Test objectives
- Definition of research package inside Tank 6
- Definition of support hardware
- Hardware preparation and installation plan
- Tank 6 Data acquisition system - instrumentation list
- Instrument data channels
- Feed-through list

The test plan was followed closely through ambient temperature vacuum testing and then modified during cold soak and orbit simulation phases to reflect the facility issues. Future testing should include appropriate facility modifications to allow multiple orbit simulations.

TEST DATA

Exhibit 7 shows a chronology of the actual power in the hole test. Based on pre-test extrapolated beam survey data, 760 watts "power in the hole" was predicted and a maximum of 696 watts was measured with the GRC canister calorimeter during ambient temperature vacuum testing. Actual radiometer test data was extrapolated to predict 743 watts. A post test beam survey was conducted by NASA GRC during the week of June 25 and validated the pre-

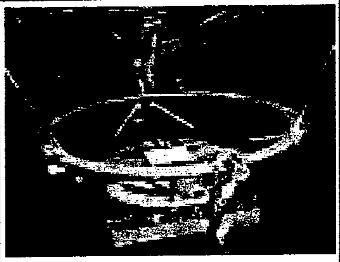
4-Foot Aperture Elliptical Concentrator
Major: 1.707 meters (67.21 inches)
Minor: 1.165 meters (45.88 inches)
Maximum Height: 0.120 meters (4.72 inches)
Aperture: 0.978 square meters

Ground Test Catenary Network and Rigid Support Ring Were Designed to Enable De-Coupled Testing of the Concentrator to Establish Edge Requirements Independent of Support Torus Effects.

The Concentrator, Catenary, Tabs, and the Rigid Ring Were Instrumented With Thermocouples.

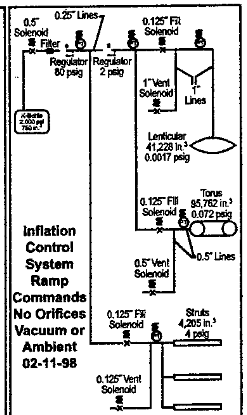
A Vacuum Rated Photogrammetry System Was Designed and Assembled to Collect Concentrator Shape Data During Vacuum Testing.

Exhibit 4 1-m Class Elliptical CP-1 Membrane Concentrator



Hexapod Selected for Tracking and Fine Focusing
- High Stiffness for Accuracy and Stability
- Parallel Structure, Closed Form Solution for Pointing
- 6 Linear Actuators, Rotating Base Ring
- 3-Inch in X and Y and 8-Inches in Z with 4 Degrees Rotation (Worse Case: 1.5-Inches in X, Y, and Z with 2

Graphite Isogrid and Woven S Glass Struts Have Been Fabricated for Orbital Thermal Bending Characterization



Inflation Control System Has Extensive Vacuum Test Experience

Exhibit 5 Hexapod, Struts, and Inflation Control System

test data. Pre-test characterization of the membrane concentrator by AFRL indicated 51% concentrator efficiency. The modeled efficiency is ~61%. The difference in efficiency is the combined effect from several contributors; 1) concentrator slope error resulted in a spot shape that did not entirely fit into the canister calorimeter aperture, 2) the concentrator was slightly over pressurized producing stray light from the edges, and 3) there are significant scratches in the aluminum reflector coating that resulted from the coating process. Exhibit 8 shows the "power in the hole" data that was collected during ambient temperature vacuum testing. The rise time is a function of the instrumentation and not necessarily representative of receiver performance.

Concentrator film temperatures were measured during ambient temperature vacuum testing as shown in Exhibit 9. As part of the test plan, the solar power was gradually increased by incrementally "turning on" the source lamps, from 1 up to 8 lamps, as part of the test article verification procedure. Thermocouples were placed on the canopy and reflector films, on the catenary tabs, catenaries, and rigid ring. Temperatures were generally in the expected ranges from thermal models.

Exhibit 10 shows temperature data from two simulated orbits. The starting temperatures for the tests are higher than desired due to the reduced capability of the facility cold walls. The second orbit starting temperature is higher than desired due to a limited cold soak. Again, measured peak temperatures matched the expected values. Additionally infrared (IR) imagery of the integrated system during on-Sun ambient testing ws collected.

Strut displacement data was collected for both test strut designs. Deflections are small in magnitude and considered to be within the range that can be compensated for by the hexapod focus control system. Photogrammetry shape measurement of the membrane concentrator was conducted. Basically, the average slope error of 6 milliradians was good enough to get the "power in the hole" for this test but <3 milliradians is desirable for flight and achievable through the use of optimized tooling.

Concentrator Shape (@10-6 torr and ~1 Sun)
RMS shape error 0.86mm
Avg shape error 0.65mm
RMS slope error 8.2mrad
Avg slope error 6.0mrad

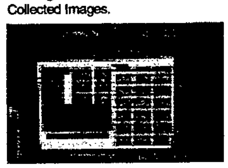
SUMMARY

From June 10-22, 2001, the DUS&T EMRCE Team conducted successful Solar Simulator testing of a membrane concentrator system at the NASA GRC Tank 6 Solar Simulator facility. All test objectives were accomplished including:

AFRL Controlled the Flux Distribution and Alignment Camera and Collected Images.

Thiokol Controlled the Hexapod and Collected Strut Displacement Data.

- 4 CCD Cameras Were Utilized to Monitor the Test and VCRs Recorded the Testing.
- NASA GRC Operated Tank 6 From the Control Room Including Vacuum Pumping and Cold Wall Operations.



NASA GRC Collected Thermocouple Data, Canister Calorimeter Data, and IR Imaging.

SRS Controlled the Photogrammetry Camera and Collected Photogrammetry Data.

Exhibit 6 Data Acquisition and Control

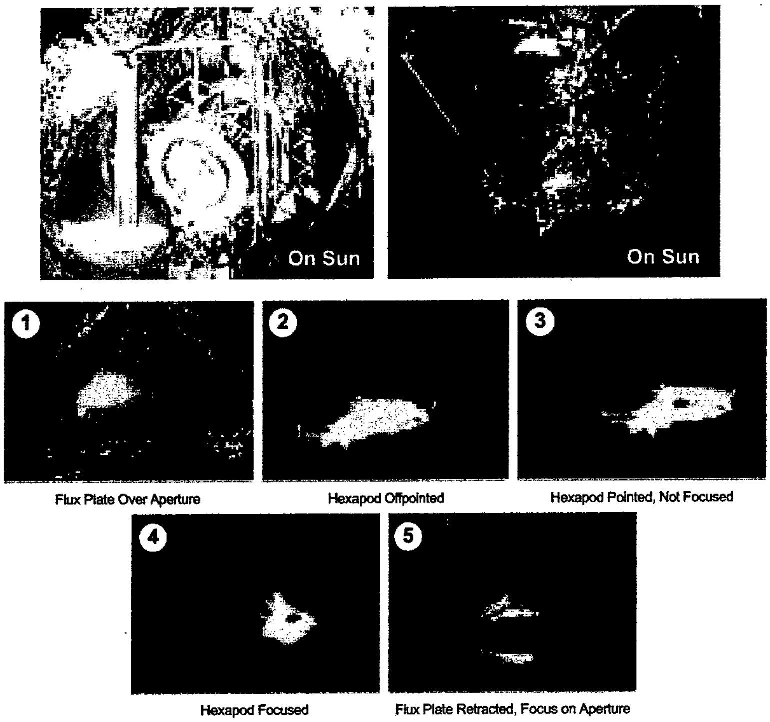


Exhibit 7 Chronology of Power in the Hole Test

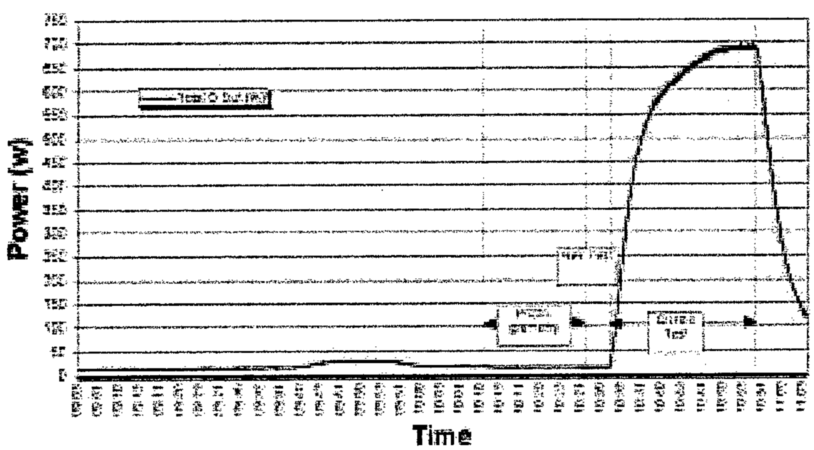


Exhibit 8 "Power in the Hole" Test Data. Tank6 Ambient Temp Vacuum Test - 6/18/01 Power Profiles

1) measurement of the concentrator throughput efficiency (measured data matched prediction)
2) thermal characterization of concentrator during a simulated orbit
3) hexapod focus control demonstrated
4) thermal characterization of membrane struts
5) photogrammetry shape characterization @ 10-6 torr

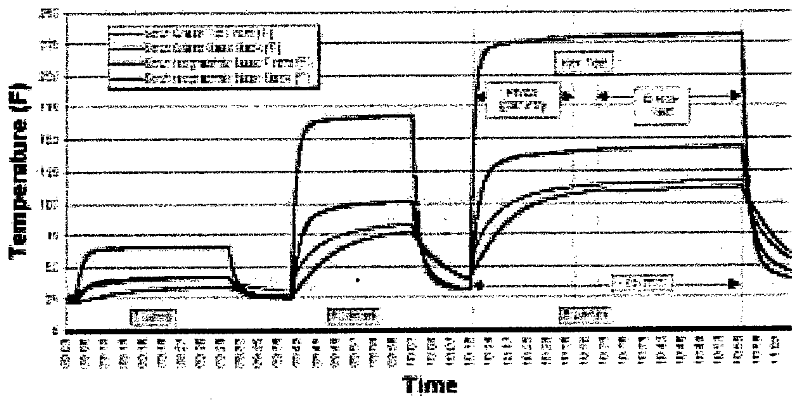


Exhibit 9 Concentrator Temperature Data

CONCLUSIONS

Membrane concentrator systems that are fabricated using similar components, designs, materials, and processes can efficiently deliver power-in-the-hole in a simulated space environment. Continued research and development will advance component and system TRLs to the flight experiment readiness level in the near term. Additional orbit simulation testing with a highly integrated flight-scale concentrator system will support development of this technology for space power, communications, and propulsion applications.

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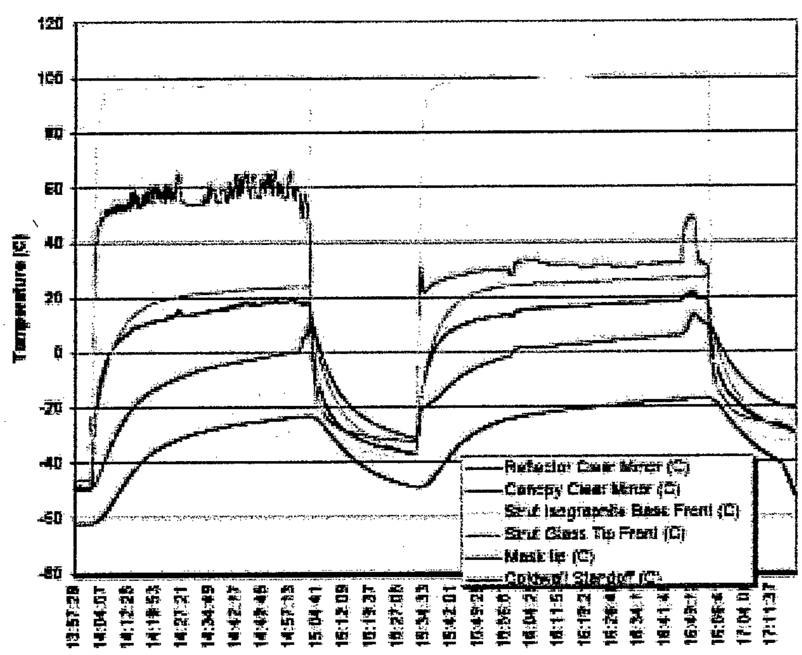

Exhibit 10 Concentrator Temperature Data for Simulated Orbit