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Update of the 2 kW Solar Dynamic Ground Test Demonstration Program

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UPDATE OF THE 2 kW SOLAR DYNAMIC GROUND TEST DEMONSTRATION PROGRAM

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Abstract

The Solar Dynamic (SD) Ground Test Demonstration (GTD) program demonstrates the operation of a complete 2 kW_e SD system in a simulated space environment at a NASA Lewis Research Center (LeRC) thermal-vacuum facility. This paper reviews the goals and status of the SD GTD program. A brief description of the SD system identifying key design features of the system, subsystems and components is included. An aerospace industry/government team is working together to design, fabricate, assemble and test a complete SD system.

Introduction

The NASA Office of Aeronautics and Space Technology initiated the 2 kW_e Solar Dynamic (SD) Space Power Ground Test Demonstration (GTD) Program which is managed by NASA Lewis Research Center (LeRC)(1,2). The primary goal of this program is to conduct testing of flight prototypical components as part of a complete SD system in 1995. The SD space power system includes thermal energy storage in an environment simulating a representative low earth orbit (LEO).

SD component technologies have been developed by NASA programs during the past 30 years and are available for near-Earth orbit applications. However, several technical challenges were identified during the Space Station *Freedom* (SSF) program which can be resolved in a ground-based test(3). These key issues are:

Flux tailoring - integration of the concentrator and receiver such that adequate solar flux is transferred into the cycle without excessive flux deposition in any one area of the receiver,

Control methodology - investigate methods of varying turboalternator compressor (TAC) speed and system management to maintain optimum system operation (energy management) as a result of long time period changes in insolation.

Transient mode performance - evaluation of startup and shutdown transients, and multiple orbit operations, including radiator thermal lag effects,

Concentrator facet fabrication and manufacturing techniques,

Thermal energy storage (TES) canister fabrication and manufacturing techniques, and

Scalability to the 20 to 25 kW_e range.

The SD GTD program will demonstrate a complete SD system in a thermal-vacuum environment, i.e. the large space environmental facility, known as Tank 6, at NASA LeRC (Fig. 1). The Tank 6 facility includes a solar simulator to supply the equivalent of "one" sun, a liquid-nitrogen-cooled wall operating at 78 K to simulate the heat sink (140 K) provided by the space environment, and an electric load simulator (ELS) capable of dissipating up to 4 kW of electrical power. Flight typical components are used in the SD system wherever possible to demonstrate the availability of SD technologies.

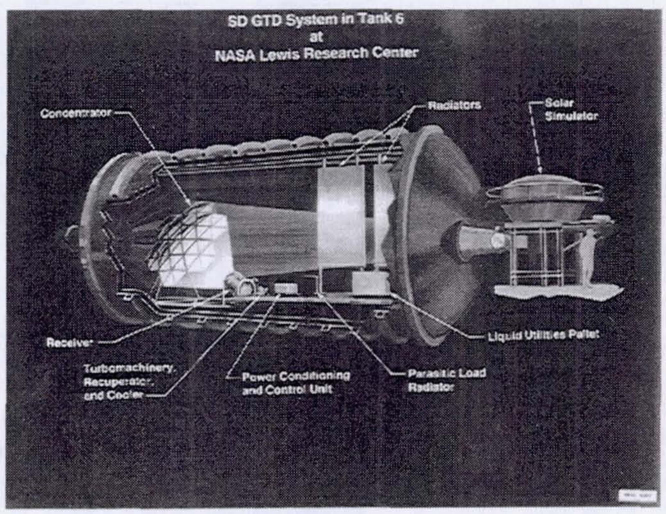

Fig. 1 - SD GTD System Installed in Tank 6

Government/Aerospace Industry Team

NASA Lewis Research Center, Cleveland, OH is responsible for overall project management and is providing the solar simulator and large thermal-vacuum facility. This includes an ELS and all the necessary interface requirements for the SD GTD system. In April 1992, NASA LeRC contracted with an industry team lead by AlliedSignal Aerospace, Tempe, AZ, for the 2 kW_e Solar Dynamic system. The aerospace contractor team includes: Harris Corporation, Melbourne, FL for the offset solar concentrator; AlliedSignal Aerospace, Torrance, CA, for the heat receiver (with thermal energy storage) and gas cooler; AlliedSignal FS, Tempe, AZ, for the power conversion system; LORAL Vought Systems, Dallas, TX for the radiator; and Rockwell International Company, Rocketdyne Division, Canoga, CA, for system integration and test support. Aerospace Design & Development (ADD), Niwot, CO is supplying the multilayer insulation (MLI) for the heat receiver and power conversion subsystem while Solar Kinetics Incorporated (SKI), Dallas, TX is supplying the reflective facets for the concentrator.

Shown in Fig. 2, is a four year schedule for delivery of a complete SD system which is being installed in the NASA vacuum facility during 1994. An overview of the activities during the first year is provided by Shaltens$_{(1)}$. During the second year the government/industry team completed the system CDR (June 1993) which allowed fabrication of the major subsystems to begin. Development of the manufacturing processes for the facets by SKI and the TES canisters by AlliedSignal and refurbishment of the TAC and recuperator were completed during the year. Fabrication and acceptance testing of two major subsystems, the solar concentrator structure, the reflective facets and radiator systems were completed ahead of schedule. The fabrication and testing for all new component hardware is underway with expected delivery to LeRC by September 1994. NASA completed the CDR for the advanced solar simulator, as planned, in September 1993 and started fabrication of the support structure along with the critical optical components. Installation of the SD components started in the spring of 1994 at LeRC with "turnkey" of the SD system moved forward to late 1994/early 1995. The NASA/industry team will begin testing of the SD system in early 1995$_{(4)}$. The SD GTD Program is ahead of schedule and within budget for completion in 1995.

Solar Simulator

A recently developed optics (controlled magnification) system which provides the basis for the advanced solar simulator design consists of nine 30 kW Xenon lamps which will provide a flux distribution of +/- 10 per cent with a subtense angle of about 1.0 degree for testing solar dynamic systems$_{(5)}$. A cross section of the solar simulator is shown in Fig. 3. Key components in the optical system are the Xenon arc lamp, the reflective collector, the lens and the turning mirror. The apparent "sun" is 0.305 m diameter which at 17.2 m subtends about one degree. This SS provides an apparent "sun" just outside the vacuum tank that shines through a quartz window into the tank to provide the desired flux density (up to 1.8 kW/m^2) at the target area. The target area is 4.79 m diameter and 17.2 m from the apparent "sun" . A shutter is provided to simulate various orbits. The advanced SS system design provides for a 50 percent improvement in system efficiency, which significantly reduces its size and initial cost as well as future operating and maintenance costs. Fabrication, assembly, installation and checkout of the SS integrated with Tank 6 by NASA LeRC personnel is scheduled to be complete by September 1994. A detailed description of the solar simulator and results from early testing of a subscale optics system are discussed by Jefferies$_{(5)}$.

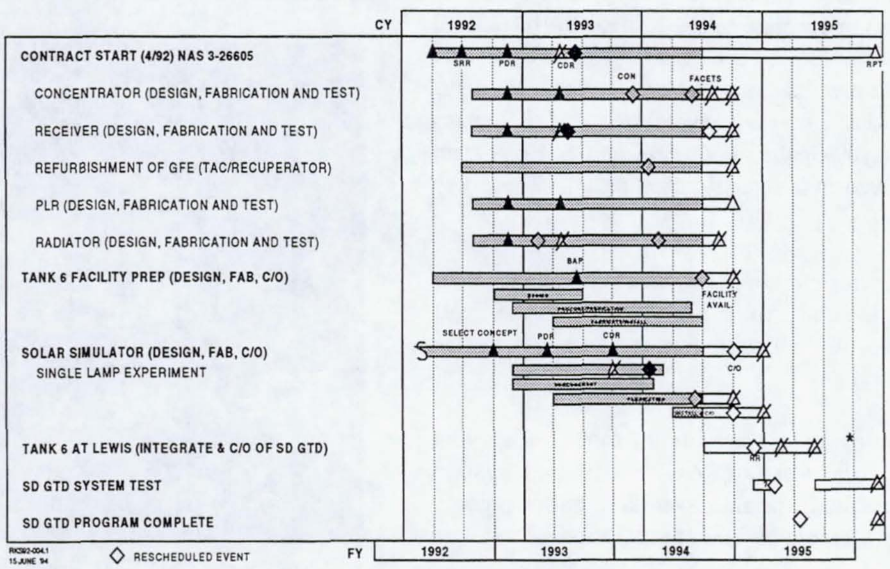

Fig. 2 - SD GTD Master Program Schedule

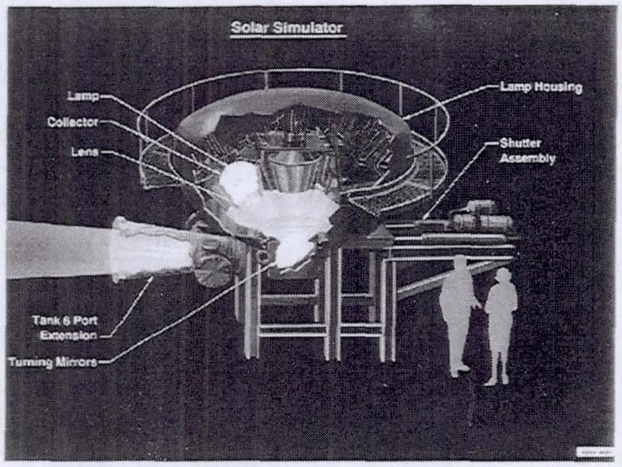

Fig. 3 - Cross-section of Solar Simulator at CDR

Solar Dynamic System

The SD GTD is a complete system which includes the following major subsystems and components: 1) a solar concentrator, 2) a solar receiver with thermal energy storage, 3) a power conversion system, 4) a waste heat rejection system, 5) the appropriate controls and power conditioning and 6) all the necessary auxiliaries required to make up the complete system. The SD system with energy storage is estimated to produce about 2 kW of electric power and has an overall system efficiency of over 15 percent. It is noted that the system performance and life were not optimized due to the constraints of utilizing existing hardware from other government programs.

The nominal design case for the GTD is the maximum insolation orbit, which represents low earth orbit (LEO) of 66 minutes of sun and 27 minutes of eclipse. The GTD system is designed for over 1000 hours of operation with up to 100 starts from a cold start condition. Fig. 1 illustrates the modular design of the system as it is configured in Tank 6. The modular design of the SD system offers the potential for NASA to evaluate advanced subsystems and components at a later date.

System Integration

The major components of the GTD system were defined based on the requirement that their interfaces be as simple as possible and that their function be readily assignable to one or another of the performing organizations. Flight packaging was not pursued because of the desire for modularity of components and simplification of their structural interfaces.

Concentrator Subsystem

The completed concentrator structure, shown in Fig 4, consists of 7 hexagonal panels with 6 reflective facets per panel. The concentrator is 4.75 m wide by 4.55 m tall and supported on a leaning tripod support structure which attaches to the NASA buildup and assembly platform. The concentrator's surface consists of 42 aluminum honeycomb facets developed by SKI(6). There are two different facet curvatures, spherical radii of 5.08 m and 6.25 m, used in different regions of the concentrator. Facet reflectivity exceeds 85 per cent and the mass is about 2.5 kg/m^2. Manufacturing development for the facets was completed by SKI in early 1994. The facets will be installed in hexagonal panels made of graphite reinforced box beams interconnected by latches. Both the box beams and the latches are oversized because they are existing hardware that is being reutilized from a previous NASA program. A detailed description of the concentrator design is provided by Bahnman (7).

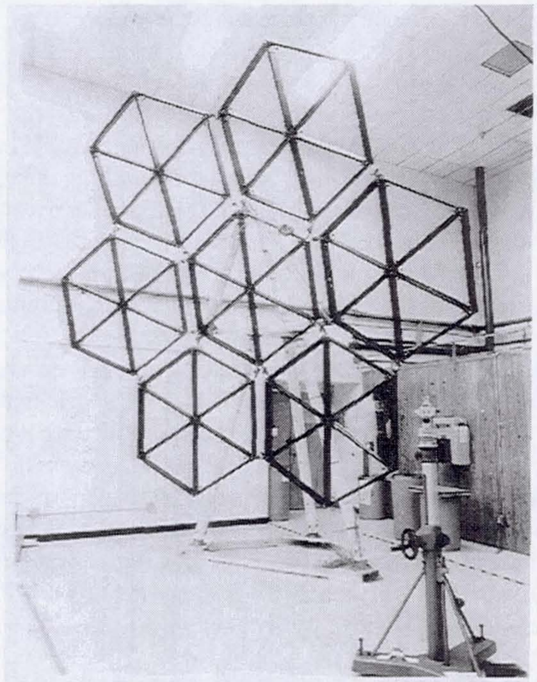
Fig. 4 - Completed Concentrator on Tripod Support Structure

A full-sized reflective facet, as shown in Fig. 5, was exposed to a thermal vacuum environment at LeRC to examine the durability of the as-produced facet to vacuum thermal cycling. Performance of the facet was evaluated measuring total and specular reflectivity, and the radius of curvature, before and after three thermal cycles between -50 and 207°F. The facet was heated with by an array of quartz halogen lamps and was allowed to cool to a gaseous nitrogen cooled cold wall. Essentially no change was observed on total or specular reflectivity or the radius of curvature after the three thermal cycles.

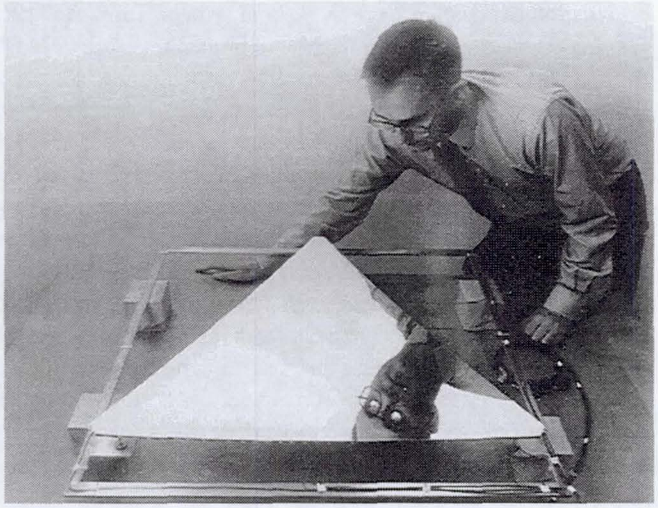

Fig. 5 - Completed Aluminum Honeycomb Facet

Special test equipment is provided for facet alignment and flux distribution. The Facet Alignment System (FAS) is a laser and video based system which is used to adjust the concentrator facets and receiver aperture plane to an alignment uncertainty of less than 1.0 mr. The FAS was used to check the alignment of the concentrator structure and facets at Harris Corp. which demonstrated a new and inexpensive method for aligning the concentrator optics and receiver in Tank 6.

The final check of the concentrator alignment occurs with evaluation of the receiver flux levels on a target grid matching the receiver with both the solar and thermal-vacuum conditions of Tank 6. A flux rake was constructed using high flux solar cells on a rotating arm to sweep a representative surface of the receiver cavity. Testing of a flux distribution rake at LeRC with a Xenon arc lamp showed an uncertainty of less than 6 per cent. A detailed description of both the FAS and the flux distribution measurement is provided by Campbell(8).

Receiver Subsystem

The receiver is used to both transfer the solar energy to the cycle working fluid and to store solar energy for system operation during eclipse. The receiver design is essentially a scale model from the SSF. The receiver uses the same thermal energy storage (TES) canister (full size) as was designed, built and tested during the SSF program. Manufacturing development and testing of the canisters has been completed by AlliedSignal ASE (9). The TES consists of the Haynes 188 canister, or hollow doughnut, filled with LiF-CaF_2 eutectic salt. The TES canisters will be placed in a scaled down receiver, which will have 23 tubes with 24 canisters per tube. A complete description of the receiver design is provided by Strumph. (10,11)

The Haynes 188 canisters require surface modifications to improve thermal emittance characteristics for radiating heat away from local hot spots, improving heat distribution which result in improved service life. LeRC and AlliedSignal specialists evaluated 14 different types of surface modification techniques for emittance and vacuum heat treatment durability enhancements. An 0.025 mm thick alumina based coating was selected due to a very high emmitance (0.85 after 2695 hrs with 32 thermal cycles) for the receiver canisters. A detailed review of the coating evaluation and selection is provided by de Groh(12).

Power Conversion Unit (PCU) Subsystem

The Power Conversion Unit (PCU) subsystem includes the Closed Brayton Cycle (CBC) Conversion unit which consists of the turboalternator/compressor (TAC), gas coolers, recuperator, ducting and support structure which is shown in Fig. 6. The TAC consists of a single stage radial flow compressor and turbine with a brushless four pole Rice Alternator. Foil gas bearings are used to provide long life operation. While operating at 52 000 rpm the TAC will produce electric power up to a maximum of 2.2 kW. The CBC unit uses either a helium-xenon gas mixture or krypton with a molecular weight of 83.8 as the working fluid. The compressed working fluid is preheated in a recuperator by turbine exhaust gases to increase efficiency of the cycle. The recuperator is a counterflow plate-fin heat exchanger designed for a 97.5 percent heat transfer effectiveness.

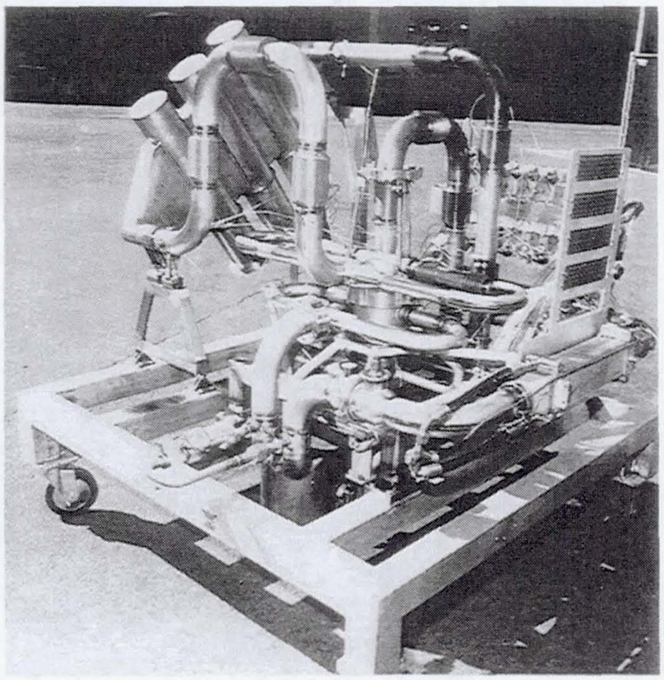

Fig. 6 - Photo of Power Conversion Unit with Electric Heater at AlliedSignal

Waste Heat Subsystem

The completed waste heat rejection system, shown in Fig. 7, consists of two (2) identical radiator panels plumbed in series and a Liquid Utilities Pallet (LUP) in a closed pumped liquid loop design. The LUP contains the pump(s) and accumulator for the *n*-heptane coolant fluid. Each bonded aluminum honeycomb panel is about 1.83 m by 3.66 m with a radiating area of 12.96 m^2. Each panel has 11 active and 11 inactive flow tubes evenly spaced to simulate thermal transient response of a fully redundant flow path design. Each panel is coated with chemglaze A276, a white epoxy paint. The waste heat system is integrated into the CBC loop by means of two gas-to-liquid heat exchangers, or gas coolers. Acceptance testing of the waste heat subsystem at the Loral-Vought facilities included operation at nominal pressure and flow in ambient laboratory conditions along with checkout of the test instrumentation. A detailed description of the analysis, design, fabrication and testing of the waste heat subsystem are described by Fleming (13, 14, 15).

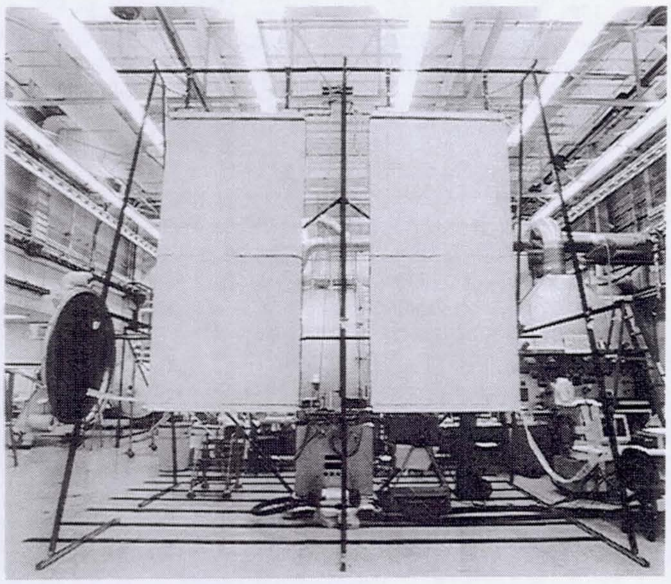

Fig. 7 - Completed Waste Heat Removal System

Power Conditioning and Control Subsystem

The Power Conditioning and Control Unit (PCCU) contains the power electronics, and is located in the thermal vacuum environment as part of the SD system. The start inverter power supply is a commercially available, variable, controllable 3 phase power supply which provides the ability to operate the TAC alternator as both an inductive and a synchronous electric motor. Starting profiles will be investigated to ascertain, by test, the optimum starting electrical characteristics. The parasitic load radiator (PLR) is an integral part of the electric loop controls and functions as an electrical sink for excess power from the TAC which is not consumed by the user load, accessory loads, and PCCU. The PLR which is controlled by the PCCU, is also located in the thermal vacuum environment. The Data Acquisition and Control System (DACS) is special test equipment (STE) whose primary function is to record system test data. The DACS also contains the ability to communicate setpoint conditions to the PCCU to vary speed, voltage and gain setpoints. This allows for changing the control parameters during the system test without the need to physically access the PCCU within the thermal vacuum environment.

Hot Loop Testing

Original plans called for integration of the major subsystems at LeRC's thermal-vacuum facility in early 1995. There was no subsystem level testing for the Power Conversion Unit (PCU) subsystem primarily because of cost and the fact that the PCU, in essentially an identical configuration, had been successfully tested at NASA at the culmination of the BIPS program in the 70's. The PCU subsystem was originally to be cold tested prior to the installation/integration at LeRC. Furthermore, there was to be only limited "pre-Tank 6" integration of the PCU with another major subsystem, the PCCU and a major STE, the DACS. As the design process of new equipment and supporting components evolved, it became apparent that the DACS was in reality becoming a major component of the SD GTD system. The functional relationship between the PCU, PCCU and the DACS became a prime concern and one which, if left unaddressed until system integration, could seriously jeopardize the success of the program by introducing difficult integration issues and associated costly solutions. Because all three subsystems were to be supplied by the same team member, AlliedSignal Fluid Systems, a decision was made to introduce an integrated system test of the PCU, PCCU and DACS prior to delivery to LeRC. Because the majority of the components were either from existing government programs or were in an advanced design stage, there was minimal design/fabrication activity required to prepare this subsystem for test, in addition, there was sufficient slack time in the delivery schedule during which a test could be performed. Incorporation of such a test did, however, require acceleration of the detailed design/ fabrication of the PCCU and DACS subsystems. Further, the test required the design/fabrication of a electric gas heater, to replace the function of the solar receiver and a waste heat removal system, to replace the function of the radiator. The PCU also required thermal insulation adequate to operate the system in a non-vacuum rather than vacuum rated multilayer insulation. This test, implemented into the program at no additional cost or schedule impact became known as the Hot Loop test and is nearly complete. The Hot Loop test integrates the PCU, PCCU and DACS with the gas heater (electric) and the waste heat removal system (LN_2 cooled ethylene-glycol bath).

The Hot Loop testing to date has successfully demonstrated TAC starting (motoring and automatic) using krypton as the working fluid. Steady state operation has been achieved up to a power level of 1.4 kW. More importantly, the test has provided an excellent, cost effective opportunity to correct functional discrepancies (unique to each subsystem and as a system as a whole) in the integration of the subsystems. Resolution of the discrepancies encountered to date, would have been extremely costly and time consuming if done after total system integration at the LeRC Tank 6 facility.

The start-up characteristics, from a "cold" (ambient) condition, demonstrated during the Hot Loop Test, to date, have qualitatively duplicated predicted start transients by Mock [16]. While simulation of on-orbit operation such as heating, is not part of the Hot Loop testing, the trend of gradually increasing power output, with time, after reaching self-sustaining speed, brought about by the gradually increasing temperatures throughout the system has been demonstrated. The PCU performance is down approximately 30 per cent from predicated, which is attributed to:

Excessive heat loss in the cycle, which will be corrected through the installation of multilayer insulation,

Excessive secondary compressor flow, due to leaking instrumentation "pass-throughs" and loose compressor clearances, which will be corrected at the re-build, and

Use of krypton working fluid instead of the prescribed Helium/Xenon working fluid.

The initial portion of the Hot Loop Test has been completed with the tear-down, inspection and rebuild to follow. The unit will then be shipped to NASA for final integration with the heat receiver for installation with the balance of the major subsystems in the LeRC thermal-vacuum facility.

Summary

The 2 kW SD GTD program provides for the demonstration of a solar dynamic power system which is of sufficient scale and fidelity to ensure confidence in the availability of solar dynamic technology for Space. Studies have shown that solar dynamic power with thermal energy storage can provide significant savings in life cycle costs and launch mass when compared with conventional photovoltaic power systems with battery storage for providing continuous electric power in near-Earth orbits. Applications include potential growth for SSF, communication and earth observing satellites, and electric propulsion.[17, 18] An aerospace government/industry team is working together to show that we can do it "cheaper, better, faster" to successfully demonstrate dynamic power for space. The SD GTD program is ahead of schedule and within budget for completion in 1995.

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