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# Initial Results From the Solar Dynamic (SD) Ground Test Demonstration (GTD) Project at NASA Lewis

Richard K. Shaltens
*Lewis Research Center*
*Cleveland, Ohio*

and

Robert V. Boyle
*AlliedSignal Aerospace*
*Tempe, Arizona*

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# INITIAL RESULTS FROM THE SOLAR DYNAMIC (SD) GROUND TEST DEMONSTRATION (GTD) PROJECT AT NASA LEWIS

Richard K. Shaltens
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, OH 44135
(216) 433-6138

Robert V. Boyle
AllliedSignal Aerospace
Tempe, Arizona
(602) 893-4904

## ABSTRACT

A government/industry team designed, built and tested a 2 kWe Solar Dynamic space power system in a large thermal/vacuum facility with a simulated sun at the NASA Lewis Research Center. The Lewis facility provides an accurate simulation of temperatures, high vacuum and solar flux as encountered in low Earth orbit. This paper reviews the goals and status of the Solar Dynamic (SD) Ground Test Demonstration (GTD) program and describes the initial testing, including both operational and performance data. This SD technology has the potential as a future power source for the International Space Station Alpha.

## INTRODUCTION

The NASA Office of Space Access and Technology initiated the 2 kWe SD GTD Program which is managed by NASA Lewis Research Center (LeRC)(Shaltens, 1995 & Calogeras, 1992). The primary goal of this program is to conduct testing of flight prototypical components as part of a complete SD system in 1995. Demonstrations of both system power delivered and total system efficiency in low Earth orbit (LEO) are key test objectives. The SD space power system shown in Fig 1. includes the solar concentrator, solar receiver with thermal energy storage integrated with the power conversion unit in a facility simulating an environment representative of low Earth orbit (LEO).

NASA programs during the past 30 years have developed SD component technologies which are now available for near-Earth orbit applications. However, several technical challenges identified during the Space Station Freedom (SSF) program are currently being investigated during the GTD testing (Jefferies, 1993). 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 thermal management to maintain optimum system operation (energy management) because of long time period changes in insolation, and

*Transient mode performance* - evaluation of start-up and shutdown transients, and multiple orbit operations, including radiator thermal lag effects.

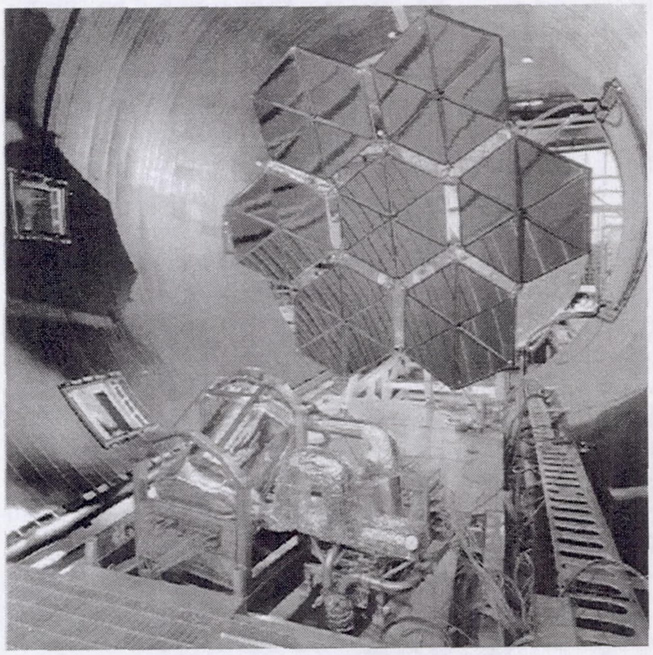

FIG. 1 - PHOTOGRAPH OF THE SD SYSTEM INSTALLED IN TANK 6

The SD GTD program has demonstrated a complete SD system in a thermal-vacuum environment, i.e., the large space environmental facility, known as Tank 6, at NASA LeRC. 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 (about 200 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.

## SD GTD TEAM

NASA LeRC, Cleveland, OH is responsible for overall project management and provided an advanced solar simulator with the large thermal/vacuum facility. This included the ELS and all the necessary interface requirements for the SD GTD system. In April 1992, NASA LeRC contracted with an industry team led by AlliedSignal Aerospace, Tempe, AZ, for the Solar Dynamic system capable of producing up to 2 kW of electrical power. The aerospace contractor team includes: Harris Corporation, Melbourne, FL for the offset solar concentrator; AlliedSignal Aerospace, Torrance, CA, for the solar heat receiver (with thermal energy storage) and gas cooler; AlliedSignal Aerospace, Tempe, AZ, for the power conversion system; Loral Vought Systems, Dallas, TX for the radiator; and Rockwell International Company, Rocketdyne Division, Canoga Park, CA, for system integration and test support. Aerospace Design & Development (ADD), Niwot, CO supplied the multilayer insulation (MLI) for the heat receiver and power conversion subsystem while Solar Kinetics Incorporated (SKI), Dallas, TX supplied the reflective facets for the concentrator. In March 1995, NASA LeRC took delivery and accepted a complete 2 kW SD system from AlliedSignal Aerospace.

The SD subsystems and system installation in the LeRC thermal/vacuum facility was completed in December 1994. Operation of the SD system by the AlliedSignal team was initiated on December 13, 1994 with LeRC personnel operating a simulated sun and the thermal vacuum facility. An overview of the activities during the previous years are provided by Shaltens & Boyle (1994, 1993). Fabrication and acceptance testing by the contractors of all the major subsystems: the solar concentrator, the reflective facets, the solar receiver, the radiator system, the power conversion unit (PCU) with power conditioning and control unit (PCCU) and the data acquisition and control system (DACS) were completed and delivered ahead of schedule during 1994. Subsystem and system verification tests were conducted by the AlliedSignal and NASA team thru March 1995. The SD GTD Program was completed with delivery of a "turnkey" SD system to NASA LeRC in March 1995, ahead of schedule and under budget.

## SOLAR SIMULATOR

The LeRC solar simulator (SS) design consists of nine 30 kw Xenon lamps and provides a nominal flux of 1.37 kW/m$^2$ with a subtense angle of about 1.0 degree for testing solar dynamic systems (Jefferies, 1994). A photograph of the solar simulator (in the upper left) next to the vacuum tank is shown in Fig. 2. 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 in diameter and 17.2 m from the apparent "sun". A water cooled 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. NASA completed the CDR for the advanced SS, as planned, in September 1993 and started fabrication of the support structure along with the critical optical components. Fabrication, assembly, installation and checkouts of the SS integrated with Tank 6 by NASA LeRC personnel was completed in September 1994, 3 months ahead of schedule. A detailed description of the solar simulator and results from early testing of a subscale optics system are discussed by Jefferies (1994).

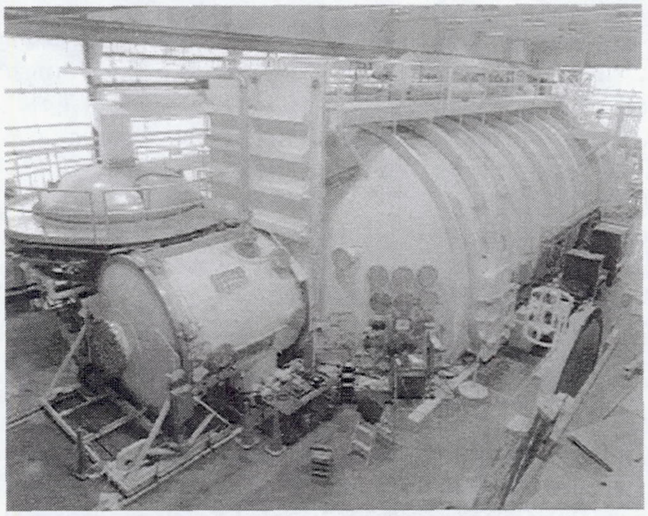

FIG. 2 - PHOTOGRAPH OF SOLAR SIMULATOR NEXT TO TANK 6

## SOLAR DYNAMIC SYSTEM

The SD system 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 was designed to produce about 2 kW of electric power with thermal energy storage 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 some existing hardware from other government programs.

A block diagram of an SD system is shown in Fig. 3. The solar dynamic power system collects the suns rays onto a solar collector which in turn focus the light into a chamber known as the receiver. This results in heating of the receiver which in turn heats a cycle working fluid, helium-xenon, that powers a turboalternator/compressor which results in the production of electrical energy. The solar receiver is designed to transfer energy to the fluid during the on sun phase of the orbit, and to store energy for operation during the shade phase. The working fluid is then cooled in the recuperator and the gas coolers and the radiator then rejects the waste heat to space.

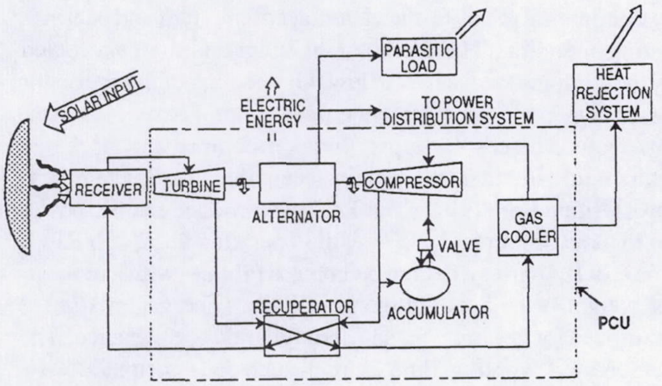


FIG. 3 - BLOCK DIAGRAM OF AN SD SYSTEM

The GTD system is designed for over 1000 hours of operation with up to 100 starts from a cold start condition. The nominal design case for the GTD is the maximum insolation orbit, which represents LEO of 66 minutes of sun and 27 minutes of shade. Fig. 4 illustrates the modular design of the SD components as it is configured in Tank 6. The modular design of the SD system offers the potential for NASA to evaluate subsystems and advanced components at a later date. Further, development, verification and qualification tests are ongoing in support of the joint U.S./Russian SD flight demonstration project (Huckins, 1994).

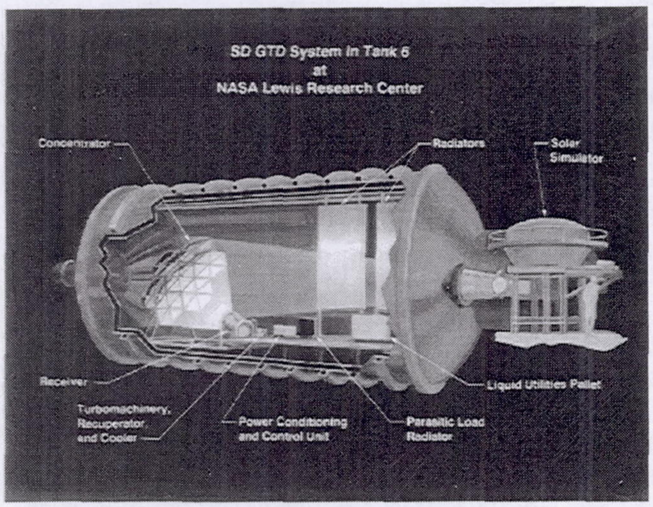


FIG. 4 - SD GTD SYSTEM INSTALLED IN TANK 6

Performance analysis (maximum insolation orbit) of the SD system, shown in Fig. 5, shows the relationship of the energy stored in the solar receiver, the TAC's turbine inlet temperature (TIT) and compressor inlet temperature (CIT), with the resultant 2 kW of electrical output over two orbits. Integrated system testing is being conducted over its full operating range to meet the objective of evaluation and validation of previously developed analytical models, by both the aerospace contractors and government in support of the joint US/Russian SD flight program.

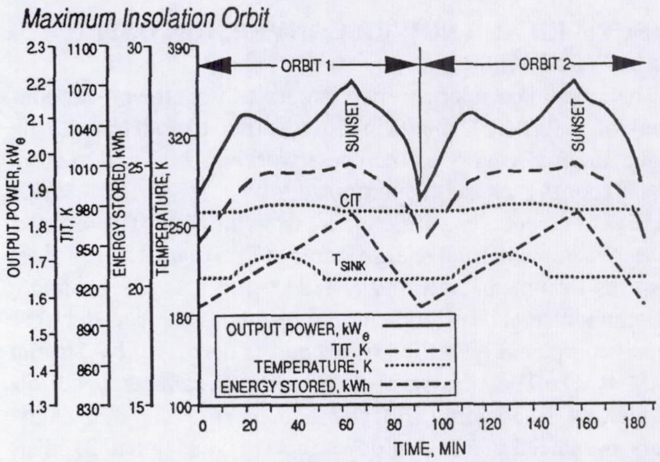


FIG. 5 - ORBITAL PERFORMANCE OF THE SD GTD SYSTEM

## 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 offset concentrator structure, shown in Fig 1, consists of 7 hexagonal panels with 6 reflective facets (mirrors) 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 (BAP). The concentrator's surface consists of 42 aluminum honeycomb facets developed by SKI (Schertz, 1991). 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$^2$. The concentrator was assembled and proofchecked on the NASA BAP in August 1994. Installation of the BAP with solar concentrator in Tank 6 and subsequent facet alignment by Harris with the Solar Simulator was completed during October/ November 1994. Verification of the optical alignment, solar simulator to concentrator to receiver optical interface surface was conducted in the thermal/vacuum environment of Tank 6 with use of a flux distribution rake. The Harris flux distribution rake simulated the interior cylindrical surface of the solar receiver which allows for direct measurement of the receiver flux. Comparison of the flux test data with analytical predictions show excellent correlation. A detailed description of the offset concentrator design is provided by Bahnman (1994). Harris provided the special test equipment for facet alignment and flux distribution in Tank 6 which is described by Campbell (1994).

## RECEIVER AND POWER CONVERSION UNIT (PCU) SUBSYSTEMS

The completed solar receiver integrated with the power conversion unit (PCU), shown in Fig. 6, is used to both transfer the solar thermal 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 and is discussed by Strump (1994). The TES consists of the Haynes 188 canister, or hollow doughnut, filled with LiF-CaF2 eutectic salt. The TES canisters are placed in a scaled down receiver, which has 23 tubes with 24 canisters per tube. The solar receiver was delivered to NASA in August 1994 and was integrated with the Power Conversion Unit in September 1994 by AlliedSignal on the NASA subpallet. Key additions to the SSF design which provide enhanced performance are heat transfer fins added to the internal flow path and a TES alumina based canister coating for improved emissivity characteristics. A complete description of the receiver design is provided by Strumph (1994, 1993).

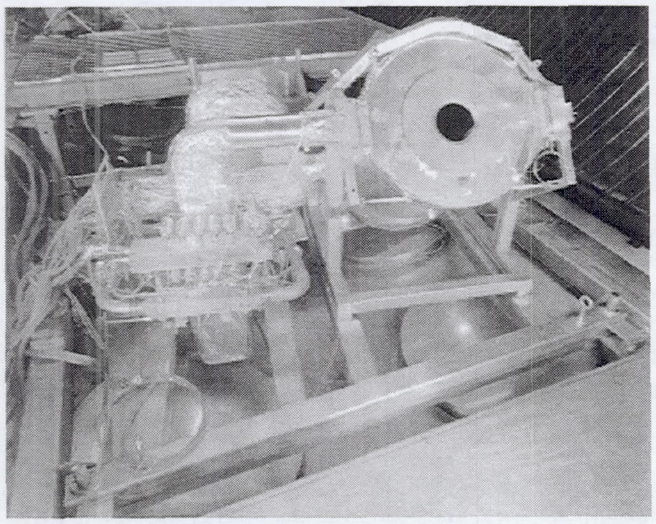

FIG. 6 - COMPLETED SOLAR HEAT RECEIVER INTEGRATED WITH THE PCU

The Closed Brayton Cycle (CBC) Power Conversion Unit (PCU) subsystem includes the turboalternator/compressor (TAC), gas coolers, recuperator, ducting and support structure. The TAC, known as the mini BRU (Brayton rotating unit), consists of a single stage radial flow compressor and turbine and a brushless four pole Rice Alternator mounted on a single shaft. Foil gas bearings are used to provide long life operation by eliminating metal-to-metal contact of the shaft and bearings during operation. The alternator, bearings and shaft are cooled by the compressor discharge flow. Gas cooling of the alternator has resulted in lower mass and reduced complexity. However, this feature places an upper limit on compressor discharge temperature in order to maintain acceptable winding temperatures (Amundsen, 1992). The TAC will produce electric power up to a maximum of 2.2 kW while operating at 52 000 RPM. The CBC unit uses a helium-xenon gas mixture with a molecular weight of 83.8 as the working fluid. The gas mixture is optimized for heat transfer and aerodynamic performance. 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. The PCU acceptance test was completed by AlliedSignal in August 1994 with demonstration of 2 kW of electrical power. This test was performed at local atmospheric conditions with an electrical heater. This "hot loop" test provided an ideal opportunity to address and evaluate many electrical, control and thermal interface issues. The PCU was delivered to LeRC in early September 1994 and integrated with the solar receiver. Prior to integration of the receiver and PCU, each assembly was covered with multi-layer foil insulation by wrapping layer upon layer of nickel and aluminum foils around the critical hot parts.

## WASTE HEAT REJECTION (WHR) SUBSYSTEM

The completed WHR system, 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), accumulator and sensors for the n-heptane coolant fluid. Each bonded aluminum honeycomb radiator panel is about 1.77 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 a white epoxy paint, chemglaze A276, a thermal control coating. The WHR system is integrated into the CBC loop by means of two gas-to-liquid heat exchangers, or gas coolers.

A detailed description of the analysis, design, fabrication and testing of the waste heat subsystem is provided by Fleming (1987, 1994). Acceptance testing of the waste heat subsystem was completed in the LeRC thermal/vacuum facilities by Loral Vought, LeRC and AlliedSignal personnel. Both steady state and transient operation of the WHR system was conducted in June and July 1994. Heat rejection during steady state tests ranged from 2.5 to 6.3 kW. To meet the desired fluid outlet temperature at GTD nominal operating conditions at the lower, apparent sink temperature, radiator #2 was covered with about 1.2 m of insulation blankets. Performance of the WHR system was as expected.

## POWER CONDITIONING & CONTROL SUBSYSTEM

The Power Conditioning and Control Unit (PCCU) contains the power electronics. The start inverter power supply (SIPS) 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, consists of an array of vacuum compatible, individually controlled cal rod heaters with enhanced emissivity characteristics.

The Data Acquisition and Control System (DACS) is special test equipment 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.

## SYSTEM TESTING

The SD System Acceptance Test includes the concentrator, receiver, radiator, PCU, PCCU, in the Lewis thermal/vacuum facility with the DACS, an ELS and the solar simulator. The acceptance testing of the SD system has successfully demonstrated startup, transient and steady state orbital operation and shutdown. Acceptance testing was accomplished in only three months, from December 1994 thru February 1995. Over 2.0 kW of electrical power was achieved on February 17, 1995 while operating at 52 000 RPM with a TIT of 1915 R (1455 °F) and a CIT of 433 R (-27 °F). Steady state orbital operation was demonstrated (66 minutes of insolation/28 minutes of eclipse) at 48 000 RPM. Acceptance testing accumulated about 40 hours of power operation with 10 orbits including five successful cold (ambient) starts with one hot restart. Early evaluation of performance data show steady state and orbital operation of the PCU is as predicted. Both thrust and journal bearings temperatures and rotor stability were shown to be within acceptable limits. During the acceptance testing the following conclusions were made by AlliedSignal: 1) system cold starting was slower than anticipated due to analytical modeling techniques which ignored certain receiver mass elements which are not required during orbital conditions, 2) a receiver pressure drop that was higher than anticipated due to incorporation of heat transfer fins between the receiver tube and centerbody, 3) an overall system energy imbalance exists between receiver calorimetric calculations and solar simulator light measurements and 4) PCCU component problems associated with vacuum and cold environmental conditions were encountered. Turnover of the SD GTD system to NASA was completed in March 1995. After turnover, SD system testing by NASA has accumulated an additional 100 hours of power operation including 51 simulated orbits (66 minutes of sun/27 minutes of shade), and five cold (ambient) orbital starts. Operation is being conducted to characterize the SD system and evaluate various analytical models over a variety of solar insolation levels, speed conditions (48 0000 and 52 000 RPM) and engine inventories in support of the joint US/Russian SD flight demonstration project.

An example of data from an operational SD system (receiver/ PCU), includes the average canister temperature, the receiver gas exit temperature, the CIT and the DC power output as shown in Fig. 7. This test was conducted over a 40 hour period with the TAC operating at 48 000 RPM and includes an orbital startup, transient and steady state orbital operation and a shutdown. The TAC was operating at 48 000 RPM thru the test, except for the shutdown at 52 000 RPM. The solar simulator provided four different insolation levels, 1.01, 1.06, 1.08 and 1.14 suns (1.37 kW/m$^2$ = 1 sun), resulting in four steady state orbital cases, during the 93 minute orbit. Balanced orbitaloperation was achieved on orbits 4, 8, 15, and 21. The first three cases are in a sensible heat receiver (canister phase change material not melted), which resulted in large temperature (247 R) and power (138 W) fluctuations. The fourth case is in a latent heat receiver state, resulted in a marked reduction of temperature (35 R) and power (49 W) fluctuations during the orbit, which are in good agreement with analytical predictions. For this off-design point, overall system efficiency, sun in to user energy, is in excess of 14 per cent, while the engine efficiency is about 24 per cent.

An example of data from the orbital start-up showing a representative solar receiver heating profile is shown in Fig. 8. The canister temperature increases during each sun interval of the first three orbits until it reaches 1900 R (1440 °F) during the third orbit. The turbine preheat requirement of 1900 R was established to overcome the potential of compressor surge effects which were observed during the "hot loop" testing of the PCU at AlliedSignal. Also shown are the receiver gas inlet and exit temperatures which are gradually increasing during the 3.5 hrs of heating.

After the canister reached 1900 R, the turbine preheat is conducted by motoring the TAC at 30 000 RPM, with the bypass (shutdown) valves open, for about two minutes. Note the relationship (reversal) of receiver inlet and exit temperatures during the two minute preheat, indicating proper flow direction. Finally, with the bypass valves closed, the TAC is started by motoring at 36 000 RPM until self-sustained operation is observed. TAC motoring for this start required about 4 minutes. Testing to date has resulted in an improved understanding of integrated SD system operations and performance.

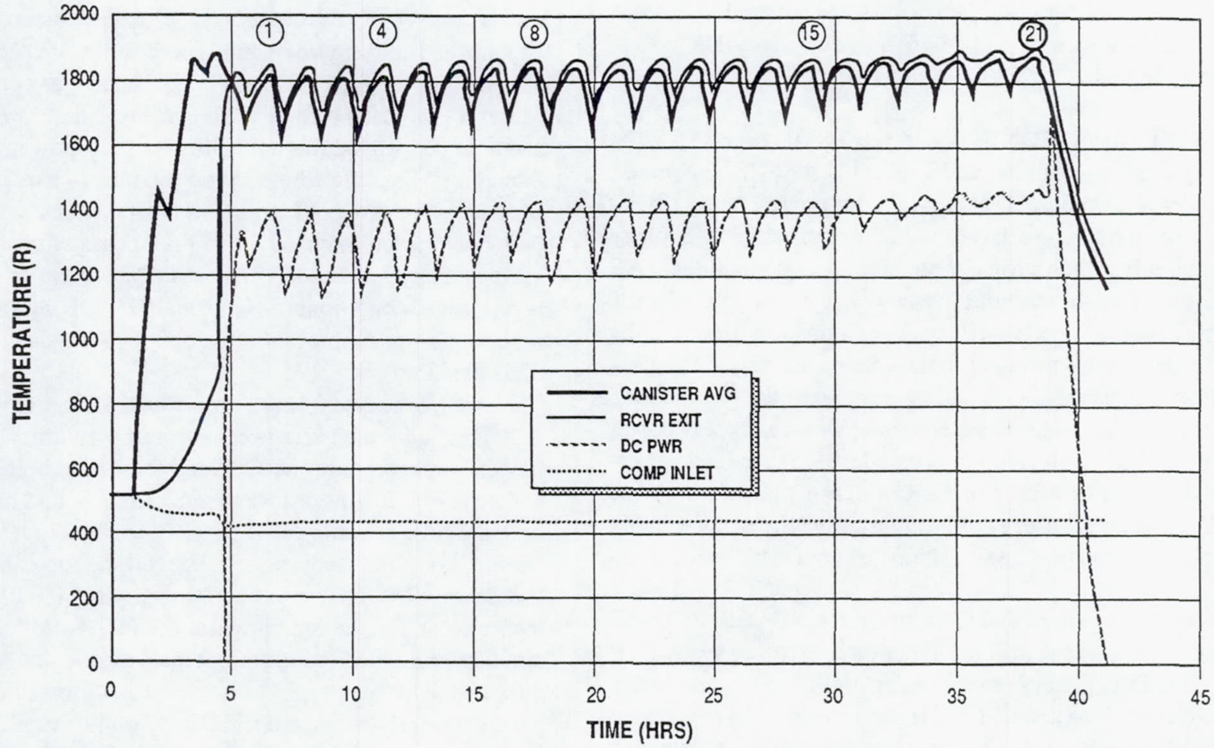


FIG. 7 -DATA SHOWING STARTUP, MULTIPLE ORBITS AND SHUTDOWN OF SD SYSTEM

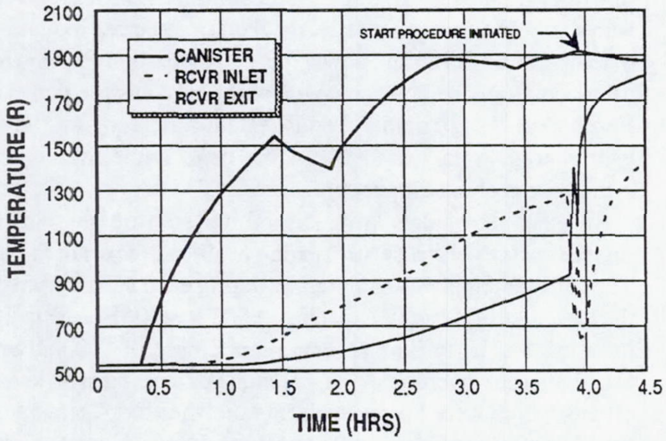


FIG. 8 - DATA SHOWING COLD (AMBIENT) ORBITAL START-UP

## SUMMARY

The collective efforts of the SD GTD Team has resulted in the first full scale demonstration of a complete space-configured SD system in a large thermal/vacuum facility with a simulated sun. Initial operational and performance data has demonstrated an SD power system which is of sufficient scale and fidelity to ensure confidence in the availability of SD technology for Space. Studies have shown that SD 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 ISS Alpha, communication and Earth observing satellites, and electric propulsion (Huckins, 1994; Brown, 1992; Calogeras, 1991). An aerospace government/industry team worked together to show that we can do it "cheaper, better, faster" to successfully demonstrate solar dynamic power for space. The SD GTD program was completed in early 1995, ahead of schedule and under budget. The government/industry team delivered the 2 kW SD system demonstration as promised.

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Richard K. Shaltens and Robert V. Boyle

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National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

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**Lewis Research Center**
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Cleveland, OH 44135-3191