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500 Hours of Operational Experience From a Solar Dynamic Power System

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500 HOURS OF OPERATIONAL EXPERIENCE FROM A SOLAR DYNAMIC POWER SYSTEM

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Abstract

Testing has been conducted on a 2 kW_e Solar Dynamic system in a large thermal/vacuum facility with a simulated Sun at the NASA Lewis Research Center. The solar dynamic system includes a Brayton conversion unit integrated with a heat receiver which includes thermal energy storage for continuous power generation throughout a typical low-Earth orbit sun/eclipse cycle. System testing to date has accumulated over 500 hrs of power generation, ranging from 400 watts to over 2.0 kW_e, including nearly 300 simulated orbits (249 producing power), 23 ambient starts and 3 hot restarts in a relevant environment. This paper will review the test program, including both operational and performance data. Data will be shown for an orbital startup and both transient and steady state orbital operation. System performance sensitivities are also discussed. The system testing is providing the experience and confidence for using solar dynamic technologies for future space power applications.

Introduction

The NASA Office of Space Access and Technology initiated the 2 kW_e Solar Dynamic (SD) Ground Test Demonstration (GTD) Project which is managed by the NASA Lewis Research Center (LeRC) (Shaltens 1996 & Calogeras 1992). The primary goal of this project is to conduct testing of flight prototypical components integrated in a complete space power SD system in a relevant environment. Demonstrations of both system power delivered and total system efficiency in low-Earth orbit (LEO) are key test objectives. Shown in Fig. 1, the SD power system includes an off-axis solar concentrator, a solar heat receiver with thermal energy storage (TES) integrated with a closed Brayton cycle power conversion unit. Major components of the GTD system were derived from designs and hardware from existing programs. The TAC (turbo-alternator/compressor) and the recuperator hardware came from the Brayton Isotope Power System (BIPS) (Dobler, 1978) and the designs of the off-axis concentrator, solar receiver, and radiator subsystems were based on designs from the Space Station Freedom Program (Jefferies, 1993). The GTD system is of sufficient scale and fidelity to ensure confidence in the technology for larger power systems in space. A complete description of the GTD system components is reviewed by Shaltens (1996) and a comparison to the Space Station Freedom designs and scaling are discussed by Amundsen (1993) and Calogeras (1992). The SD system is installed in a large thermal/vacuum facility with a solar simulator. The LeRC facility provides an accurate simulation of the temperature, high vacuum and solar flux as encountered in LEO.

Fig. 2 illustrates the modular layout of the GTD components in the LeRC thermal/vacuum facility. Testing was initiated in December 1994 and resulted in the World's first operation of a complete SD space power system in a relevant

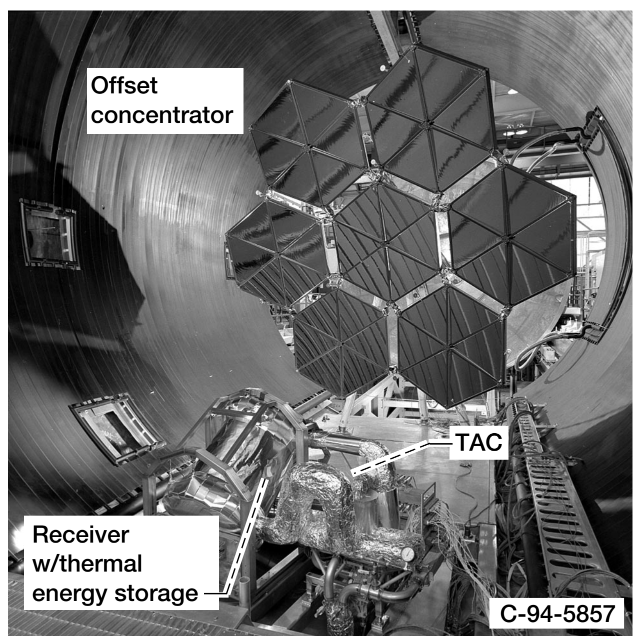

FIGURE 1.—PHOTOGRAPH OF THE SOLAR DYNAMIC SYSTEM IN TANK 6.

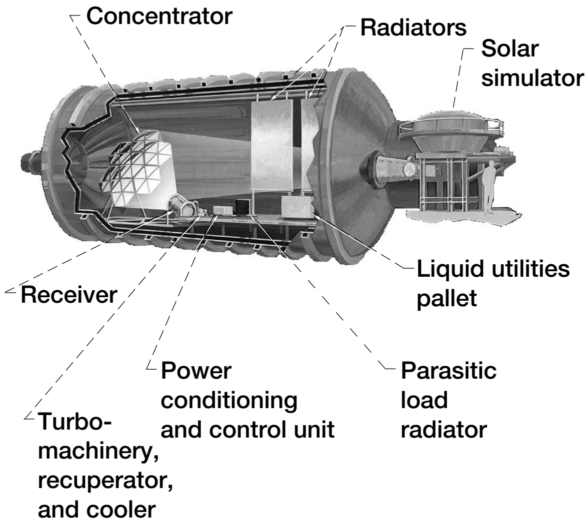

FIGURE 2.—SOLAR DYNAMIC SYSTEM LAYOUT IN TANK 6.

environment. A review of the SD GTD project activities with the government/industry team and discussion of the component analysis and design are provided by Shaltens & Boyle (1995b, 1994 & 1993). Discussion of the initial testing are provided by Shaltens & Mason (1996), Shaltens (1995a) and Alexander (1996).

System Operation and Testing

Integrated system testing is being conducted over the system operating range in order to evaluate and validate previously developed analytical models. The test program is being conducted in two phases: 1) system acceptance tests by AlliedSignal, and 2) system characterization tests by NASA. Testing conducted by NASA was divided into the following areas: 1) code evaluation and system benchmarking, 2) offdesign evaluation for the SD flight demonstration, and 3) flight system development testing as shown in Table I. The latter two phases of NASA testing was conducted to support the development, verification and qualification of the Power Generation System (PGS) for the joint United States/Russian SD flight demonstration project (Wanhainen & Tyburski, 1995).

System testing to date includes 23 individual tests, ranging from a few minutes to 53 hrs of continuous operation in a 10^{-6} torr vacuum environment. Average operation per test is about 22 hrs. Almost 300 orbits have been simulated, which includes 43 orbits during system heatup (13 orbital startups) and 249 orbits producing power (ranging from 400 watts to over 2.0 kW_e). Operation includes three hot restarts and an overspeed

TABLE I.—SUMMARY OF SD TESTING

- Contractor Acceptance Testing
  - 8 tests and 40 hrs
    - Initial operations and checkout
- Code Evaluation and System Benchmarking
  - 6 tests and 130 hrs
    - Orbital simulations
    - Receiver energy balance
    - Insolation levels
- Off-Design Evaluation for SD Flight Demonstration
  - 5 tests and 248 hrs
    - Speed variations
    - Orbit variations
    - Speed algorithms
    - Heat rejection variations
- Flight System Development Testing
  - 4 tests and 90 hrs - ongoing
    - Probe heater
    - Aperture shield off-pointing
    - Max power operation

shutdown. Over 55 TAC starts and shutdowns have been demonstrated using non-contacting journal and thrust foil bearings. SD system testing has successfully demonstrated orbital startups, transient and steady state orbital operation and shutdowns. Operation during the NASA testing program has shown the SD system to be very reliable and robust.

System Performance

An example of data from a typical SD system test is shown in Fig. 3. Shown is a test sequence which was conducted over a 25 hr period and illustrates the following: a two orbit startup, transient and balanced orbital operation for both a sensible (i.e., canister phase change material not melted) and latent (i.e., phase change material melted) heat regimes for the receiver. Over 2.0 kW (peak at 120 V_{dc}) was achieved during this test. Data shown from the integrated system test are: the average receiver canister temperature, the receiver gas exit temperature (or turbine-inlet temperature (TIT)), the compressor-inlet temperature (CIT) and the DC power output. Test variables include: a solar simulator providing 1.22 Suns (1.67 kW/m^2); simulated orbits with a period of 66 minutes of sunlight/27 minutes of eclipse and a period with 72 minutes of sunlight/21 minutes of eclipse.

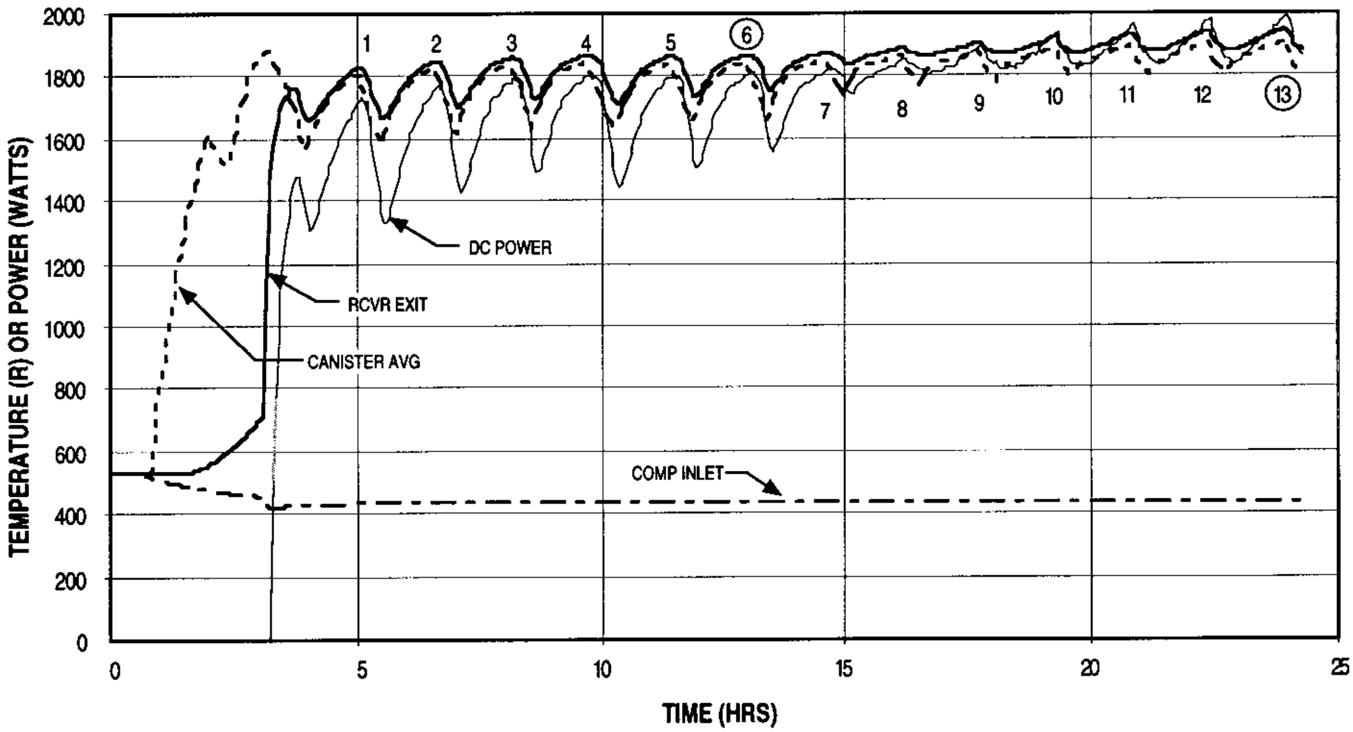

FIGURE 3.—DATA SHOWING STARTUP, TRANSIENT AND BALANCED ORBITAL OPERATION.

The 25 hr test period was conducted at a constant TAC speed of 52 000 rpm. As shown in Fig. 3, system power output is strongly dependent on receiver exit temperature which varies over the orbit period based on the energy content of the solar receiver.

Orbital Startups

Thirteen orbital startups have been conducted from ambient conditions during the NASA testing program to date. Ambient start temperature is defined as the receiver gas temperature at 530 R (70 °F). Due to test variations for the solar flux, the heating profile has varied and the number of orbits to reach the startup criteria (when the receiver canister temperature reaches 1900 R (1440 °F)) has ranged from two to five.

An example of data which shows a representative solar receiver heating profile for a two orbit startup is shown in Fig. 4. The solar input was 1.22 Suns (1.67 kW/m^2) which provided about 11.8 kW$_t$ into the receiver. The simulated orbit provided 66 minutes of sunlight and 27 minutes of eclipse. As noted in Fig 4, the following sequence occurs during the startup: 1) the receiver canister temperature increases during each Sun interval of the first two orbits until it reaches 1900 R during the second orbit (a turbine preheat requirement was established during hot loop testing of the PCU at AlliedSignal and is discussed in detail by Shaltens & Mason (1996)); 2) after the canister reaches 1900 R, the turbine preheat is conducted by motoring the TAC at 30 000 rpm, with the bypass (shutdown) valves open for two minutes (note the relationship (reversal) of the receiver inlet and exit temperatures during the two minute preheat, indicating proper flow direction); 3) the bypass valves are closed and the TAC is started by motoring at 36 000 rpm; 4) until self-sustained operation is achieved; 5) after which time the TAC accelerates to the intended operating speed. TAC

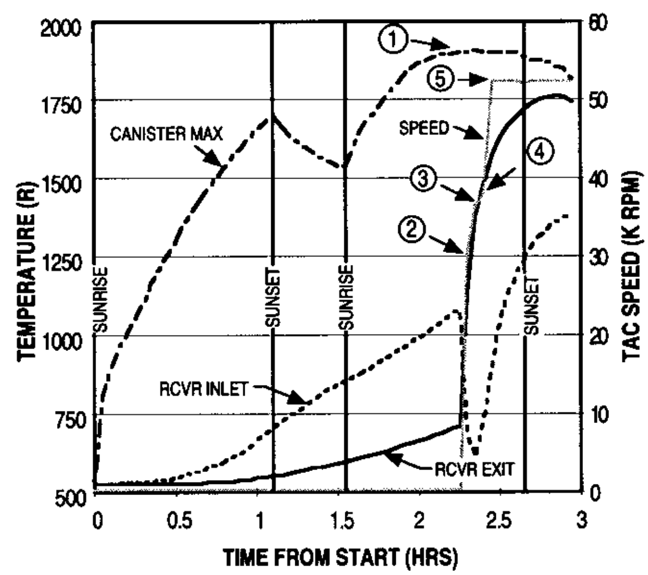

FIGURE 4.—DATA SHOWING AMBIENT ORBITAL STARTUP.

motoring for this start required about five minutes. Motoring times have ranged from 2 to 6.4 minutes, and are a function the solar input.

Sensible Heat Receiver

In Fig. 3, orbits 1 to 6 show operation with the receiver in a sensible heat regime with the TAC operating at 52 000 rpm. During the 6th orbit, the system was balanced, with a sunset turbine-inlet temperature (TIT) of 1865 R (1405 °F) and a compressor-inlet temperature (CIT) of 437 R (-23 °F). Balanced operation is defined as successive orbits with repeatable conditions at sunrise and sunset exhibiting less than 2 R change in the receiver gas temperatures and less than 5 W change in output power. The average orbital power produced was 1.70 kW_e (at 120 V_{dc}). The Brayton conversion efficiency (alternator output power divided by working fluid heat input) was 28 percent and the overall system efficiency (Sun in to user energy) was measured at 16 per cent. Illustrated in Fig. 5 is the balanced orbit 6, during which the receiver gas exit temperature is below the melting point (1873 R (1413 °F) of the TES phase change material (LiF-CaF_2). When the energy storage material is not melted, the receiver is considered to be in the sensible heat regime.

Transition Operation

Fig 6. shows the transition from a balanced sensible receiver (orbit 6) to a balanced latent receiver (orbit 13) with the TAC operating at 52 000 rpm. While maintaining the solar insolation at 1.67 kW/m^2, the sun/eclipse period was changed from 66/27 to 72/21 minutes to provide additional heat. Note the change in

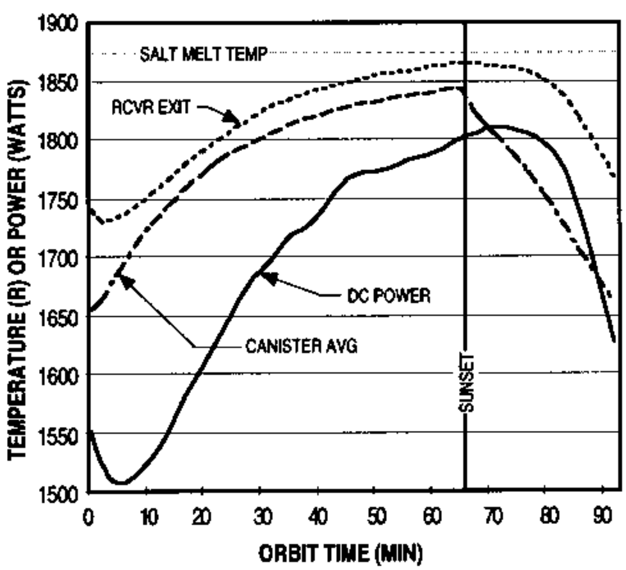

FIGURE 5.—DATA SHOWING BALANCED ORBITAL OPERATION (SENSIBLE HEAT REGIME).

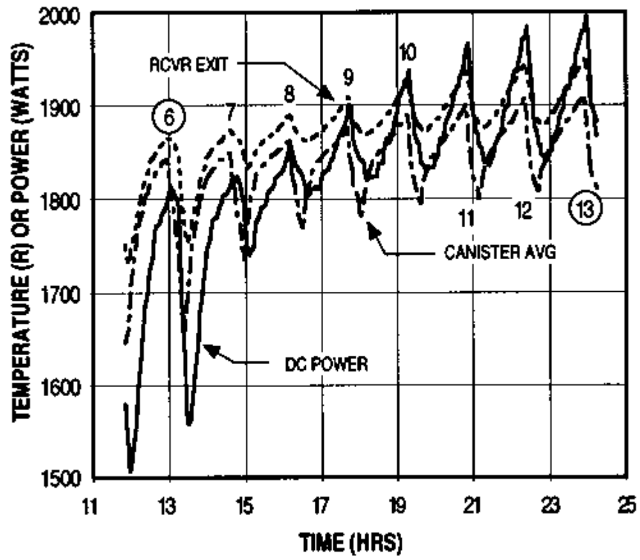

FIGURE 6.—DATA SHOWING TRANSITION FROM SENSIBLE TO LATENT HEAT REGIMES.

the shape of the peak (at sunset) for both the receiver canister and gas exit temperatures during orbits 7 and 8. This occurs while the temperature is increasing to above the melting point of the phase change material. Peaks during sensible heat regime are rounded while the peaks during latent heat regime appear to be pointed. Fig. 6 is a good representation of the slow thermal response in the SD system, and the time needed for the system to come to a balanced condition after a change. Typically, thermal balance takes many hours, and usually ranges between 4 to 6 orbits.

Maximum Power Operation and Latent Heat Receiver

Approximately 2.0 kW_e (peak at 120 V_{dc}) was achieved on April 2, 1996 while operating at 52 000 rpm with a TIT of 1948 R (1488 °F) and a CIT 438 R (-22 °F), as shown in Fig. 7 (orbit 13). The orbital average power produced was 1.905 kW_e (at 120 V_{dc}). The closed Brayton conversion efficiency was measured at 30 percent and the overall system efficiency was measured at about 17 percent. As shown in Fig. 7, during orbit 13, the received gas exit temperature is above the melting point 1873 R (1413 °F) of the eutectic phase change material throughout the orbit. When the energy storage material is melted, the receiver is considered to be in a latent heat regime.

Table II provides a comparison of operating parameters between orbit 13 and the system design point at the Critical Design Review. The design point was established based on the requirement to produce an average alternator output of 2 kW over the orbit. As shown in Table II, several essential adjustments, shown in bold, were necessary to achieve 2 kW average. The orbit insolation period was increased from 66 to 72 minutes and the coolant supply temperature was depressed by 16 R.

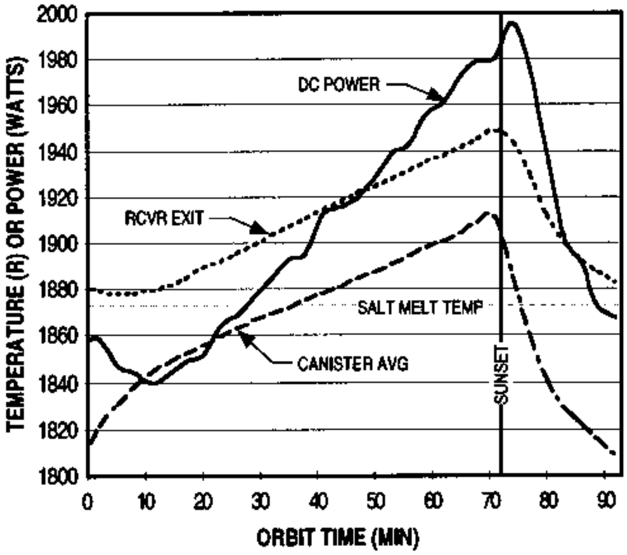

FIGURE 7.—DATA SHOWING BALANCED ORBITAL OPERATION (LATENT HEAT REGIME).

These changes were needed to compensate for a receiver pressure drop that was much larger than expected (Alexander, 1996).

TABLE II.—2 kW ORBIT SYSTEM PARAMETERS

Parameter	Design	Orbit 13
Qin Rcvr, kWt	11.57	11.77
Req'd Insol, Suns	1.20	1.22
Sun/Eclipse Period, min	**66/27**	**72/21**
TAC Speed, rpm	52 000	52 000
Relatve Gas Charge, %	100	100
Gas Flow Rate, lb/s	0.33	0.34
Qin Gas,kWt	6.40	6.93
Coolant Supply Temp, R	**452**	**436**
Coolant Flow Rate, GPH	29.1	30.3
Qrej Coolant, kWt	4.05	4.75
Engine Conditions at Sunset		
Rcvr Exit Temp, R	1881	1948
Rcvr Exit Press, psia	87.2	90.4
Rcvr ΔP, psia	1.43	3.49
Comp Inlet Temp, R	456	438
Comp Inlet Press, psia	55.2	57.1
Comp Press Ratio	1.62	1.65
Cycle Temp Ratio	4.13	4.44
Alt Output, kW-hrs	3.12	3.23
Avg AC Power, kW	2.00	2.08
Avg DC Power, kW	1.90	1.91
Conversion Efficiency, %	31.3	30.0

System Performance Sensitivities

Fig. 8 shows the relationship of orbital performance versus receiver input power. The data points are balanced orbits of 66 minutes of sunlight and 27 minutes of eclipse with the TAC operating at the design speed of 52 000 rpm. A receiver input power of 9.6 kW_t corresponds to 1.37 kW/m^2 (1 Sun) solar insolation on the off-axis concentrator. Increasing receiver power provides a near linear increase in the output power. Increases in conversion and overall efficiency with receiver input power are the result of higher gas temperatures to the turbine. Overall efficiency begins to level-off at higher receiver power levels due to increased radiative losses from the receiver (aperture and skin) with increasing cavity temperature.

System performance sensitivity to variations in TAC speed are shown in Fig. 9. The data points represent balanced orbits (66 minutes of sunlight and 27 minutes of eclipse) at constant receiver input power (approx. 9.6 kW_t). The receiver input power corresponds to 1 Sun solar insolation on the off-axis concentrator. Peak output power and overall efficiency is evident with a TAC speed of 48 000 rpm. Optimum performance results from the tradeoff between gas flow rate and turbine-inlet temperature. Increasing speed provides a corresponding increase in mass flow rate which increases the mechanical power derived from the turbine work. However, increases in flow rate also serve to cool the receiver faster which reduces the turbine inlet gas temperature. Lower turbine-inlet temperatures relate to decreases in cycle temperature ratio (T_{max}/T_{min}) which result in lower cycle efficiency.

The optimum operating speed would vary as a function of receiver input power. An increase in the receiver input power would result in a higher optimum speed point. Fig. 10 shows the effect of the receiver input power on DC output power for two

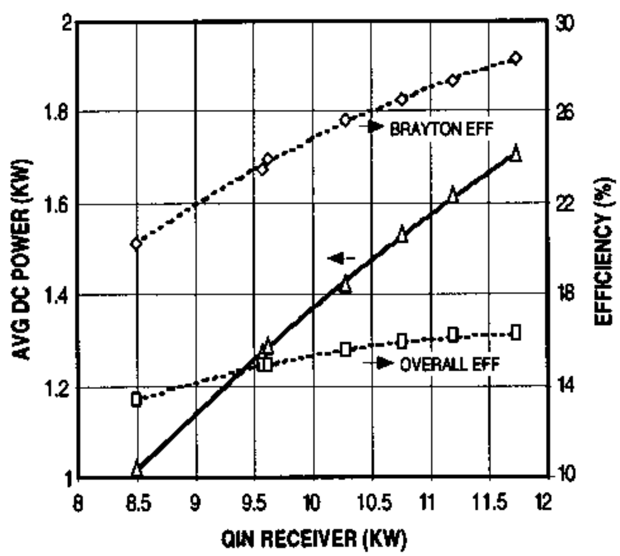

FIGURE 8.—ORBITAL PERFORMANCE VS. RECEIVER INPUT POWER.

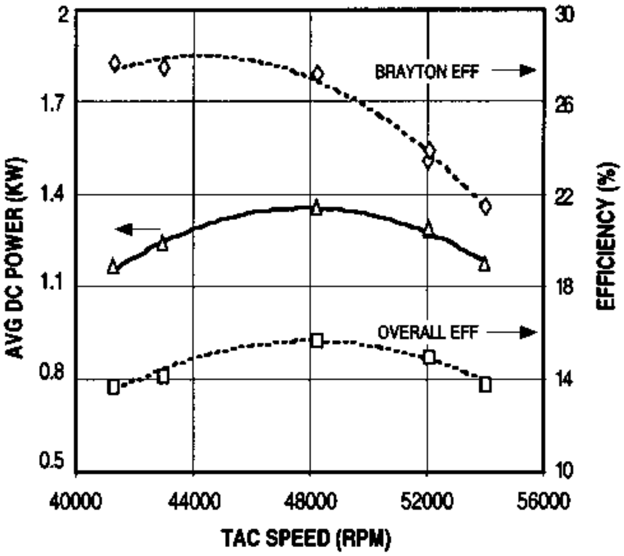

FIGURE 9.—ORBITAL PERFORMANCE VS. TAC SPEED.

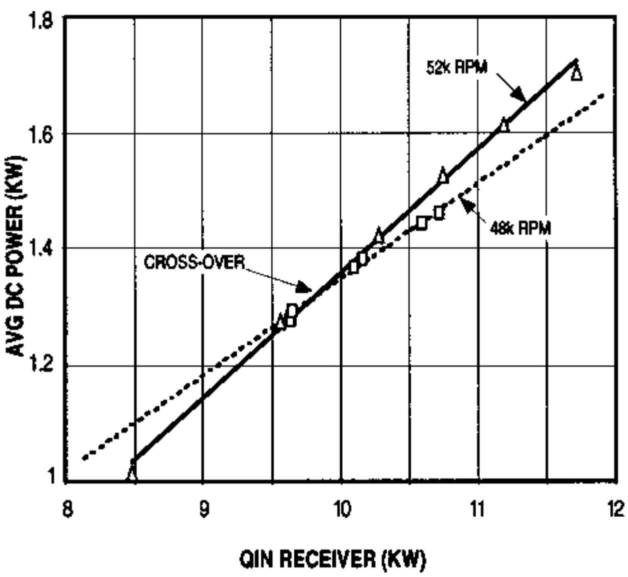

FIGURE 1O.—DC OUTPUT POWER VS. RECEIVER INPUT POWER (FOR 52 AND 48 K RPM).

different TAC speeds. The linear curve fits of the balanced orbital average power data indicates a cross-over at 9.8 kW_t. Below the cross-over point, higher output power can be achieved by operating the TAC at 48 000 rpm and above the cross-over, 52 000 rpm appears to provide superior performance. If similar data sets were collected at speeds below 48 000 rpm and 52 000 rpm, the result would be a series of cross-over points indicating optimum operating speed as a function of receiver input power.

Summary

Operational and performance data has demonstrated a prototypical SD power system which is sufficient scale and fidelity to ensure confidence in the potential of the SD technology base for future space power applications. A key feature of the SD system is the use of thermal energy storage in the heat receiver which allows for continuous power generation throughout the orbit. The prototypical SD system has been operated over 500 hrs in a relevant environment and has demonstrated orbital startups, both transient and steady state orbital operation, sensible and latent heat receiver operation, and shutdowns. With almost 300 low-Earth orbits being simulated, operation has included power generation ranging from 400 watts to over 2.0 kW_e. Testing has included 13 orbital startups and over 55 successful TAC starts and shutdowns on non-contacting foil bearings. Operation during the NASA testing program has shown the SD system to be very reliable and robust. Testing to date has resulted in an improved understanding of integrated system operations and performance.

SD system efficiencies have been measured up to17 per cent, during simulated low-Earth orbital operation. The demonstrated ene-to-end system efficiency is very good when compared to large photovoltaic/battery systems. End-to-end orbital efficiencies of large photovoltaic/battery systems are currently estimated to be about 4 per cent for the International Space Station.

Acknowledgements

The collective efforts of the SD GTD government/industry team has resulted in the World's first full scale demonstration of a complete SD system in a relevant environment. The authors wish to acknowledge the contributions of all the government and industry scientists, engineers, technicians and other support personnel for their dedicated effort which allowed for the successful testing of a complete system in the LeRC large thermal/vacuum facility known as Tank 6.

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Testing has been conducted on a 2 kWe Solar Dynamic system in a large thermal/vacuum facility with a simulated Sun at the NASA Lewis Research Center. The solar dynamic system includes a Brayton conversion unit integrated with a heat receiver which includes thermal energy storage for continuous power generation throughout a typical low-Earth orbit sun/eclipse cycle. System testing to date has accumulated over 500 hrs of power generation, ranging from 400 watts to over 2.0 kWe, including nearly 300 simulated orbits (249 producing power), 23 ambient starts and 3 hot restarts in a relevant environment. This paper will review the test program, including both operational and performance data. Data will be shown for an orbital startup and both transient and steady state orbital operation. System performance sensitivities are also discussed. The system testing is providing the experience and confidence for using solar dynamic technologies for future space power applications.

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