NASA/TM—1999-208840

800 Hours of Operational Experience From a 2 kW_e Solar Dynamic System

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January 1999

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Prepared for the
Space Technology and Applications International Forum
cosponsored by the Boeing Company, Lockheed Martin, National Aeronautics and Space Administration, U.S. Air Force, and the U.S. Department of Energy
Albuquerque, New Mexico, January 31–February 4, 1999

National Aeronautics and
Space Administration

Lewis Research Center

January 1999

Acknowledgments

The collective efforts of the government/industry team have resulted in the World's first full-scale demonstration of a 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 efforts, which allowed for the successful testing of a complete SD system in the large solar-thermal/vacuum facility at the Lewis Research Center in Cleveland, Ohio.

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Abstract. From December 1994 to September 1998, testing with a 2 kWe Solar Dynamic power system resulted in 33 individual tests, 886 hours of solar heating, and 783 hours of power generation. Power generation ranged from 400 watts to over 2 kW_e, and SD system efficiencies have been measured up to 17 per cent, during simulated low-Earth orbit operation. Further, the turbo-alternator-compressors successfully completed 100 start/stops on foil bearings. Operation was conducted in a large thermal/vacuum facility with a simulated Sun at the NASA Lewis Research Center. The Solar Dynamic system featured a closed Brayton conversion unit integrated with a solar heat receiver, which included thermal energy storage for continuous power output through a typical low-Earth orbit. Two power conversion units and three alternator configurations were used during testing. This paper will review the test program, provide operational and performance data, and review a number of technology issues.

BACKGROUND

Demonstration of the technology readiness of Solar Dynamic systems was initiated in 1992 with the Solar Dynamic (SD) Ground Test Demonstration (GTD) project (Calogeras, 1992 and Shaltens, 1993). The primary goal of the project was to demonstrate operation of an integrated space power system in a relevant space environment. Demonstration of system power output and total system efficiency in low-Earth orbit (LEO) were the key test objectives. Figure 1 shows the SD power system, which included an off-axis solar concentrator, a solar heat receiver with thermal energy storage (TES) integrated with a closed Brayton cycle power unit.

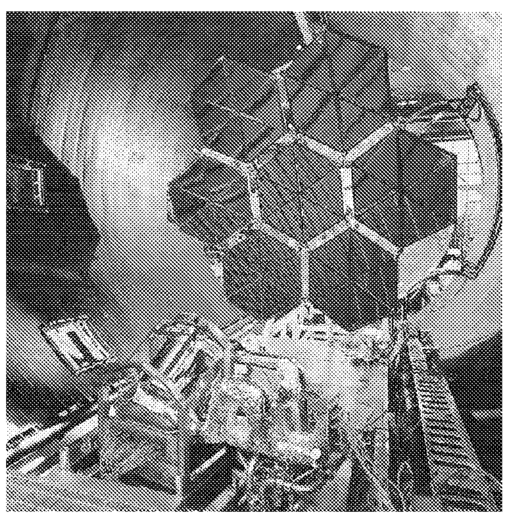

FIGURE 1. Photograph of the Solar Dynamic System installed in the Solar-Thermal/Vacuum Facility known as Tank 6. Shown are the off-axis concentrator, power conversion unit with TAC (right side) and the solar receiver with thermal energy storage (left side).

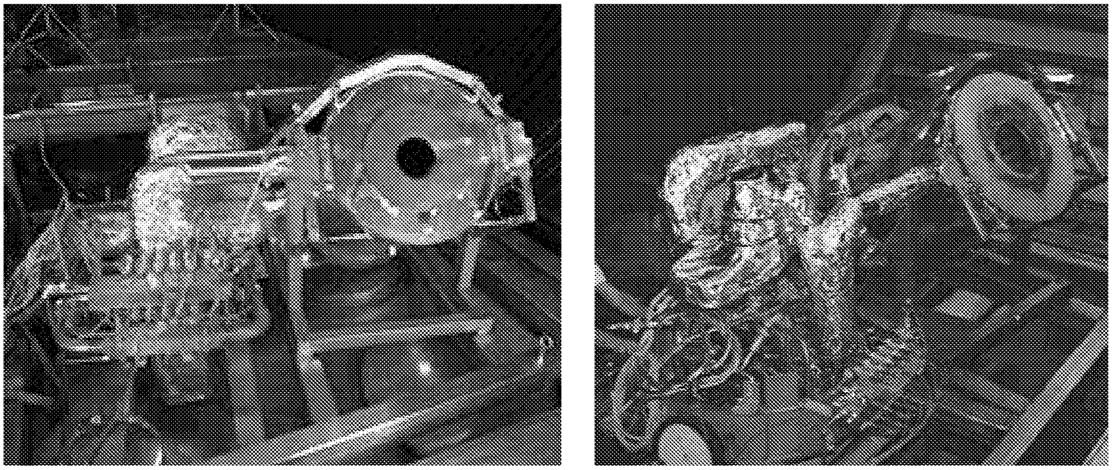

FIGURE 2. Photographs of the Power Conversion Units (PCU's) with the Solar Receiver in the GTD Configuration (left) and the Flight Configuration (right) installed in the Solar-Thermal/Vacuum Facility known as Tank 6.

Major components of the SD system were derived from designs and hardware from previous programs. The Brayton Isotope Power System (BIPS) Program (Dobler, 1978) provided the TAC (turbo-alternator-compressor) and the recuperator, while the Space Station *Freedom* program (Jefferies, 1993) provided the designs of the off-axis concentrator, solar receiver, and radiator subsystems. A complete description of the SD GTD system is contained in reports by Shaltens (1994 and 1995) and Alexander (1996). The SD GTD system in its original configuration was operated from December 1994 through June 1996. Later, the joint US/Russian Solar Dynamic Flight Demonstration project (Wanhainen, 1995) provided the designs and hardware for the permanent magnet (PM) alternator which was operated in the GTD system in 1996 and a flight power conversion unit (PCU) in 1998. Subsequently, the US/Russian system planned for a September 1998 delivery to Mir, was cancelled due to Shuttle manifest changes.

The SD GTD system was assembled in a modular manner to allow replacement of the components when newer technology became available. Two PCU's and three alternator configurations were used during testing, which resulted in three system configurations: 1) the 'SD GTD' with the 120 V Rice-Lundell alternator, 2) the 'hybrid' GTD with a 28 V permanent magnet (PM) alternator, and 3) the 'flight' PCU with a 120 V PM alternator. The solar concentrator, solar receiver and the radiator systems where used throughout the testing. Shown in Figure 2 are the solar receiver with thermal storage and PCU's from the GTD system (left) and the flight system (right). The PCU contains the TAC, recuperator, cooler(s), ducting and support structure.

OPERATIONAL EXPERIENCE

System testing was conducted over a wide range in order to evaluate and validate previously developed analytical tools. Testing was conducted with three configurations: 1) the SD GTD, 2) the hybrid GTD, and 3) the flight PCU. Table 1 provides a brief summary of the testing completed from December 1994 to September 1998.

TABLE 1. Summary of System Tests

• **SD GTD Configuration** - Contractor Acceptance Testing – 8 tests and 40 hrs - Code Evaluation and System Benchmarking – 6 tests and 130 hrs - Off-Design Evaluation for SD Flight Demo – 5 tests and 248 hrs - Flight Demo Hardware Configurations – 5 tests and 143 hrs
• **Hybrid GTD Configuration** - Flight System Development Testing – 6 tests and 143 hours
• **Flight PCU Configuration** - Flight Autonomous Control Development & Testing – 3 tests and 79 hrs

Testing was conducted in a large thermal/vacuum facility known as Tank 6 with a simulated Sun at the NASA Lewis Research Center. The Lewis facility provided a vacuum (less than 10^{-5} torr) to simulate the space environment, a liquid nitrogen cold wall to provide representative sink temperature (about 200 K) and a solar simulator to supply solar flux at 1.37 kW/m^2 (1 Sun). The Solar Dynamic System included a closed Brayton conversion unit integrated with a heat receiver, which included thermal energy storage for continuous power throughout a typical low-Earth orbit. The balance of the system includes the waste heat radiator system, an electrical control system including a power conditioning and control unit (PCCU) and a parasitic load radiator (PLR). The SD system was designed to produce nominally 2 kW of electrical power and demonstrate system energy efficiencies in low-Earth orbit (LEO) in excess of 15 per cent.

From December 1994 to September 1998, testing with the 2 kW_e Solar Dynamic system resulted in 33 individual tests, 886 hours of solar heating, and 783 hours of power generation. Power generation ranged from 400 watts to over 2 kW_e, which included 372 simulated orbits. Further, the turbo-alternator-compressor (TAC) successfully completed 100 successful start/stops on foil bearings, including 33 ambient starts and 19 hot restarts in the thermal/vacuum environment. Table 2 compares operational experience of the three SD system configurations. Orbital efficiency is defined as the ratio of electrical energy produced to solar energy collected over a complete orbit period. The maximum values shown in the table are from thermally balanced, orbital test points.

TABLE 2. Summary of SD Operational Experience in the Simulated Solar-Thermal/Vacuum Environment.

System Configuration	Year	Test Runs	Heating Hours	Orbit Cycles	Maximum Orbital System Efficiency (%)
SD GTD	1994 - 96	24	645	278	16.6
Hybrid GTD	1996	6	155	69	17.1
Flight PCU	1998	3	86	25	16.1
Totals		**33**	**886**	**372**	

The solar receiver and Brayton PCU shown in Figure 1 were operated with two different TAC (turbo-alternator-compressor) assemblies. The original TAC included a Rice-Lundell alternator with a 120Vdc bus (BIPS design) was operated for 561 hours. A second TAC, from the joint US/Russian flight demonstration project, included a permanent magnet (PM) alternator configured for a 28Vdc bus (OSS Mir design) and was operated for 143 hours. The PM alternator stator from the second TAC was rewound to deliver power to a 120Vdc bus (ISS design), and was operated for about 80 hours. The TAC units accumulated a total of 783 hours generating power with the three alternator assemblies. Table 3 is a summary of the TAC experience operating in the three system configurations.

TABLE 3. Summary of Turbo-Alternator-Compressor (TAC) Operational Experience

Alternator Type	Year	System Starts/Stops		System Generating Hours	TAC Starts/Stops	Max Power Generated (W)	Max Engine Speed (RPM)
		Ambient	**Hot**		**Ambient**		
120 V Rice	1994 – 96	24	4	561	58	2044	54000
28 V PM	1996	6	10	143	21	2347	58000
120 V PM	1998	3	5	80	21	2241	56000
Totals		**33**	**19**	**783**	**100**		

The original TAC, which consists of a single stage radial flow compressor and turbine with a Rice-Lundell alternator. The rotor is supported by two journal foil bearings and one thrust foil bearing. The Brayton conversion unit is hermetically sealed and used an inert gas mixture of Helium-Xenon. The Rice alternator is designed to provide 2 kW_e while operating at 52000 rpm, while the PM TAC was designed to provide 2 kW_e while operating at 56000 rpm. A detailed discussion and a comparison of the Rice and PM alternators which provide an insight in the startup and operating subtleties are provided by Mason (1997). All three TACs provide 3 phase AC electrical output which are conditioned with PCCU's to appropriate bus voltage.

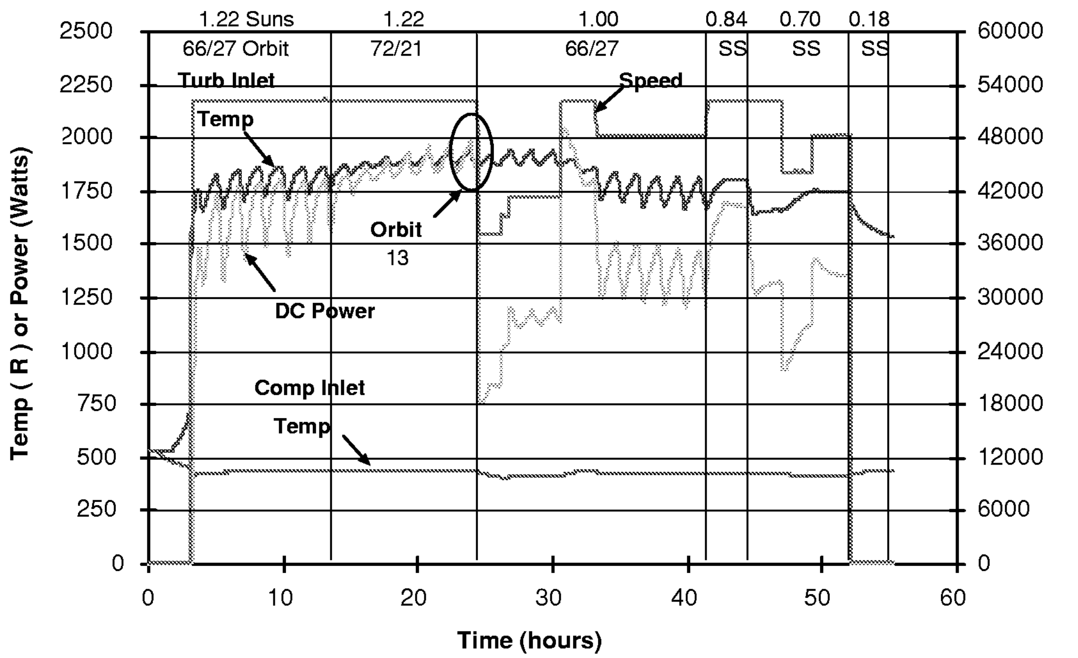

FIGURE 3. Typical data from a SD GTD test showing startup, multiple orbits, steady state points and shutdown of the system.

Shown in Figure 3, is typical data from an operational SD GTD system (receiver and PCU), and includes the turbine inlet temperature, the compressor inlet temperature, the DC power output and TAC rotor speed. The test was conducted over a 52-hour period while the TAC was operating at variable speed and solar input. The test included an orbital startup, transient and steady state operation and a shutdown. Orbit 13 represented a thermally balanced orbital condition providing an average power of 1.9 kW (DC) at a cycle efficiency of 29 per cent and an orbital energy efficiency of 17 per cent. A detailed description of startup, operation and shutdown is discussed by Shaltens (1995 and 1996).

TECHNOLOGY ISSUES

A number of technical issues have been raised over the years concerning dynamic power systems and include the use of gas bearings, hermetic sealing of the power conversion unit, potential vibration concerns, and system mass limitations.

Gas Bearings

The gas bearing design supports the turbine, alternator and compressor on a single shaft and is a critical element in the TAC. While prior BIPS TAC operating experience with gas bearings was successful, the experience was limited to continuous operation during life endurance testing. The BIPS experience was limited to only a few starts and stops.

During SD GTD system testing, starts and shutdowns were successfully demonstrated using non-contacting journal and thrust bearings. Operation with the Rice TAC included 24 tests with 561 hours of power generation, with many (58) ambient test verifications, and 24 system startups and 4 hot system restarts. Data from the Rice TAC operation indicated that performance was within expected ranges. Post inspection of the gas bearing components did not reveal any degradation with these bearings. Operation with the PM TAC included 9 tests with 223 hours of power generation, with many (42) ambient test verifications and 9 system startups and 15 hot system restarts. Data from the PM TAC operation showed all temperatures were within the expected ranges, which suggest normal operation. This experience provides confidence to future designers that many start/stop cycles can be combined with long life operation.

Hermetic Sealing

The solar receiver and the PCU are connected together with a complicated ducting arrangement which is subjected to thermal loads due to high temperatures (greater than 1050K) that must maintain system pressure (below 7.5 MPa). It is required that the system maintains structural integrity (no gas leaks) without the need for a complex gas makeup system. All of the interfaces adjoining the ducts to the receiver and PCU components were hermetically sealed with nickel-based weldments. The SD GTD system configuration (1994 - 1996) was able to maintain the original charge of He-Xe with no need for recharging due to joint and/or material degradation. Although operated under the severe conditions of ground testing (many ambient/hot/ambient cycles not representative of a flight unit) this experience has provided designers the confidence that a hermetically sealed gas system can be fabricated with adequate margin for a flight unit.

Vibration

Vibration remains an issue for all of the potential dynamic systems for space power. Although no direct measurements were made during these system tests, no vibration issues were identified during or after any of the testing. Each rotor assembly (shaft, turbine, alternator and compressor) is balanced as a unit (3.53×10^{-6} N-m) prior to installation in the TAC housing. Critical shaft and component run-out measurements are made during each buildup in order to assure assembly integrity and balance. Verification of the TAC balance after assembly can be made part of the manufacturing process, assuring properly balanced units prior to final assembly in the PCU.

System Mass

The design heritage used for the SD GTD project was based on the designs and hardware from the Space Station *Freedom* and the BIPS programs. This resulted in a state-of-the-art hardware and system configuration that was not optimized for either performance or weight. Component weights from the SD GTD system resulted in a specific power of about 3 W/kg, while the *Freedom* design was estimated at about 5 W/kg for human-rated SD system in LEO with thermal energy storage for the eclipse (Jefferies, 1993). Reduction in the SD system is desirable to assure competitiveness with other space power systems. Table 4 compares the characteristics of a SD system using Space Station *Freedom* designs with advanced technologies that may be available in the near term. The specific power of an advanced LEO SD system has the potential to improve to about 13 W/kg (Mason, 1999).

TABLE 4. System Characteristics for a 30 kW LEO Brayton SD Power Module

	Space Station *Freedom* State-of-Art	**Advanced Technology**	**ADV Tech Comments**
Power (avg) to bus (kW_e)	30	30	
Mass of Components (kg)			
- Concentrator	1520	365	2 kg/m^2
- Receiver w/Storage	1755	871	5 kg/kW
- Brayton Engine	792	316	
- Heat Rejection	1359	445	6 kg/m^2
- Structure	376	200	
- PMAD	288	151	
Engine Efficiency, %	28	34	
Concentrator, m^2	178	183	
Radiator, m^2	128	74	
Specific power, W/kg	5	13	

CONCLUSIONS

Operational and performance data have demonstrated successful operation with a proto-typical flight power system of sufficient scale and fidelity to ensure confidence in the potential of the SD technology base for future space power applications. The proto-typical system has been solar heated for over 800 hours in a relevant environment and has demonstrated orbital startups, both transient and steady state orbital operation and shutdowns. With 372 low-Earth orbits simulated, operation has included power generation from 400 watts to over 2 kW_e. Testing has included 33 orbital startups and 100 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, with no subsystem failures. Testing has resulted in an improved understanding of integrated system operations and performance of the SD system.

SD system efficiencies have been measured up to 17 per cent, during simulated low-Earth orbit operation. Data from the system testing provides confidence to future designers that the technology exists for the operation of solar dynamic system as a space power system. Specific power for the *Freedom* SD module, estimated at 5 W/kg, can be improved to 12 W/kg using advanced component technologies.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1999	Technical Memorandum

4. TITLE AND SUBTITLE

800 Hours of Operational Experience From a 2 kW_e Solar Dynamic System

5. FUNDING NUMBERS

WU–632–1A–1D–00

6. AUTHOR(S)

Richard K. Shaltens and Lee S. Mason

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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

8. PERFORMING ORGANIZATION REPORT NUMBER

E–11452

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—1999-208840

11. SUPPLEMENTARY NOTES

Prepared for the Space Technology and Applications International Forum cosponsored by the Boeing Company, Lockheed Martin, National Aeronautics and Space Administration, U.S. Air Force, and the U.S. Department of Energy, Albuquerque, New Mexico, January 31–February 4, 1999. Responsible person, Richard K. Shaltens, organization code 5490, (216) 433–6138.

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14. SUBJECT TERMS

Solar power; Solar dynamic; Brayton cycle; System testing

15. NUMBER OF PAGES 12

16. PRICE CODE A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	