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2 kWe Solar Dynamic Ground Test Demonstration Project

Volume I: Executive Summary

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Space Administration

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Foreword

To the scientists, engineers, technicians, and all the supporting staff who have worked nearly 30 years in the development of the technologies, components, and subsystems which led to the successful test of a solar dynamic electrical power system. We are indebted to your many years of dedication and hard work. Thank you.

Rev	By	Approved	Date	Revision Summary
NC	MAB	D. Alexander	October 26, 1995	Initial issue.
A	MAB	D. Alexander	December 14, 1995	Italicize *Freedom* in Space Station *Freedom*

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1. SUMMARY AND CONCLUSIONS

The Solar Dynamic Ground Test Demonstration (SDGTD) successfully demonstrated a solar-powered closed Brayton cycle system in a relevant space thermal environment. In addition to meeting technical requirements the project was completed 4 months ahead of schedule and under budget. The following conclusions can be supported:

- The component technology for solar dynamic closed Brayton cycle technology has clearly been demonstrated.
- The thermal, optical, control, and electrical integration aspects of systems integration have also been successfully demonstrated. Physical integration aspects were not attempted as these tend to be driven primarily by mission-specific requirements.
- System efficiency of greater than 15 percent (all losses fully accounted for) was demonstrated using equipment and designs which were not optimized. Some preexisting hardware was used to minimize cost and schedule.
- Power generation of 2 kWe.
- A NASA/industry team was developed that successfully worked together to accomplish project goals.

2. INTRODUCTION

Beginning in the early 1960s AlliedSignal Aerospace (then Garrett AiResearch), NASA Lewis Research Center, and the Department of Energy began development work on the components necessary for a closed Brayton cycle electrical generating system for space applications. Several projects were conducted during the 1960s and 1970s, such as the Brayton Rotating Unit (BRU), the Brayton Isotope Power System (BIPS), and the Mini-Brayton Recuperator. These projects produced the technology for the turbomachinery and heat recovery heat exchanger required in a closed Brayton cycle. The solar concentrator technology was advanced as part of the Space Station *Freedom* Program through the Solar Concentrator Advanced Development Project conducted by Harris Corp. and NASA LeRC. Radiator technology was developed by Loral Vought Inc. as part for the Space Station *Freedom* Program. A heat receiver with integral thermal energy storage design concepts was also developed by AlliedSignal Aerospace as part of the Space Station *Freedom* Program. Integration concepts were developed by Rocketdyne as part of the Space Station *Freedom* Program.

The projects which preceded this effort were conducted as component or subsystem efforts and required substantial support equipment. The scope of this effort was to combine all the required technologies of a solar dynamic power system into an integrated test unit and to conduct a system test in a relevant space environment except for microgravity. Fortunately, the Brayton cycle is an all-gas-phase cycle and is not effected by the presence or absence of gravity.

The specific purpose or objectives of this effort were to

- Investigate the optical, thermal, control and electrical integration aspects of solar dynamic power systems.

- Demonstrate a generation efficiency greater than 15 percent, fully accounting for all parasitic power losses. This efficiency would be demonstrated even though 1) many components were 20 years old and 2) new component designs compromised performance in order to demonstrate manufacturing technologies for larger sizes.
- Demonstrate design and manufacturing technologies necessary to produce optical facets and thermal energy storage canisters consistent with 25 kWe sized systems.
- Demonstrate that NASA and industry can successfully conduct projects cheaper, better , and faster.

The material presented in this report will show that the technology necessary to design and fabricate solar dynamic electrical power systems for space has been successfully developed and demonstrated. The data will further show that achieved results compare well with pretest predictions. The next step in the development of solar dynamic space power will be a flight test.

3. OBJECTIVES AND ACCOMPLISHMENTS

The objectives of the project and the accomplishments relative to those objectives are as follows:

Objective	Accomplishment
1. Demonstrate solar dynamic closed Brayton cycle power system in relevant thermal environment	Completed. 48 hours of system test in thermal environment accomplished. Technical objectives achieved.
2. Demonstrate 15 percent orbital system efficiency = user power divided by sunlight intercepted	14 to 17.4 percent end-to-end orbital efficiency achieved.
3. Demonstrate 2.0 kWe	System generated 2.08 kWe.
4. Evaluate component codes	Component codes for receiver, concentrator, radiator and power conversion provided realistic predictions compared to test data.
5. Demonstrate orbital thermal control concept	Thermal control concept demonstrated which requires only voltage and current measurement. No direct measurement of stored thermal energy required.
6. Demonstrate "cheaper, better, faster" project capability	Project completed 4 months early, under budget and meeting technical requirements.
7. Complete development and manufacturing process of facets and thermal energy storage canisters	Facet and thermal energy storage canister manufacturing processes were successfully demonstrated for sizes appropriate for designs up to 25 kWe.
8. Develop NASA/industry team for dynamic power system	Working relationships developed between contracting team members and NASA.

4. PROJECT TEAM

A team of industry contractors and NASA LeRC was formed to accomplish the SDGTD technical and project objectives. The team members and their respective roles were as follows:

Team Member	Project Technical Role
NASA Lewis Research Center	Solar simulator and Tank 6 preparation
AlliedSignal Aerospace	System integration, power conversion subsystem, receiver, recuperator, cooler, engine controls, liquid loop components and data acquisition
Rockwell International Corp., Rocketdyne Div.	Test integration
Harris Corp., Government Aerospace Systems Div.	Concentrator
Solar Kinetics Inc.	Concentrator facets
Loral Vought Systems Corp.	Radiator panels
Aerospace Design & Development, Inc.	Multilayer insulation

The typical hierarchical organization of contracting agency, prime contractor, and subcontractor was not used to conduct this project. The limitations of this vertical type of responsibility pyramid are well known and do not need further condemning here. A team of equal contributors was formed to conduct the SDGTD. At the project kickoff this team adopted the following rules of conduct to promote speed and cost containment:

- A prime contract and supporting subcontracts which provided a common incentive fee structure. The intent was that failure by one would be failure by all. This made it much easier to find quick and efficient solutions for technical issues since everyone had a stake in everyone else's problems.
- Team building exercises early in the project to assist in the formulation of a working team. Specialists in team building concepts were brought in and helped in breaking down many barriers and establishing understanding.
- No restrictions on communications. A list of project contributors with phone numbers was generated and distributed. Individuals were encouraged to communicate with others outside their organization. Agreements and commitments were documented and distributed. Management worked on the back end of the process, not the front end. Everyone knew their roles, responsibilities, and scope of the work undertaken.
- All attendees considered equals during technical meetings. Each member, whether NASA or second-level subcontractor, was requested to speak up and question any position which they did not understand or agree with. Design reviews were very lively, entertaining and productive. The only dumb questions were those which were not asked!
- No attempts to find the best or optimum solution. "Best" and "optimum" are subjective terms. The requirement was to find a solution which adequately met the requirements and move forward.

- "If we don't use it, we don't need it." This motto applied to technical paperwork as well. This test eliminated a lot of "stuff" which is generated on a typical project and goes immediately into file cabinets, never to see the light of day again.
- Trust in each others' abilities to do their jobs. Each organization, including NASA, took care of its own tasks and didn't worry about what others were doing.
- No stigma was placed on any individual for making an error. Emphasis was placed on making decisions, conducting reviews, correcting approach and moving forward.

5. DESIGN SUMMARY

5.1 System Integration

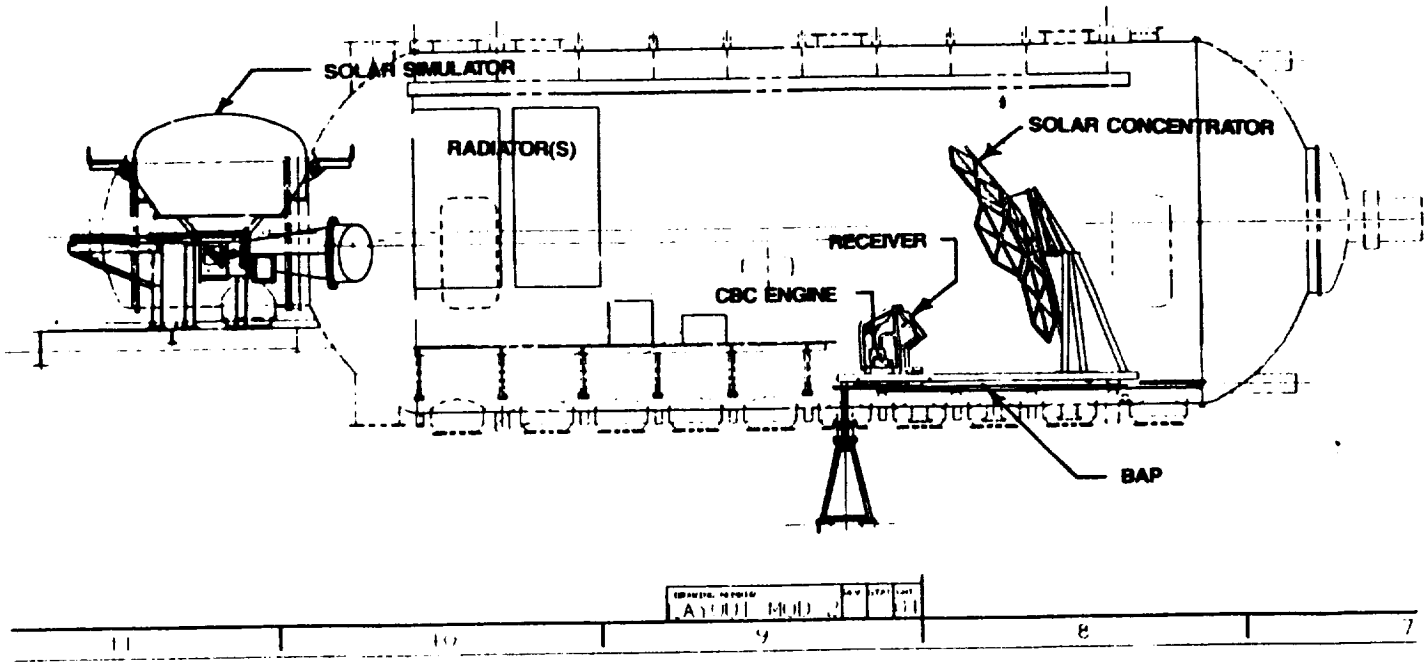
The selected configuration of the SDGTD system installed in Tank 6 at NASA LeRC is shown in Figure 1. Key features of the overall system design approach are as follows:

- Except for equipment necessary to simulate the space environment and the data acquisition system, the SDGTD is self-sufficient and requires no laboratory support.
- The components are integrated optically, thermally and electrically.
- The light source provides up to 1.3 solar intensities with ray divergence of only 1 degree, whereas other existing solar light source designs have 4 or more degrees of optical divergence.

5.2 Solar Simulator

One of the most difficult parts of the SDGTD project was not in development of the test unit but in design and fabrication of the light source which simulates the sun. This task was accomplished successfully by NASA. The objective was to provide sunlight with high intensity (>1.6 kW/m2), uniform intensity (< ±10 percent), and minimum optical ray divergence (< 1 degree). The traditional designs of solar simulators use a light source and a collimating mirror to produce parallel light rays.

Figure 1. SDGTD System in Tank 6



These designs are expensive and did not meet the divergence requirement. NASA developed a system which used significantly fewer lamps and eliminated the collimating mirror. This system fully met technical, cost and schedule needs and required only a minor change in concentrator optical curvature. The features of this light system, shown in Figure 2, are as follows:

- Nine 30 kW Xenon arc lamps each individually controlled
- Turning mirror, water cooled, to direct light into the tank and onto the concentrator
- Water-cooled quartz window to allow light to pass into the tank
- Shutter to interrupt light during eclipse periods so that lamps will not have to be cycled on and off
- Each lamp fully illuminates the entire concentrator surface to minimize intensity variations.

5.3 Solar Concentrator

The solar concentrator consists of three elements:

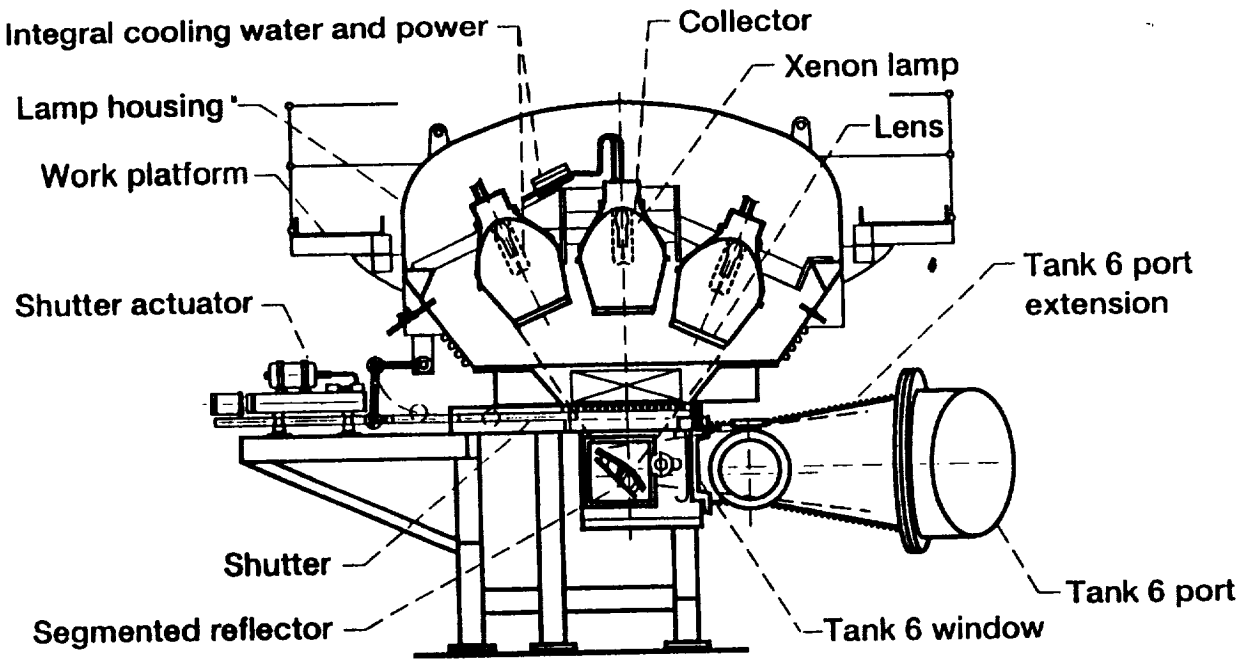
- Seven hex shaped graphite structures to support mirrors (facets)
- Forty-two reflective facets
- Support structure

The completed concentrator installed in Tank 6 is shown in Figure 3. The concentrator structure was designed and fabricated by Harris Corp. The hex assemblies which support the optical facets are made of graphite box beams which have low thermal expansion and are therefore thermally stable. The box beams used in the SDGTD were originally used in a much larger concentrator. These beams were cut to desired length and installed into new corner fittings. The hex beams are much larger than would be required for a concentrator of this reflective area but they were free. The latches and strikers were also "borrowed" from the larger concentrator project and are significantly oversized for SDGTD. The result of using these devices is much larger gaps between hex assemblies than would otherwise be required.

The concentrator facets were designed and fabricated by Solar Kinetics, Inc. The facets are made of aluminum honeycomb with aluminum face sheets bonded to the front and rear. The bonding process is done over a curved surface to provide the appropriate radius of curvature. After the honeycomb structure is bonded the optical subsurface is leveled with an epoxy. The reflective surface used was aluminum and it was applied by vapor deposition. Aluminum oxide is then added to the optical surface for oxidation protection. The construction of the facet is shown in Figure 4. The SDGTD used relatively large facets to demonstrate the manufacturing technology required for larger systems. This resulted in fewer facets and slightly limited concentrator performance. Optical performance could also be improved by using silver reflective surfaces rather than aluminum. This would increase reflectivity from 86-87 percent to 94-95 percent.

The support structure for the seven linked hex panels is a tripod which attaches to the center hex panel and rests on the tank floor. This support structure is unique to the Tank 6 installation (see Figure 3).

Figure 2. Advanced Solar Simulator



Solar simulator characteristics	
Beam size	188.5-in. diam at 56-1/2 ft from apparent sun
Collimation	None - point source
Irradiance	1.8 kW/m^2 (1.27 sun) max
Uniformity	±10%
Subtense angle	About 1 deg

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Figure 3. Concentrator, Receiver, and Power Conversion System in Tank

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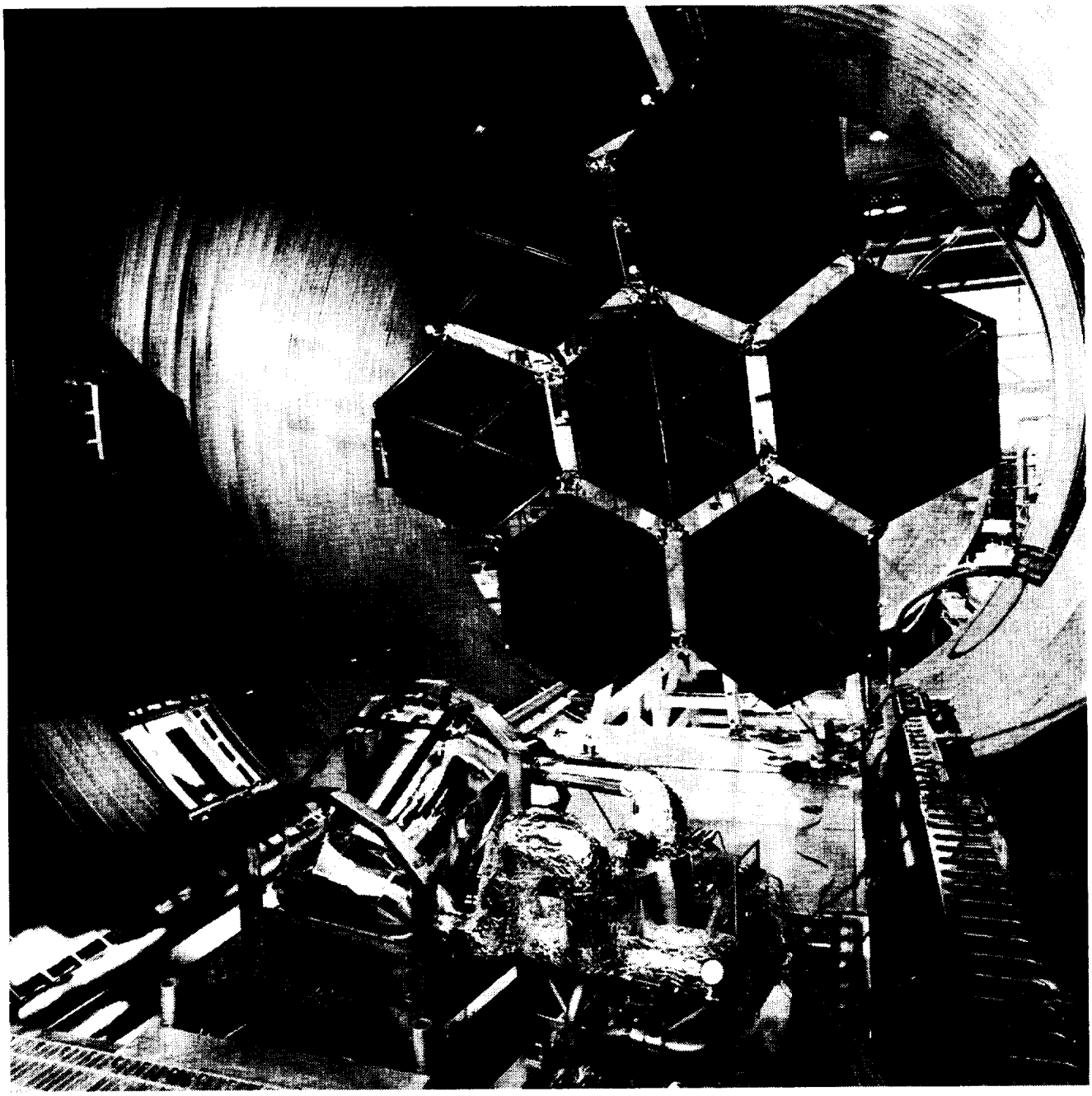

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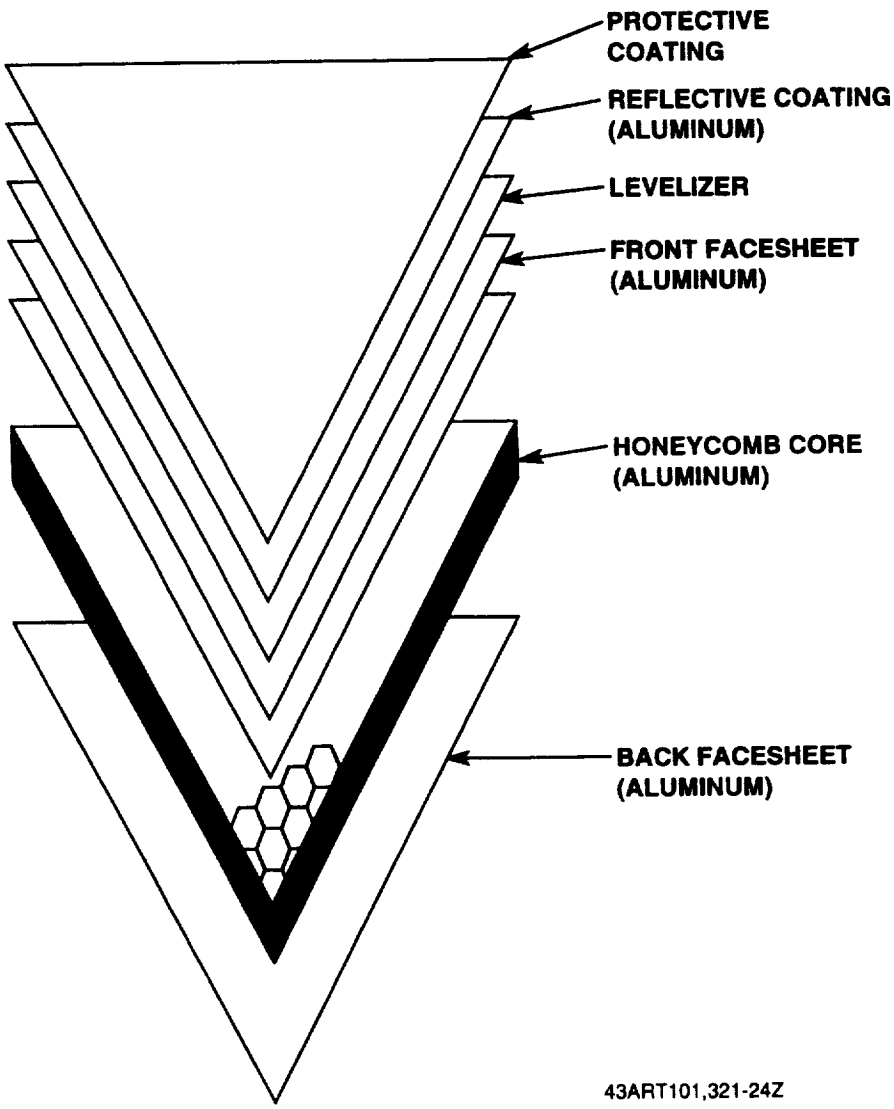
Figure 4. Facet Design



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5.4 Solar Receiver

The solar receiver, like the concentrator design, is a continuation of the design started for the Space Station *Freedom* Work Package 4, solar dynamic power unit. The design, development, and fabrication of the solar receiver and thermal energy storage canisters was accomplished by AlliedSignal Aerospace. A cross section of this receiver is shown in Figure 5. The unit consists of 23 tubes arranged in a cylindrical configuration. Each tube has 24 doughnut-shaped canisters brazed to the outer diameter of the tubes. These canisters are filled with a lithium fluoride-calcium difluoride eutectic salt. A cross section of a tube assembly is shown in Figure 6. The 23 tubes are connected to circular manifolds on both ends to provide inlet and outlet connection. The diameter of the tubes and the design of the canisters was taken directly from the previous Space Station design. The Space Station design was of significantly larger power class, and the gas flow rate through the tubes was much larger than the SDGTD. To maintain flow velocity and heat transfer characteristics, a center body and fins were added to the interior of the tubes. The outside of the receiver was covered with layers of nickel and aluminum MLI to reduce heat loss via radiation. The MLI was designed, fabricated, and installed by Aerospace Design & Development Inc. A segmented graphite aperture plate was incorporated to

- allow solar "walk on," which would occur in an actual flight system where acquisition of the sun would require the hot spot to be moved into the aperture (not required in Tank 6 because the "sun" and concentrator locations were fixed
- absorb the "spillage" of light from the concentrator which is not directed through the aperture (approximately 4-5 percent of reflected sunlight).

The receiver was then suspended from a structure attached to the tank floor.

The light energy is projected through the aperture by the concentrator during the sunlight portion of the orbit. This energy falls directly on the canister surfaces and is absorbed. The temperature of the canisters is raised and the salt heated and melted. Gas from the power conversion system flows through the tubes and absorbs heat from the inner surface of the canisters. During the eclipse portion of the orbit, heat stored in the canisters, both sensible and latent, continues to provide energy to the gas until the eclipse portion of the orbit ends. In rough terms, the eclipse period is one-third of the orbit. Therefore approximately two-thirds of the incoming light energy is transferred through the canisters to the gas during the sunlit portion of the orbit and the remaining one-third is stored in the canisters for the eclipse period.

5.5 Power Conversion System

The power conversion system for the SDGTD is a closed Brayton cycle. The unit selected for this task was designed and fabricated by AlliedSignal in the mid-1970s for NASA/DOE as part of the Brayton Isotope Power System (BIPS). This unit had been run at AlliedSignal and placed in long-term storage at NASA's Plumbrook facility. This equipment was disassembled, cleaned and inspected. The turboalternator compressor (TAC), recuperator, interconnecting structure, and various ducts were selected for use in the SDGTD project.

Figure 5. Receiver Section View

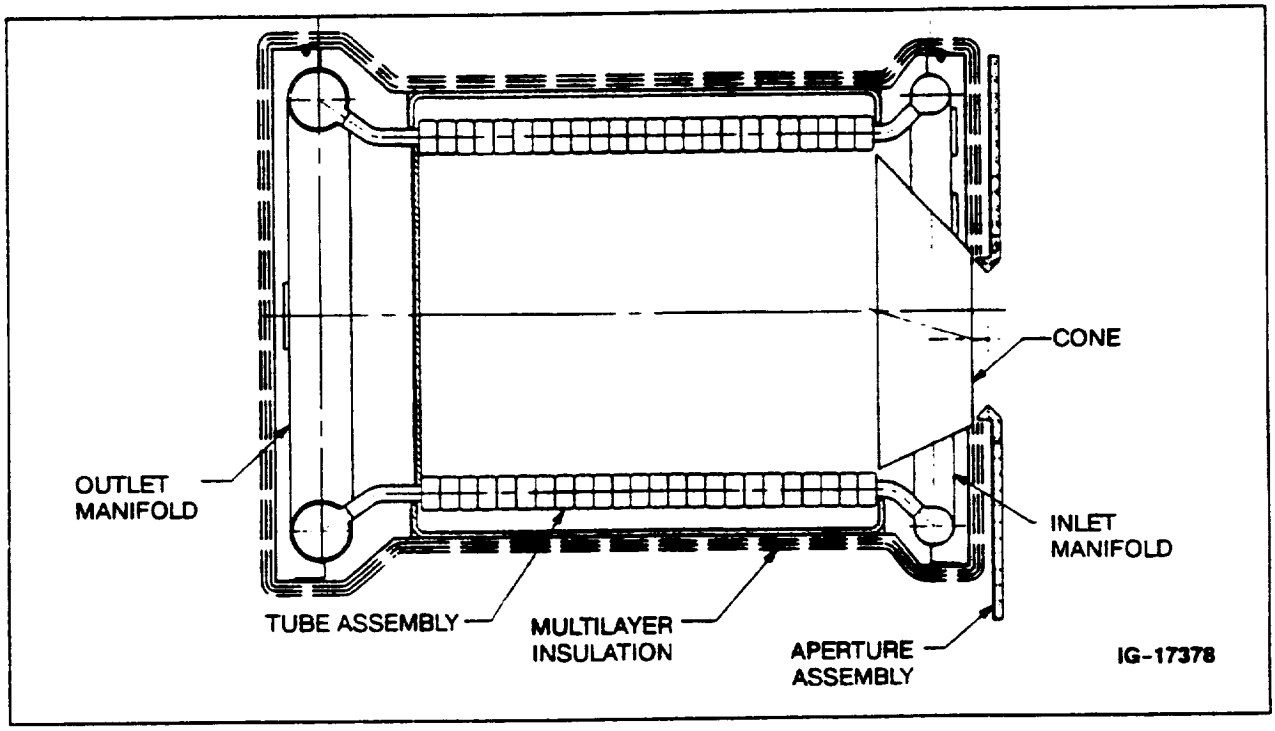
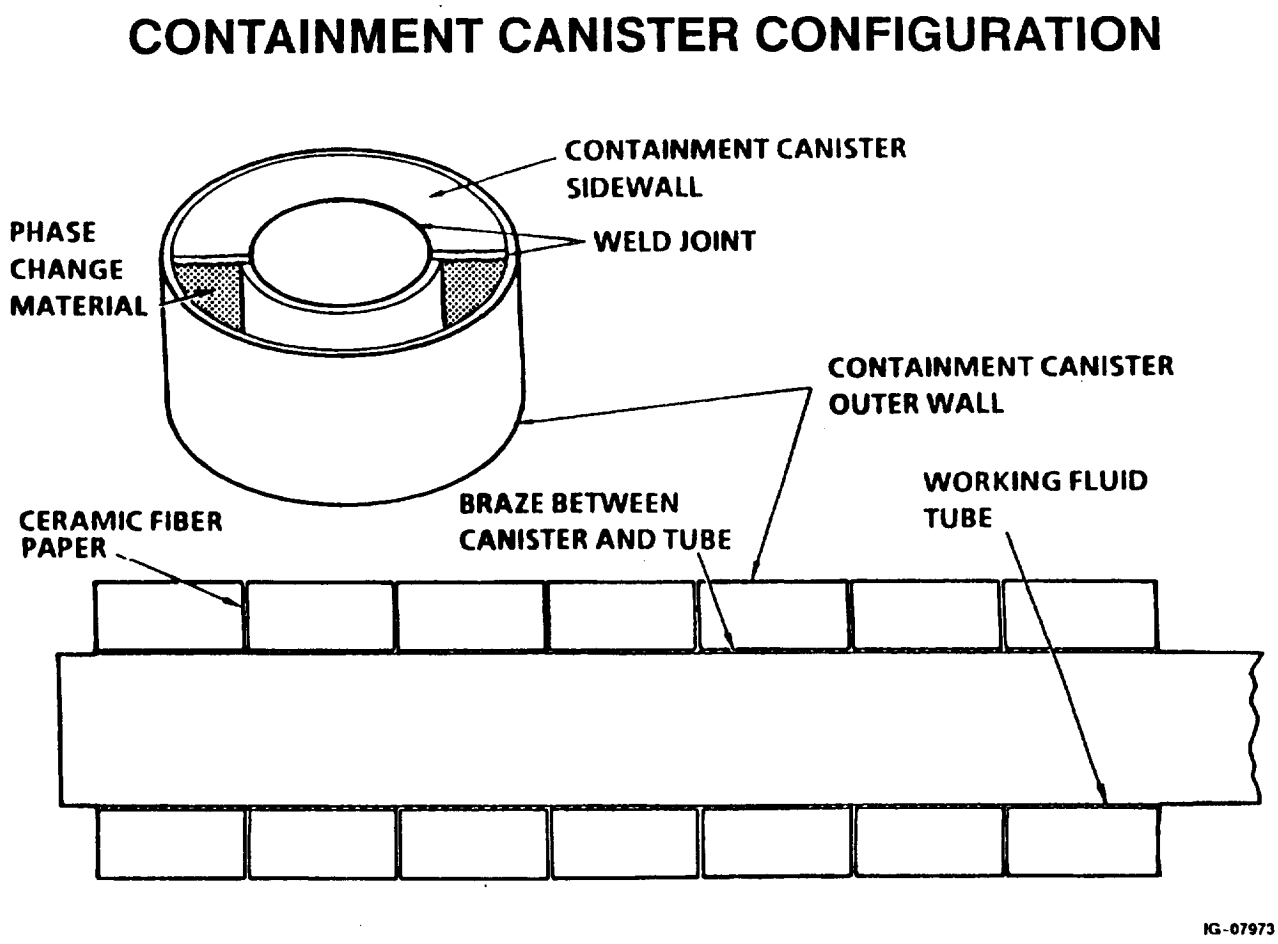


Figure 6. Containment Canister Configuration



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The TAC contains the cycle compressor, turbine and modified Lundell (Rice) alternator all mounted on a common shaft. The alternator is mounted inside the gas system, and no mechanical drives with attendant seals are required. A hermetic system is therefore achieved. A cross section of the TAC is shown as Figure 7. The rotor is supported on gas foil bearings which require no lubrication other than cycle gas. Foil bearing technology has advanced since this unit was originally designed and newer bearings were incorporated into the unit. Additionally, instrumentation was added to monitor motion of the rotating shaft in both radial and axial directions.

A heat exchanger called a recuperator is used to recover waste heat from the turbine exhaust and transfer it to the discharge of the compressor before the cycle gas enters the receiver. This heat exchanger significantly improves cycle efficiency. The recuperator was also designed, fabricated and tested as part of the BIPS project. The recuperator is a counterflow plate fin design and the arrangement is shown in Figure 8. This particular heat exchanger was designed for a power system which used isotope as the heat source. Since isotope is very expensive and in very limited supply, system optimization results in very high component efficiencies. The recuperator has a tested thermal effectiveness in the 0.97 range, making it one of the most effective heat exchangers ever built. In addition to its high thermal effectiveness the mechanical design is very tolerant of thermal shock.

The cycle selected used a liquid loop radiator which would probably be selected for flight systems greater than 6 kWe. A heat exchanger is required to transfer waste heat from the gas to a liquid for transport to the radiator. This heat exchanger is referred to as a cooler. A cooler was not available from the BIPS project as it did not incorporate a radiator. A cooler designed for Phillips Lab for a cryocooler application which used helium-xenon and Freon was adequate for the SDGTD. Two of these cryocoolers were placed in series to provide the necessary heat transfer. This cooler was also of plate fin construction and is shown in Figure 9.

5.6 Waste Heat Radiator

The waste heat radiator design was also borrowed from Space Station *Freedom* concepts. It was designed and fabricated by Loral Vought. The radiator panel is a honeycomb structure with aluminum face sheets and special optical paint. Special tubes which conduct the liquid loop fluid (n-heptane) were embedded in the honeycomb and are bonded to the face sheets. These tubes are welded to manifolds on both ends of the panels. The design of the panel is shown in Figure 10. Radiator panel dimensions were selected to maximize use of production tooling being used to fabricate current Space Station radiators. This saved significant tooling resources and allowed quick fabrication. Two panels connected in series provided the required heat transfer area.

Figure 7. Turboalternator Compressor

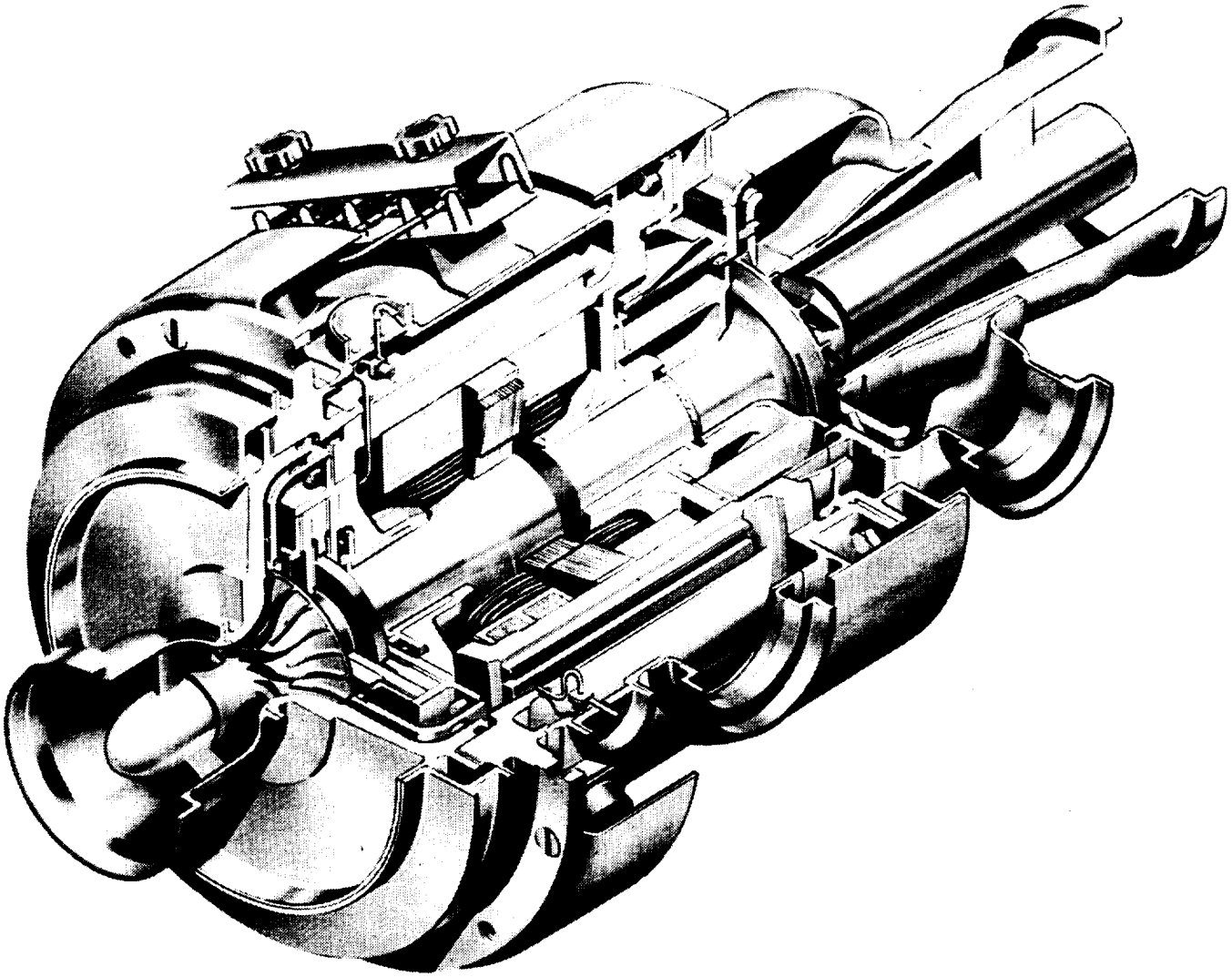
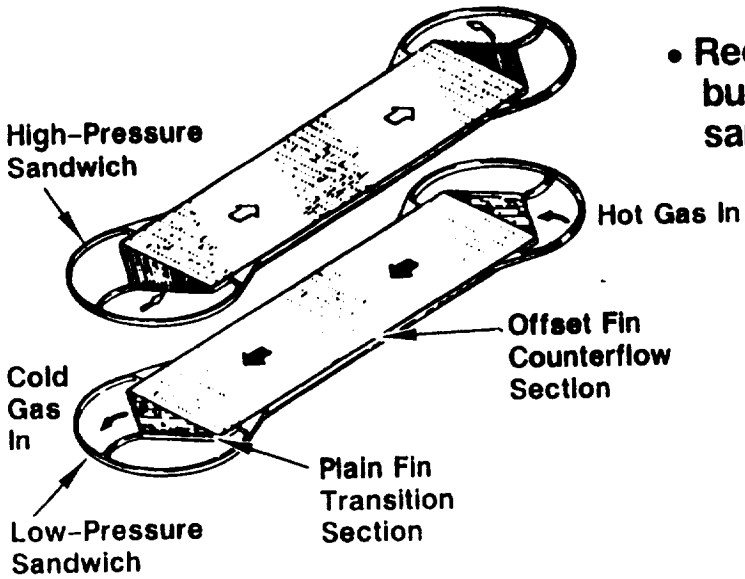


Figure 8. Recuperator



- Recuperator cores are built from plate-fin sandwiches

- Stacked to form the heat exchanger core with integral manifolds

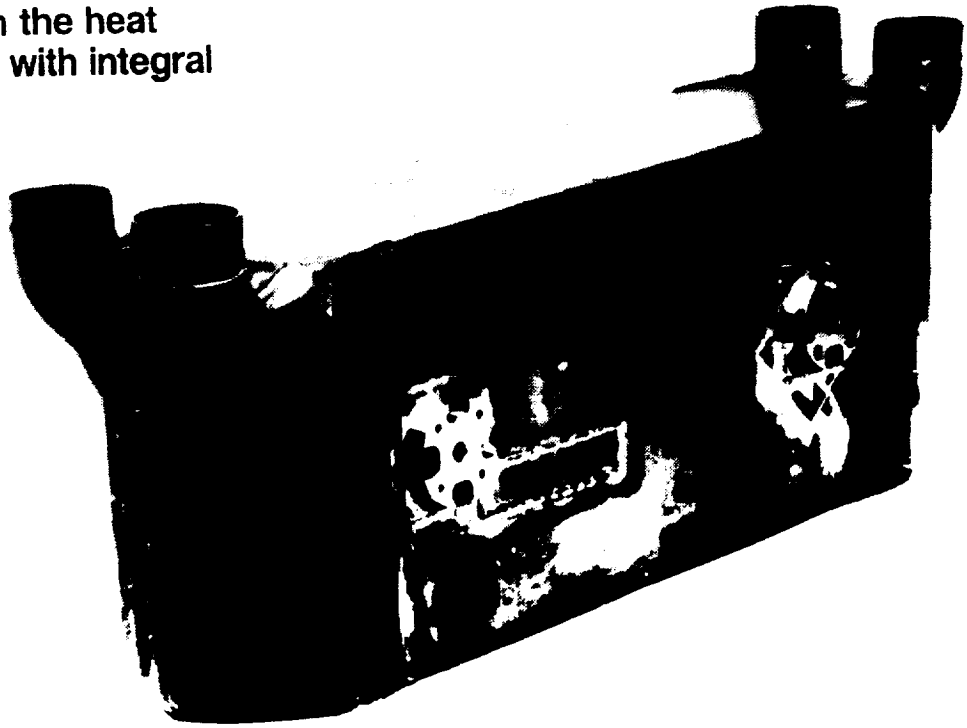


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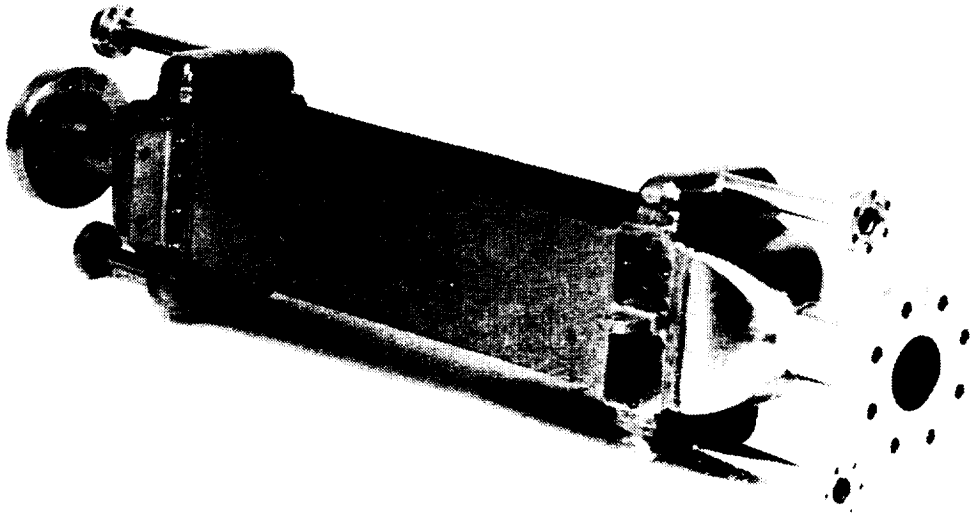
Figure 9. Cooler Configuration



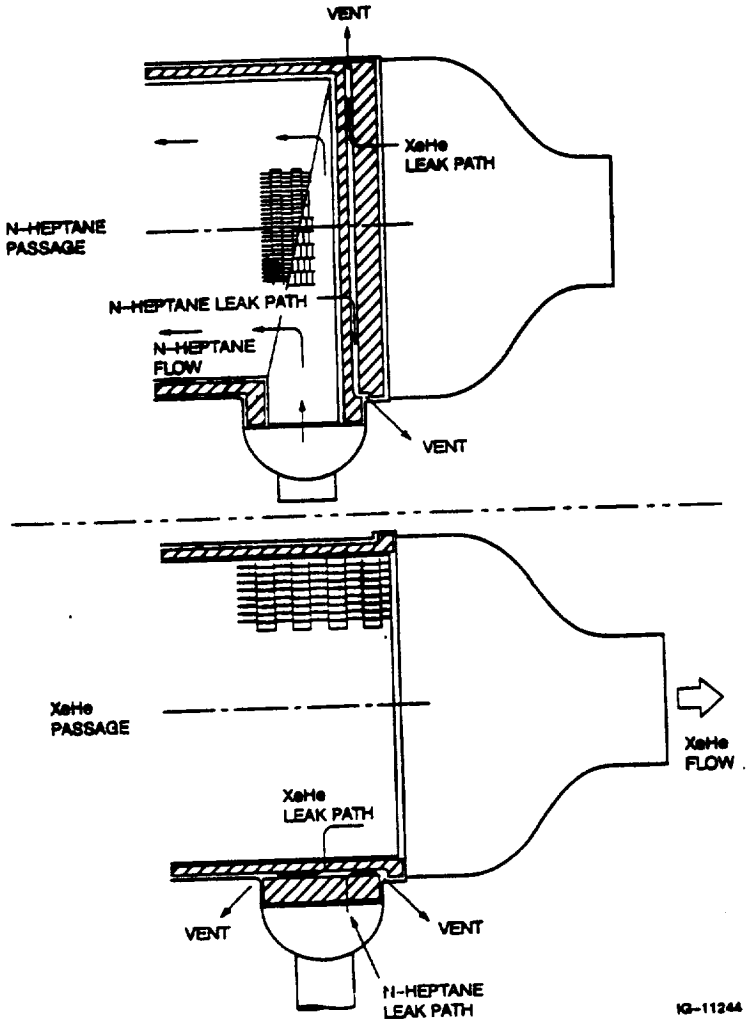
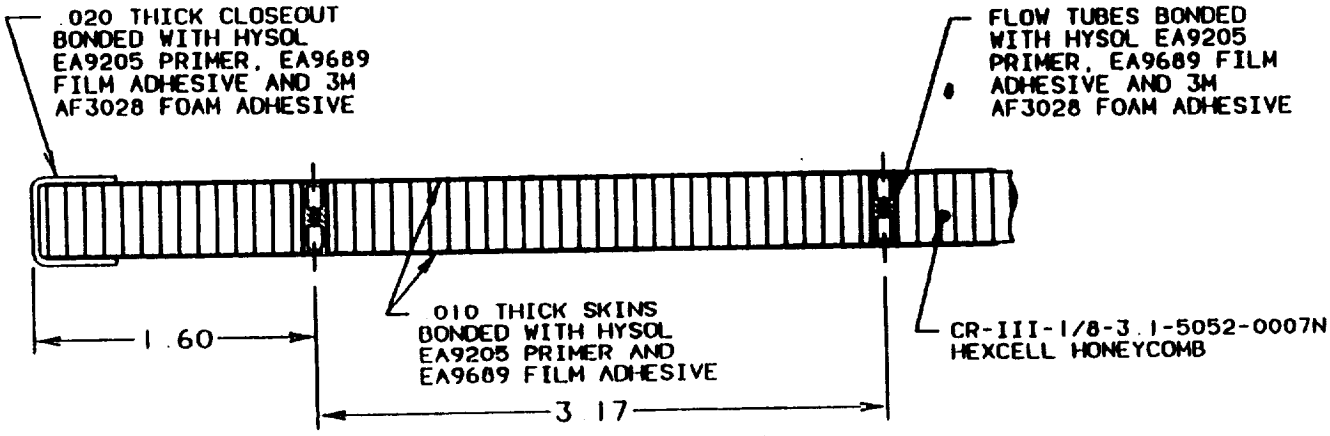


Figure 10. Radiator Cross Section



5.7 Engine Control

The Power Conversion and Control Unit (PCCU) was designed and fabricated to perform the following electrical functions:

- Maintain output electrical voltage at 120 Vdc
- Maintain engine speed at the commanded value
- Operate the alternator as a brushless dc motor during starting
- Maintain constant electrical load on the alternator
- Provide fault monitoring and fault protection.

Three control loops were used to provide engine control. A voltage control circuit using proportional, integral algorithms monitors the output voltage. Field current to the Rice alternator is adjusted to maintain output voltage. Since a Rice alternator has no intrinsic magnetic field one must be created. The intensity of the field is proportional to the current applied to the field windings. This allows for constant electrical output voltage over a wide range of operating speeds. A second circuit monitors the rectifier output current and adds or subtracts resistive load at the Parasitic Load Radiator to maintain the commanded level. If the user adds load to the output, the PCCU immediately reduces the load at the PLR by an equivalent amount. A third loop monitors engine speed. If the speed is higher than the commanded value, the electrical load level is increased. Conversely, if the engine speed is lower than the commanded level, the electrical load is reduced. The frequency used for the PLR load control was 1 kHz. The frequency used for the voltage regulator and speed control loops was 20 Hz. Excellent power quality was demonstrated during the test even during very large (50 percent) load changes. A commercial full-wave rectifier was used to convert alternator 3 phase ac to dc.

6. TEST SUMMARY

The following component and subsystem tests were performed prior to delivering the equipment to NASA LeRC:

Concentrator
- Structural tests on hex panel assemblies
- Optical tests on facets
- Environmental tests on facets and facet coupons
- Function tests on alignment and flux testing fixtures and procedures.

Radiator/Liquid Loop Components
- Leak test of radiator panels
- Ambient air test of radiator panels using hot working fluid to verify pressure drop and panel thermal uniformity. Liquid loop components planned for the system test were used to condition the working fluid.

Receiver
- Thermal performance test of single-tube assembly
- Leakage and flow test of the completed unit.

Solar Simulator
- Performance test on single lamp to verify optics design
- Optical performance mapping of optical interface plane.

Multilayer Insulation (MLI)
- Thermal performance test on candidate MLI specimens.

Power Conversion System, Engine Control, and Data Acquisition Subsystems
- Motoring test of TAC to verify bearing and electrical integrity
- Leak test of recuperator
- Leakage and flow test of gas coolers
- Functional test of Engine Control using air turbine driven alternator test rig (ATR)
- Operating test of Power Conversion Subsystem using laboratory heaters and heat removal. Deliverable engine control and data acquisition subsystems used to conduct test.

Following the component and subsystem tests, hardware was delivered to NASA and the following test sequence conducted:

1. The radiator panels and the liquid loop components were installed in the tank. A series of tests was conducted to characterize the performance of the radiator panels in the Tank 6 thermal environment.
2. The concentrator was installed, aligned to the solar simulator and a flux test was conducted using a special target fixture to characterize the intensity distribution of the light at the receiver canister interface. The data acquisition system was used to collect the data from this test.
3. The receiver, power conversion system, and engine control were installed in the tank. A complete checkout of all instrumentation and control functions was conducted without heating the receiver. After all functions were verified, the solar simulator was turned on and system testing began. The highlights of this testing were as follows:

- System testing begun 12-12-94
- Self sustaining operation achieved 12-13-94
- 1.4 kWe orbital operation achieved 2-1-95
- 2.08 kWe maximum electrical power achieved 2-17-95
- 1.96 kWe orbital operation achieved 2-17-95
- NASA turnkey operation 3-6-95.

The engine was operated for 48 hours by the contracting team prior to being turned over to NASA. A maximum of 2080 watts of ac power was produced during the test operation. An efficiency in the range of 14 to 17 percent was demonstrated during the test. This efficiency is available user dc energy divided by solar energy projected at concentrator averaged for an entire orbit, including the eclipse portion. The

range in efficiency is due to the uncertainty in various test measurements. A graph of the major system parameters for the 2-17-95 test appears as Figure 11. A cycle schematic with test data for the maximum power point on the 2-17-95 test is shown in Figure 12. NASA LeRC continues to operate the SDGTD in support of the joint US-Russian Solar Dynamic Flight Test Project, which will place a comparable system on the Russian Mir in 1997.

Figure 11. Power and Temp vs. Time

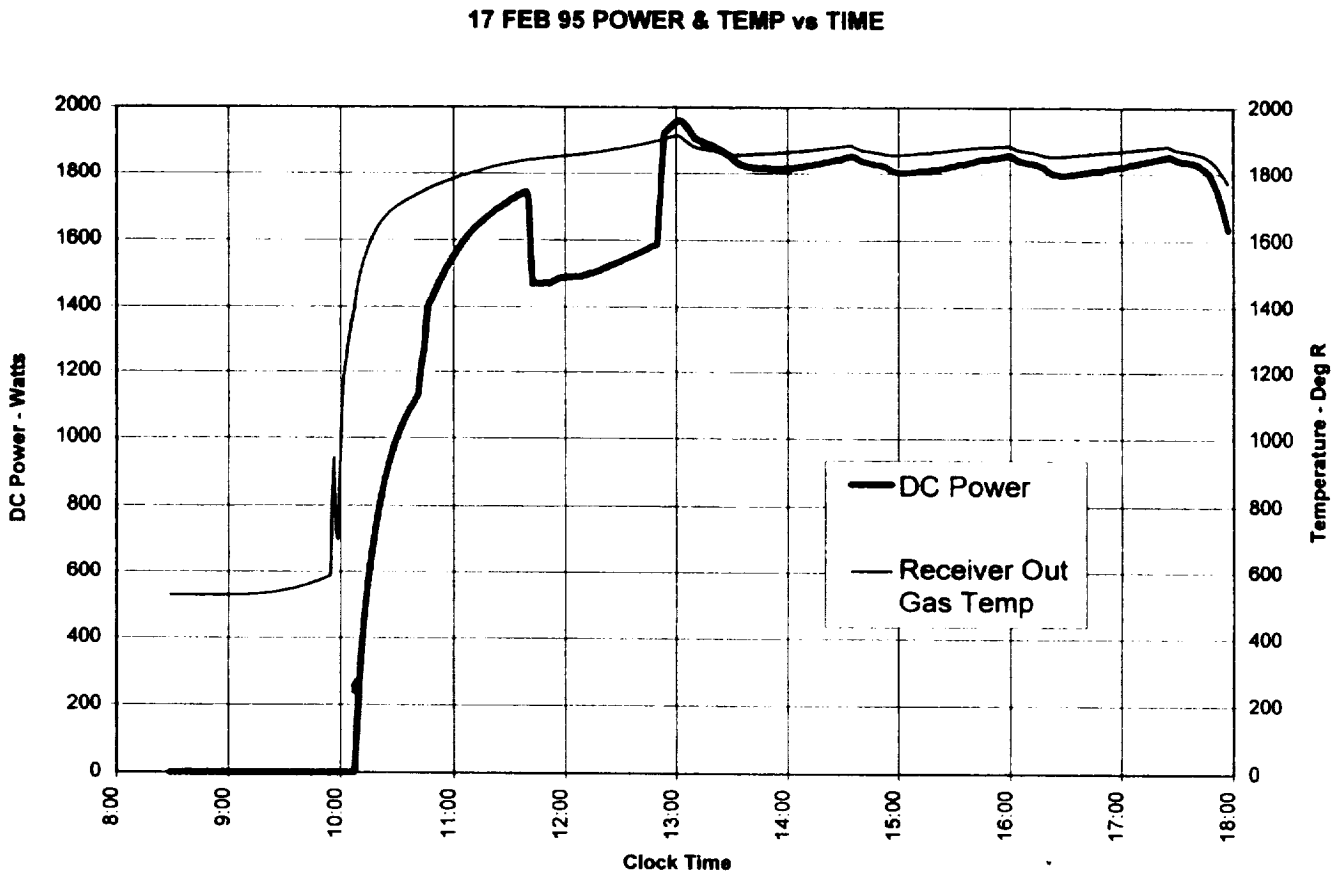
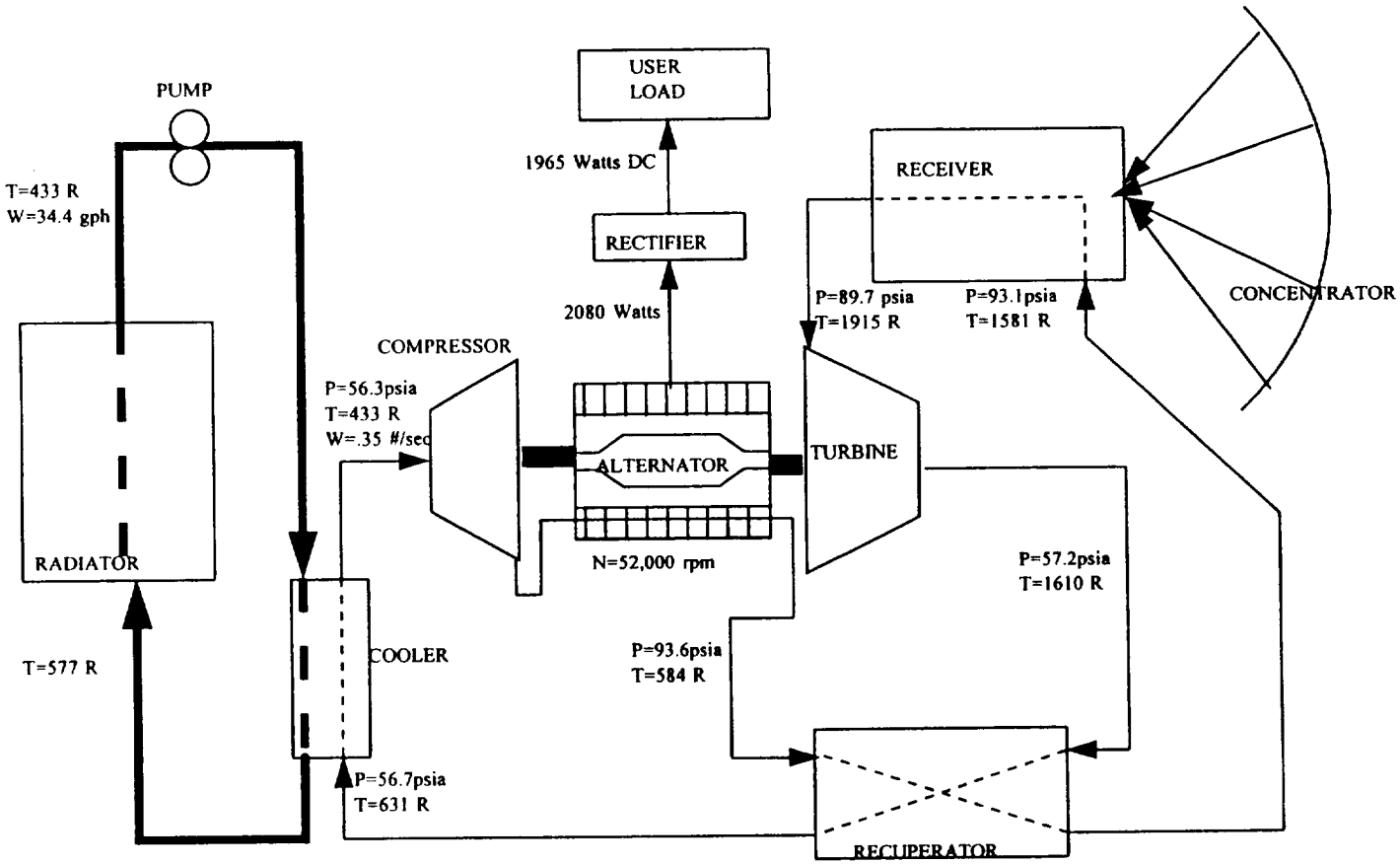


Figure 12. SDGTD Test Data, Maximum Power Point, 2-17-95



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13. ABSTRACT ***(Maximum 200 words)***

The Solar Dynamic Ground Test Demonstration (SDGTD) successfully demonstrated a solar-powered closed Brayton cycle system in a relevant space thermal environment. In addition to meeting technical requirements the project was completed 4 months ahead of schedule and under budget. The following conclusions can be supported:

1. The component technology for solar dynamic closed Brayton cycle technology has clearly been demonstrated.
2. The thermal, optical, control, and electrical integration aspects of systems integration have also been successfully demonstrated. Physical integration aspects were not attempted as these tend to be driven primarily by mission-specific requirements.
3. System efficiency of greater than 15 percent (all losses fully accounted for) was demonstrated using equipment and designs which were not optimized. Some preexisting hardware was used to minimize cost and schedule.
4. Power generation of 2 kWe.
5. A NASA/industry team was developed that successfully worked together to accomplish project goals.

The material presented in this report will show that the technology necessary to design and fabricate solar dynamic electrical power systems for space has been successfully developed and demonstrated. The data will further show that achieved results compare well with pretest predictions. The next step in the development of solar dynamic space power will be a flight test.

14. SUBJECT TERMS

Space power; Solar dynamic; Brayton cycle; System testing

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