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Progress Update of NASA's Free-Piston Stirling Space Power Converter Technology Project

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PROGRESS UPDATE OF NASA'S FREE-PISTON STIRLING SPACE POWER CONVERTER TECHNOLOGY PROJECT

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ABSTRACT

A progress update is presented of the NASA Lewis Research Center Free-Piston Stirling Space Power Converter Technology Project. This work is being conducted under NASA's Civil Space Technology Initiative (CSTI). The goal of the CSTI High Capacity Power Element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space initiatives. Efforts are focused upon increasing system power output and system thermal and electric energy conversion efficiency at least five fold over current SP-100 technology, and on achieving systems that are compatible with space nuclear reactors.

This paper will discuss progress toward 1050 K Stirling Space Power Converters. Fabrication is nearly completed for the 1050 K Component Test Power Converter (CTPC); results of motoring tests of the cold end (525 K), are presented. The success of these and future designs is dependent upon supporting research and technology efforts including heat pipes, bearings, superalloy joining technologies, high efficiency alternators, life and reliability testing and predictive methodologies. This paper will compare progress in significant areas of component development from the start of the program with the Space Power Development Engine (SPDE) to the present work on CTPC.

The 1050 K Stirling space power converter development is being conducted under contract to Mechanical Technology Incorporated (MTI) in Latham, New York.

INTRODUCTION

The NASA Stirling Space Power Converter (SSPC) Project originated in 1983 as part of the SP-100 Program - a joint NASA, DOD, and DOE effort to develop the technology necessary to provide space nuclear power systems for military and civil applications. The SP-100 Program is directed toward the development and validation of technology for a versatile space nuclear reactor power system having the capability to generate from tens to hundreds of kilowatts of electrical power for at least seven years at full power. A 2.5 MWt reactor with thermoelectric power conversion is the baseline space nuclear power system, scheduled for development by the year 2001. The Stirling Space Power Converter Project is a part of NASA's Civil Space Technology Initiative (CSTI) High Capacity Power Program, a program to complement and enhance SP-100, which is aimed at identifying and developing technology options for achieving significantly higher performance and system growth potential, significantly reduced specific mass, and longer lifetimes at acceptable reliability for civil applications.

The specific elements of the CSTI High Capacity Power Project include Conversion Systems (Stirling and Thermoelectric), Thermal Management, Power Management, System Diagnostics, and Environmental Interactions. Technology advancement in all of these areas, including materials, is required to assure the gains in power and performance illustrated in Figure 1.

NASA mission needs to date have been met with Photovoltaic/Energy Storage Systems; or with Radioisotope Thermoelectric Generators (RTG), where Photovoltaic (PV) systems would be too heavy or too bulky, or would not function because of distance from the Sun. The largest power requirement foreseen by the year 2000 is 75-100 kWe for Space Station Freedom. The Space Exploration Initiative, proposing to return to the Moon to stay and then to journey to Mars in the 21st century requires further increases in power; this necessitates the development of advanced power systems such as the 1050 K Stirling and the 1300 K Stirling highlighted in Figure 1.

The development of advanced Stirling power conversion is based upon the high efficiency of dynamic power systems (Stirling has the highest potential) and the long-life potential of the free-piston, linear alternator concept first invented in the U.S. in 1963.

Possible applications for Stirling space power in the multi-hundred kilowatt range include lunar and Martian bases, electric propulsion power for science and unmanned cargo missions to the outer planets, power for air and ocean traffic radar control systems, higher power communication platforms and earth observing platforms, and in-space materials processing facilities. Reference 1 provides a description of potential future civil space missions that could be enabled or substantially enhanced by the use of nuclear reactor power.

The requirements and goals foreseen in the 21st century set the framework for the technology programs of the 1990s. The NASA Stirling Space Power Converter Project, diagrammed in Figure 2, is a series of significant steps in technology capability, bringing the free-piston/linear alternator Stirling from its auspicious debut as a technology demonstration in 1985 to its 1050 K space capability in 1994.

Table I tabulates the performance objectives of each of the evolutionary steps in this quest for a long lived 1050 K superalloy Stirling space power converter.

SPRE POWER CONVERTER

In 1984, NASA awarded Mechanical Technology Incorporated (MTI) a contract to demonstrate the Free-Piston Stirling Engine (FPSE) for space applications. In October of 1986, the 650 K Space Power Demonstrator Engine (SPDE) developed 25 kW of engine PV power. Results of this engine testing are discussed in references 2 and 4.

The SPDE was a dual opposed configuration consisting of two 12.5 kWe converters. After this successful demonstration, the engine was cut in half creating two 12.5 kWe converters now called Space Power Research Engines (SPRE). One half has completed testing at the contractor's site, MTI in Latham, NY. The other half has undergone testing at NASA-LeRC (Figure 3) and has served as a test bed for evaluating key technology areas and components.[3, 4, 5, 6] Recent testing has been guided by sensitivity studies using the MTI HFAST performance code and has resulted in improvements in PV power of 2.4 kW and improvements in PV efficiency of 1.9 percentage points.[7]

COMPONENT TEST POWER CONVERTER (CTPC)

The 12.5 kWe/piston Component Test Power Converter was fabricated to develop technology for the next generation Stirling Space Power Converter (SSPC). Both converters will be similar except for the material of the heater. The heater of the CTPC has been fabricated from Inconel 718 and has a relatively short design life (100-1000 hours at 1050 K). The heater of the SSPC will be fabricated from Udimet 720LI and will have a design life of 60,000 hr. The mean working gas pressure of both converters is 150 bar, heater temperature is 1050 K, and cooler temperature is 525 K. The dynamic components of the converters oscillate at 70 Hz.

The CTPC will evaluate critical technologies to be incorporated into the SSPC. These critical technologies have been identified as: bearings, materials, coatings, linear alternators, mechanical and structural issues, and heat pipes.

CTPC Cold-End Testing [Figure 4]

The Cold-End hardware includes all dynamic components and hardware of the CTPC except the heat exchangers. The purpose of the cold-end test was to verify mechanical operation, internally pressurized gas bearing operation, and alternator performance at the high operating temperature of 525 K before adding the heat exchangers to complete the assembly of the CTPC. A dummy heater head, which contained an SPRE cooler was connected to a hot oil pumped loop to heat the Cold-End to 525 K. The Cold- End was motored to provide motion of the piston and displacer by applying power to the linear alternator which then functioned as a linear motor.

After a period of testing as described by Dochat[8], beginning at ambient and increasing the temperature in steps, successful operation of the Cold-End was achieved at design operating conditions: at a temperature of 525 K and helium working gas pressure of 150 bar, a frequency of 70 Hz, and with power piston and displacer strokes of 28 mm.

Operation of the Cold-End at 525 K demonstrated major accomplishments in bearing and alternator design. The power piston and displacer were supported on internally supplied hydrostatic gas bearings and were capable of dry starts and smooth mechanical operation at temperature levels from ambient temperature to 525 K. The alternator stator coil and insulation materials were able to operate with minimum performance penalty at temperatures to 573 K. The linear alternator's permanent magnet design permitted operation at a temperature of 548 K.

CTPC Permanent Magnet Linear Alternator

The prior generation SPRE permanent magnet linear alternator demonstrated 85% efficiency in an operating power converter at design conditions: 150 bar pressure, a cold end temperature of 325 K, a temperature ratio of 2.0, 20 mm piston stroke and 105 Hz frequency. This alternator demonstrated a basic understanding of linear machine technology and validated the design codes used in its development.

The current generation CTPC linear alternator is similar in design to the SPRE [Figures 5 and 6] with the exception that it must operate at a cold end temperature of nominally 525 K, 200 K hotter than the SPRE. This higher temperature environment mandated an unconventional alternator design to accommodate alternator coil operating temperatures of 573 K and alternator magnet temperatures of 548 K. Other operating parameters were 28 mm piston stroke and 70 Hz frequency. Magnet testing at LeRC indicated that sufficient design margin exists for Sm_2-Co_{17} magnets operating at this temperature, provided the design takes into account the effects of high temperature on magnet performance, especially demagnetization. [9]

A series of tests were conducted by MTI on the first build of the CTPC alternator. A bench top investigation showed that the alternator assembly procedure caused many of the individual magnet segments to be electrically shorted to their supporting Inco 718 tie rods and spacer rings; the shorts generate unwanted eddy currents which result in 3 points of efficiency loss. As designed, each magnet was to be electrically insulated from the support structure. Table II lists the measured and code predicted values of the alternator parameters. The predictions were made by MTI using their "LPMMA" code.

MTI conducted lab tests with various subassembly or components sequentially removed to determine the loss in each subassembly or component. Table III summarizes those losses. (Measurements do not identify eddy current losses.)

The measured values of the CTPC alternator parameters and power losses compared well with the code predicted values. As a result of conducting the detailed loss tests, a second alternator has been designed and is being built to eliminate eddy current losses and achieve the design point alternator efficiency of 88%. This second alternator takes advantage of a ceramic insulation on the tie rods and spacer rings to electrically insulate the magnets from the support structure. Long term improvements have been identified which should permit alternator efficiencies above 90%.

CTPC Hydrostatic Gas Bearing System

Free-piston Stirling space power converters must rely upon non-contacting bearings to eliminate wear and thereby achieve long life. Several types of bearings have been considered including: hydrostatic gas bearings, hydrodynamic gas bearings, flexures and magnetic bearings. Both hydrostatic and hydrodynamic bearings were evaluated for the SPRE with hydrostatic bearings being selected for the final design. Flexures and magnetic bearings are being studied for possible application to high power converters (>10KWe/piston) but they have not yet been demonstrated at these power levels.[10]

MTI has successfully demonstrated that hydrostatic gas bearings are feasible for high power converters. The new CTPC hydrostatic bearing designs have been demonstrated with self-pumped operation over a power range of 50% to 100%. The hydrostatic gas bearing is a simple, passive system that relies upon the piston gas springs to supply gas to bearing plenums that are located within the pistons. The plenums are charged through ports in the piston and cylinder walls that open at appropriate times as the piston traverses its stroke. Each piston is supported by gas that flows from the supply plenum, through orifices in the piston wall, along a gas gap between the piston and its mating cylinder, and then into the drain plenum.

The new hydrostatic CTPC bearing system is efficient because it uses the gas spring full pressure wave to charge the supply plenum and to discharge the drain plenum. In contrast, the SPRE hydrostatic bearing systems used only half of the pressure wave to charge the supply plenum <u>only</u> and thus required a greater gas spring pressure amplitude with resultant greater hysteresis power loss. Because of the more efficient bearing design, the hydrostatic bearing losses for the CTPC are only 600 watts compared to bearing losses of 1700 watts for the SPRE. The radial stiffness of the new bearing is 1.48×10^6 lbf/in. of radial deflection.

The new CTPC hydrostatic bearing also incorporates other mechanical improvements compared to the SPRE. For example, bearing plenums were previously placed in the cylinder and involved tortuous flow paths which could neither be inspected nor cleaned; the new bearing system incorporates straight passages that can easily be inspected and cleaned.

CTPC Heater

The CTPC heater, known as the Starfish heater because of the heat exchanger fin configuration, is a novel heater concept that was proposed by MTI. As shown in Figures 7 and 8, the heater consists of 50 fins extending radially outward from the inner annular radius; each fin contains 38 one-millimeter diameter gas passageways. The holes are drilled by a STEM (shaped tube electrochemically machined) process. A single-fin STEM-drilled specimen is shown in Figure 9. The fins are formed by an electrical-discharge-machined (EDM) slot between each fin as shown in Figures 7 and 10.

Since the Starfish heater is machined from a single piece of superalloy material, the reliability of the heater is expected to be greatly improved. In comparison, the SPRE heater required 3200 braze joints. The walls of the Starfish heater are of nearly constant thickness, which will minimize thermal shock effect. Gas passages through the fins add very little dead volume to the working space. The external fin surface will become the condenser surface of a heat pipe connected to a heat source.

SSPC Heater Materials

Because the SSPC has a design life of 60,000 hr, the heater head will be fabricated from Udimet 720LI. It will be a similar Starfish heater design to the CTPC heater except that it will be fabricated from Udimet 720LI alloy instead of Inconel 718 alloy. Udimet 720LI is a relatively new superalloy, therefore, a development program was initiated to better characterize the material. Such characterization includes determination of the most suitable product form: cast wrought or powdered; evaluation of creep and fatigue properties; evaluation of sodium compatibility; and evaluation of joining methods.

Joining methods selected for evaluation are E-beam welding and transient liquid phase diffusion bonding (TLPDB).[10] Both Udimet 720LI-to-Udimet 720LI joints and Udimet 720LI-to-Inconel 718 joints are required in the SSPC design. Although it is generally believed that Udimet 720LI cannot be welded by E-beam methods, MTI has successfully fabricated both types of joints by an E-beam welding process. Testing continues to validate the integrity of these welds.

CTPC Heat-Pipe Heat Transport System

This system consists of an Inconel 718 annular enclosed ring that attaches to the outer radius of the Starfish heater as shown in Figure 8. The inner surface of this annular heat pipe is covered with 316L stainless steel screen wick with arteries that extend radially outward from the root of each condenser slot to the outer radius of the evaporator section. The evaporator is heated by electrical radiant heaters that heat the external surface on one side of the annular heat pipe.

Backup Radiant Heat System for the CTPC

First testing of the CTPC will be accomplished with direct heat input to the CTPC by electrical radiant heaters. This is necessary because of the longer time needed to develop the heat pipe. Radiant heaters as shown in Figure 11 will be installed in the slots of the Starfish heater. Two heaters will be installed in each of the 50 slots. Figure 12 shows a heat transfer test rig used to evaluate the radiant slot heaters.

SSPC Heat-Pipe Heat Transport System

This heat transport system will be similar to the CTPC heat transport system except that it is designed for 60,000 hr life. The heat pipe external walls will be fabricated from Inconel 718 which will be joined to the Udimet 720LI heater by an E-beam weld or TLPDB joint. Wick material has not yet been selected for this heat pipe. An assessment of the compatibility of both Udimet 720LI and Inconel 718 with sodium was performed.[11] It was learned that to minimize oxygen-induced corrosion, the oxygen level in the sodium of the heat pipe must be kept below 10 ppm. Therefore, early in the program, small heat pipes were fabricated to develop a process for filling heat pipes with sodium from a high-purity sodium loop. The detailed procedures for this process were prepared by NASA LeRC, MTI, Thermacore, and Energy Technology Engineering Center (ETEC) and carried out by ETEC personnel. A 1/10 segment of the CTPC heat pipe is shown in Figure 13 attached to a sodium loop in preparation for filling with sodium.

Even if corrosion by oxygen-related mechanisms can be minimized, there remains the probability that some metal alloy components of Udimet 720LI and Inconel 718 can dissolve directly into the sodium. Analyses were performed by Alger and Tower for the dissolution of nickel in sodium.[11, 12] Alger indicated that a heat pipe can be designed to accommodate the SSPC life requirements. At the heat pipe operating conditions, the sodium in the condenser wick will be partly saturated with nickel which reduces the nickel concentration gradient between heat pipe wall and wick material and the sodium, thus reducing the dissolution rate.

The heat pipes that were fabricated by Thermacore and loaded with sodium from ETEC's high-purity sodium loop, will be placed on long-term test at MTI to evaluate the corrosion rates of these heat pipes.

CONCLUDING REMARKS

Stirling Space Power Converters have the potential to significantly advance the state-of-the-art of high capacity nuclear space power systems and can provide low mass, compact power systems for a wide range of future NASA missions. Studies have shown that current Stirling designs scale well and provide high efficiency systems from 100 watts to 100 kWe. Modified designs scale to significantly higher power. Because

Stirling can operate efficiently over a broad temperature range, it is a candidate power converter for low, medium, and high temperature applications.

Significant advancements have been made in free-piston Stirling space power converter technology for space applications since the inception of the Stirling Space Power Converter project in 1984. The second generation Stirling power converter, the CTPC, is planned to be on test in July 1992. This power converter and its follow-on SSPC will demonstrate nearly all of the technologies required for a flight-type power converter.

To date, no technical barriers have been discovered to prevent successful technology development. As stated repeatedly in the past, Stirling technology simply needs sound engineering and continued funding support.

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TABLE I

STIRLING POWER CONVERTER PERFORMANCE ACHIEVED AND FUTURE OBJECTIVES

	CURRENT SOA SPDE/SPRE	CTPC (Future 7/92)	SSPC (Future 2/94)
POWER/CYLINDER, kWe	11.2	12.5	12.5
HOT-END TEMPERATURE (Th), K	630	1050	1050
TEMPERATURE RATIO, Th/Tc	2.0	2.0	2.0
EFFICIENCY, %	18	>20	>25
SPECIFIC MASS, kg/kWe (Projected to Space Configuration)	7.2	7.3	6.5
DESIGN LIFETIME, HRS.	1000 at 900 K	300 at 1000 K	60,000 at 1050K
HEATER MATERIAL	INCONEL 718	INCONEL 718	UDIMET 720
HEAT INPUT	PUMPED SALT LOOP	SODIUM HEAT PIPE	SODIUM HEAT PIPE
NO. OF HEATER HEAD JOINTS/CYLINDER*	6500	<10	<10
TECHNOLOGY DEMONSTRATION DATE	1990	1992	1994

* Heater Head includes heater and cooler joints

TABLE II

ALTERNATOR PARAMETERS

Parameter	Units	Measured at Room Temperature	Predicted at Room Temperature
Coil Flux Linkage due to magnets	Webers	1.039	1.023
Axial Force per unit current	Newton/Amp	77.7	77.9
Coil Inductance	Henries	0.0145	0.0149
Coil Resistance	Ohms	0.087	0.087

TABLE III

POWER LOSS (WATTS)

Parameter	Measured at Room Temp.	Code Predicted at Room Temperature	Extrapolated from Measured Room Temp. Data *	Code Predicted at Design Temperature
I^2R loss @ 50.6 amps rms	221	221	465	465
Bare Stator Loss (excl. I^2R) @ 425 V	274	274	274	274
Structure losses	237	201	237	201
Plunger losses	787	750	787	750
Total loss	1519	1446	1763	1690
Efficiency at 14 kW shaft power	89.1%	89.7%	87.4%	87.9%

* To account for higher coil resistance at design temperature

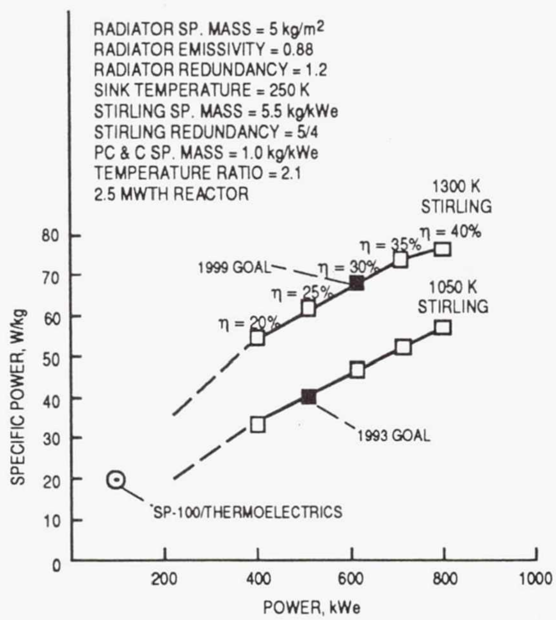

Figure 1 - Projected Performance of Advanced Stirling Power Converters

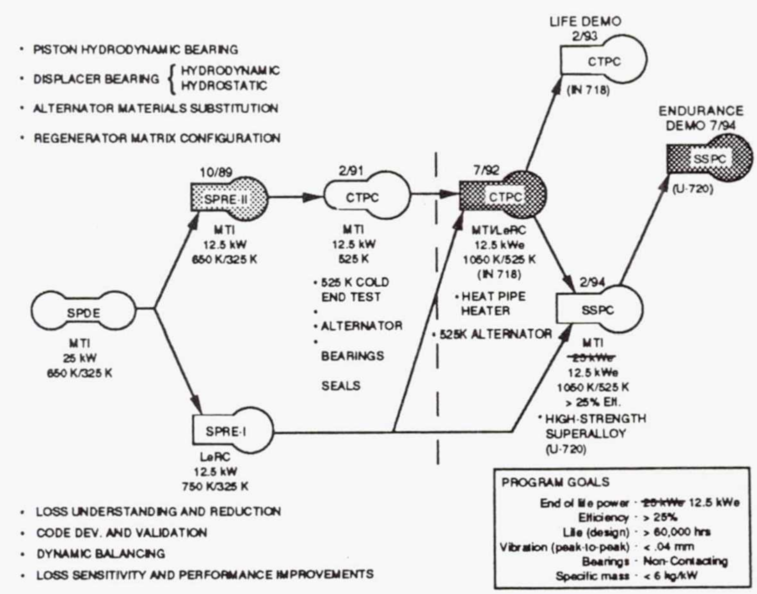

Figure 2 - Stirling Development Plan

Figure 3 - Free-Piston Stirling Engine

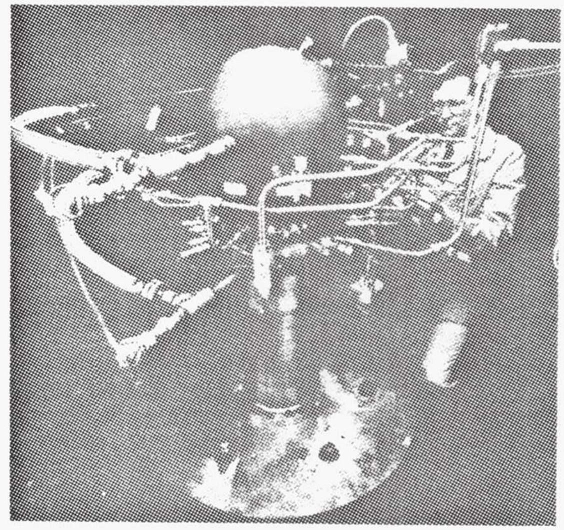

Figure 4 - CTPC Cold-End Test

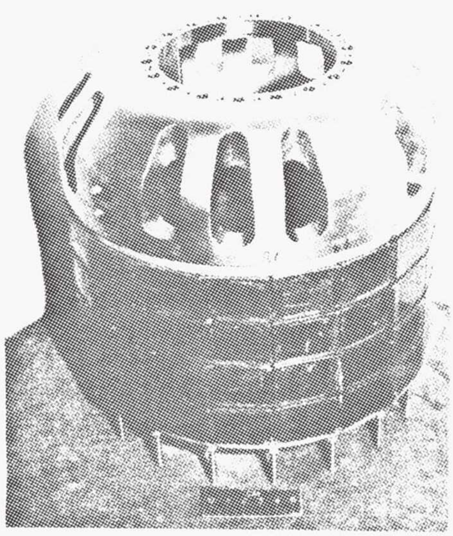

Figure 5 - CTPC Alternator Magnet Carrier
Before Final Machining

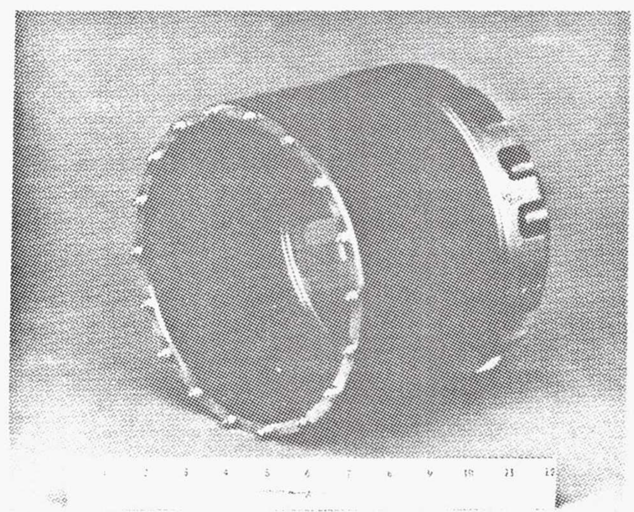

Figure 6 - CTPC Finished Alternator Magnet Carrier

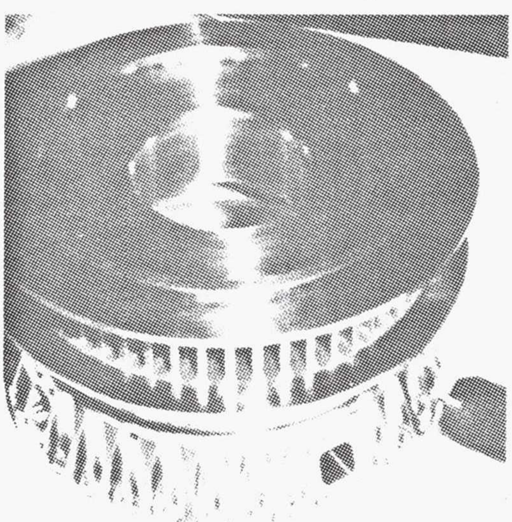

Figure 7 - CTPC Starfish Heater Head

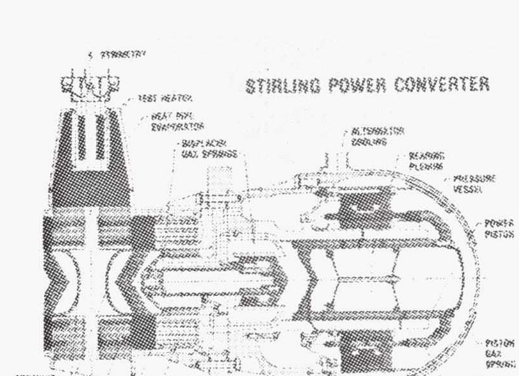

Figure 8 - CTPC Schematic

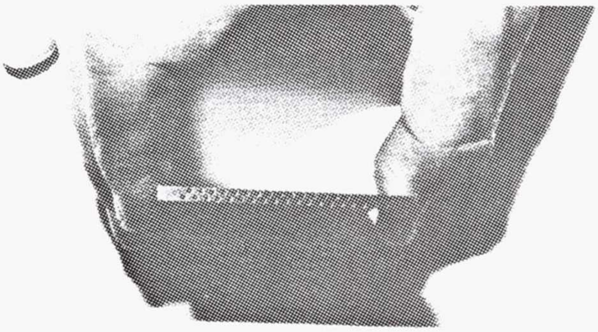

Figure 9 - Sample Fin with STEM Drilling

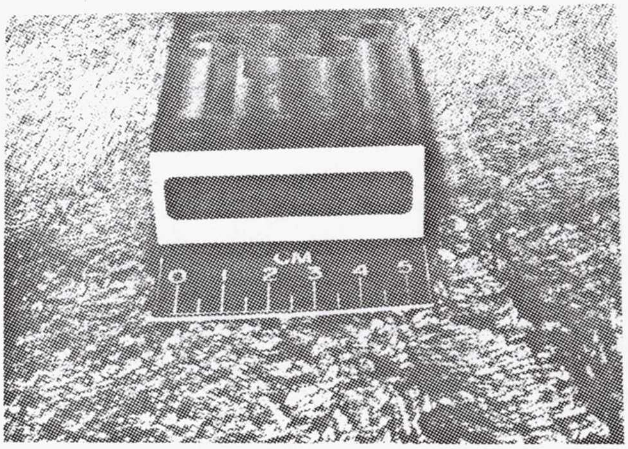

Figure 10 - Sample EDM Starfish Pocket

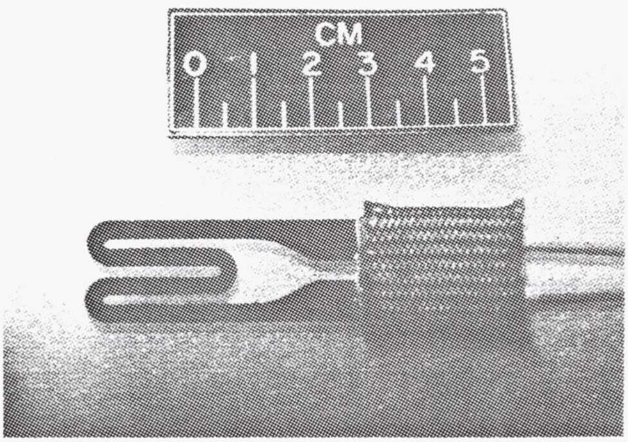

Figure 11 - Starfish Backup Radiant Heater

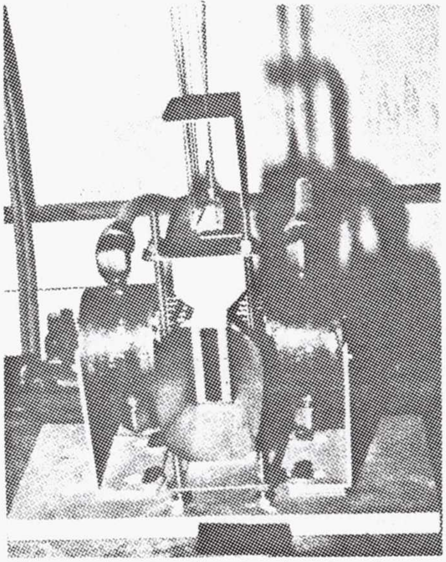

Figure 12 - Starfish Pocket/Radiant Heater Test Fixture

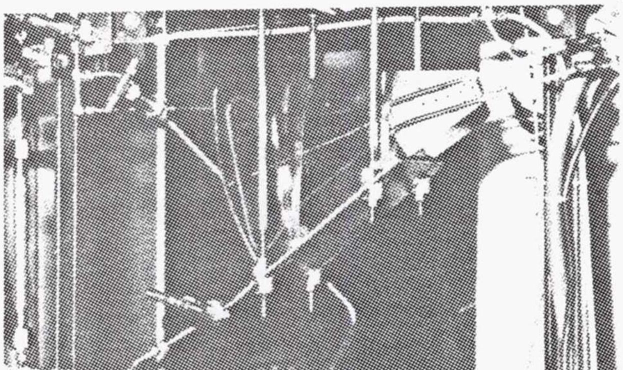

Figure 13 - Starfish 1/10 Segment with Heat Pipe - Sodium Fill Test

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