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THE DESIGN AND FABRICATION OF A STIRLING ENGINE HEAT EXCHANGER MODULE WITH AN INTEGRAL HEAT PIPE

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ABSTRACT

The conceptual design of a free-piston Stirling Space Engine (SSE) intended for space power applications has been generated under a National Aeronautics and Space Administration (NASA) contract. This contractual effort was funded by the SP-100 project and managed by the Lewis Research Center (LeRC). The engine was designed to produce 25 kW of electric power with heat being supplied to the engine by a nuclear reactor. A novel heat exchanger module was designed with the intent of reducing the number of critical joints in the heat exchanger assembly while also incorporating a heat pipe as the link between the engine and the heat source. Before incorporating this novel design into a 25 kW Stirling power conversion unit it is desirable to conduct some inexpensive verification tests. Two such approaches are planned. The less costly approach entails attaching 3 heat pipe modules to components remaining from the previously tested RE-1000/dashpot loaded 1 kW engine. A more comprehensive verification test modifies the 12.5 kW Space Power Research Engine (SPRE) for 40 heat pipe modules similar to those proposed for the SSE.

Heat exchanger modules of this type have not appeared in previous Stirling engine designs. There is no existing performance data base that can be used for support when generating a new design. The entire heat exchanger assembly, and in particular the interface between the heat source and the heat exchangers are considered to be critical technologies required for future space power systems.

This report describes the SSE heat exchanger module and outlines the operating conditions for the module. The design process of the heat exchanger modules, including the sodium heat pipe, is briefly described. Similarities between the proposed SSE heat exchanger modules and the LeRC test modules for two test engines are presented. The benefits and weaknesses of using a sodium heat pipe to transport heat to a Stirling engine are discussed. Similarly, the problems encountered when using a true heat pipe, as opposed to a more simple reflux boiler, are described. The instrumentation incorporated into the modules and the test program are also outlined.

INTRODUCTION

As a part of the SP-100 Advanced Technology Program the Free-Piston Stirling Engine (FPSE) technology is currently being developed. This program has generated the Space Power Demonstrator Engine (SPDE) which was later converted into 2 separate Space Power Research Engines (SPRE). The progress of these engines is outlined in references 1 and 2. The purpose of this engine was to demonstrate the feasibility of operating a FPSE at a temperature ratio of 2.0 and still maintain high efficiency. The hot end of the SPDE and SPRE engines operated at approximately 650°K. The next step in the development of a space ready FPSE is the Stirling Space Engine (SSE). One half of the SPDE is shown in figure 1 and the proposed SSE is shown in figure 2. The SSE conceptual design has been completed and incorporates a new type of Stirling engine heat exchanger. This new heat exchanger has a heater, a regenerator, and a cooler built into a single module. This engine is intended to operate at a temperature ratio of 2.0 but with the hot section at approximately 1050°K. Current NASA SP-100 advanced technology program plans call for another generation of engine which will operate with the heater at approximately 1300°K while maintaining a temperature ratio of 2.0.

This report presents the new type of Stirling engine heat exchanger module with an integral heat pipe. The operation of the unit is described along with a discussion of the matching of the heat pipe operation to that of the engine. The incorporation of this type of module in the SPRE currently under test at Mechanical Technology Incorporated (MTI) is outlined. The design, fabrication, and testing of some prototype modules on an existing dashpot load used in the RE-1000 Sensitivity Tests is presented.

PREVIOUS STIRLING ENGINE/HEAT PIPE WORK

It has long been recognized that Stirling engines suffer in performance when there exists a maldistribution of temperature or heat flux in the heater. One method of transferring heat from a heat source to the engine is by utilizing the excellent thermal transport capability of a vaporizing and condensing fluid. This can be in the form of a reflux boiler or a heat pipe. Research into the integration of this type of heat transport system had been conducted in the past at the Philips Laboratories in Holland. Other work on similar systems is currently under way at Stirling Thermal Motors (STM) in Ann Arbor, Michigan as reported in reference 3, and at ECA in France as presented in references 4 and 5. More recently an effort has started at Stirling Technology Company (STC), of Richland, Washington as outlined in reference 6. While most of the efforts relied on gravity to assist the return of the condensate back to the evaporator, the STC design is intended to work without the aid of gravity.

Engine tests at LeRC and at other test facilities have shown that any nonuniform temperature profile around the circumference of a heater head causes a severe performance degradation in both power and efficiency. The mixing losses incurred are sizable when the working fluid of an engine can flow through parallel paths that are not identical in temperature and configuration. When properly designed, a heat pipe or a reflux boiler can make the heater temperature profile become relatively uniform.

HEAT PIPE CHARACTERISTICS

An obvious benefit derived from the use of a heat pipe as the interface between the heat source and the engine is the uniform temperature profile that should exist at any location around the condenser. Although a four cylinder engine with four separate heat pipes may have a slightly different temperature at each of the condensers, each individual condenser should have a rather uniform temperature profile. This will benefit the engine by reducing mixing losses in the working fluid and also by enabling the engine to operate nearer the maximum allowable heater metal temperature.

To a great extent, a heat pipe or a reflux boiler can also make the engine heater have a minimal temperature gradient in the axial direction. An axial temperature gradient may exist in some engines not only because of the nonuniformities in the heat supply side of the heating system, but also due to the nonuniform thermal load that the working fluid places on the gas side of the heater. In a very idealized situation, the condensing fluid of the heat pipe will supply as much heat to the engine as the working fluid can absorb at any axial location. This situation may be approached in the STM and the ECA concepts where the vapor flow to the engine heater is perpendicular to the heater tubes and in a rather large cavity.

Although the heat-pipe heat transport system has some great advantages over other alternatives, there are some critical issues that must be addressed. If the heat pipe is to operate in a gravity free environment or operate against gravity, special attention must be paid to the pumping capability of the wick and artery system. In the case of the LeRC heat pipes, a large fraction of the pumping force required by the wick structure is to overcome the gravitational forces. If arteries are used in the heat pipe to reduce the liquid flow resistance, care must be taken to prevent vapor from entering the artery and causing the artery to become deprimed. In some designs the arteries are not self-priming and the pipe must be manipulated in a manner that will force the arteries to become primed.

HEAT PIPE MODULE CONCEPT

As part of the NASA SP-100 Advanced Stirling Technology program, Sunpower, Inc., with MTI acting as a consultant, completed the conceptual design of the 25 kWe SSE. The design includes a linear alternator for conversion of the linear piston motion to electricity. The detailed design, fabrication, and check-out will be performed under a future competitive procurement. Although the heat rejection from the engine is intended to be a pumped loop, the heat input to the engine from the nuclear heat source is to be via heat pipes.

One of the features incorporated in the SSE design is the modular heat exchanger which includes the heat-pipe heater, the regenerator, and the cooler contained within a module. The purpose of using the modular heat exchanger concept was to lower the number of critical joints in the heat exchanger assembly. The SPDE used approximately 3200 tubes in the heater and 3800 tubes in the cooler for a 25 kWe engine. The SSE 25 kWe design has replaced the shell and tube approach with 40 heat exchanger modules. A model of one module is shown in figure 3. The figure shows the module with the cooler on the left, the regenerator in the middle, and the heater on the right. The slots in the heater and the cooler are the gas passages. The two tubes shown above the heat exchangers are the close-out tubes that slide over the finned heat exchangers to finish forming the rectangular gas passages. The heat pipe can be seen entering the module from the lower right hand corner.

As part of the testing of the SPRE at MTI, a new heater head will be built to replace the original shell and tube type heater and incorporate this new style of heater. The regenerator and cooler of the engine will remain as before. Approximately 40 heat pipes and finned sleeves will be used in the conversion of the heater. This will test the heater section of the modular heat exchanger concept at the design conditions of the SPRE, 150 bar of helium working pressure and about 100 Hz frequency. Since the heat pipes will be filled with sodium, the heater temperature will be raised to the 1050°K range.

HEATER MODULE TEST RIG

As an early test of the heat exchanger module concept, an engine was redesigned to use three of the modules and will be tested at the NASA LeRC. This engine will operate with 70 bar helium pressure and at a frequency of 30 Hz. The power output should be between 1 and 2 kW depending on the operating conditions. The dynamics will be tuned to be the same as in the RE-1000 that was used in the Sensitivity Tests as described in reference 7. The engine will also use the dashpot load from the sensitivity tests and the dynamic balancer as described in reference 8. The layout of the heater head is shown in figure 4.

As mentioned earlier, the dashpot load and the dynamics of the engine will be the same as existed in the RE-1000 Sensitivity Tests. Other components left over from the Sensitivity Tests include the power piston, the power piston cylinder, the pressure vessel, the displacer and the displacer rod. The entire heat exchanger assembly and the working space cylinder will be new. The design and fabrication of the new components was performed by Sunpower, Inc., with the heat pipe design and fabrication subcontracted to Thermacore.

Sodium was chosen as the working fluid of the heat pipes so that the SSE heat exchanger modules could be simulated as closely as possible. Initial check-out of the heat pipes was performed at the contractors site by means of a gas gap calorimeter as the load. These tests confirmed the performance predicted for this design. Figure 5 shows the heat transport capability of the heat pipes along with the curves representing the heat required by the engine. Due to the relatively poor thermal conductivity of the sodium heat pipe at the lower temperatures, some of the test conditions shown in figure 5 cannot be attained. The engine will be tested at temperatures up to 950°K where the use of sodium heat pipes is more appropriate. One of the heat pipes is shown in figure 6.

The heating system transfers heat from electric resistance heating elements to the evaporators of the heat pipes by radiation. The evaporator of each heat pipe is located coaxially inside of a cylindrical silicon-carbide heating element. Figure 7 shows the heater head assembly with one of the three radiant heaters shown. This system of heating the evaporators was chosen to minimize any instrumentation problems that may be encountered with other systems such as radiofrequency (rf) heating and also to provide a uniform heat flux to the pipes. The disadvantage of this system however, is the rather slow response of the system. Due to the large thermal inertia of the heaters, a purge system was incorporated near the heaters to provide a quick and safe emergency shutdown capability. The heater canister will be calibrated so that the losses to the atmosphere can be accounted for during engine tests and a good heat balance obtained.

The heat pipes were designed to be able to operate with the sintered powder metal wicks pumping the liquid sodium against gravity. This pumping capability was incorporated because the eventual application of these modules is in space power applications where gravity cannot be used to return the liquid to the evaporator. The LeRC test rig however, was designed such that the entire engine and heating system can be inverted to permit the heat pipes to also work in a refluxing mode. Tests will be performed with the heat pipes working with the aid of gravity and also working against gravity. The reason for incorporating this capability is to be able to determine the influence of any excess sodium inventory of the heat pipes on the engine performance. This will be accomplished by having the pool of liquid reside in the condenser of the heat pipe when the engine is in the standard position, and then reside in the evaporator when the engine has been inverted.

HEAT EXCHANGER MODULE DESIGN

The goals of this test program were to demonstrate and investigate the operation of the modular heat-pipe heat exchanger design for the benefit of the SPRE heat exchanger conversion. The SPRE testing will then provide additional information for the SSE design and fabrication program. It was decided that the heat exchangers to be tested on the LeRC engine should be designed to operate at conditions matching the SSE heat exchanger modules as closely as possible. The LeRC engine will have three modules and produce between 1 and 2 kW of power output while the SSE will use 40 heat exchanger modules to produce nominally 25 kW of power. By varying the number of gas passages in the LeRC design, the modules were made to simulate the SSE module operation.

Since the intent of this program was not to research any materials related difficulties that arise in sodium heat pipes designed for long life, the heat pipes were fabricated from a 300 series stainless steel. The life of the heat pipes is expected to be at least on the order of thousands of hours. Each heat pipe was built with a sintered powder metal wick and two arteries as shown in figure 8. The pipe should be able to operate with only one of the arteries working but the second artery was incorporated as insurance against failure. Many of the design features were directed towards a conservative design since this program was not intended to be of a high risk nature.

LeRC TEST PROGRAM

The test program was formulated to demonstrate the operation of the new heat exchanger module and also to investigate the operational characteristics of a Stirling engine coupled to a heat source via a heat pipe. Along with these primary goals however, some other items of interest will be researched. The hardware was designed with a great amount of flexibility so that future modifications could be adapted to the rig. For example, the configuration of the heat exchanger manifold and the regenerator geometry can be altered.

The temperature gradient along the heater will be monitored closely so that the effect of the heat-pipe heat transfer capability along with the engine heat load characteristics can be evaluated. As mentioned earlier, another test will be performed with the entire engine inverted so that the location of the excess inventory of sodium will remain at the evaporator end of the heat pipe rather than at the condenser. The engine will be operated with the cooling water at 300^{O}K and the heater at temperatures up to 950^{O}K. As the temperature of the heater is lowered, the sonic limit of the heat pipe will be encountered. It is presently thought that operating against this limit presents a stable situation whereby the heat pipe evaporator will not dry-out. The characteristics of operating in this mode will therefore be investigated not only for the sake of Stirling engine research but also for test data to aid in the validation of the LeRC heat pipe simulation as described in reference 9.

CONCLUDING REMARKS

The conceptual design of a 25 kWe FPSE has been generated under a NASA contract. This was designed by Sunpower Inc., of Athens, Ohio, and is intended for space power applications. The proposed design uses a novel heat exchanger module that has an integral heat pipe to couple the engine to the heat source. Heat exchangers of this type have not been used in Stirling engine designs in the past and therefore little is known about their operational characteristics.

The 12.5 kW SPRE that is currently under test at MTI will have a new heater head designed and fabricated for testing that incorporates the heater section of this type of heat exchanger module. The SPRE will require about 40 of these heaters to operate properly. The SSE conceptual design as proposed also shows approximately 40 of these heat exchanger modules. The SSE will be carried on through a detailed design and fabrication under a future competitive procurement. In both cases, the fabrication of this new type heat exchanger represents a large investment.

A relatively simple, quick and inexpensive demonstration and verification of the heat-pipe heat exchanger module was developed. This test will be conducted at the LeRC and will use three of the heat exchanger modules operating at conditions similar to those of the proposed SSE. The sodium filled heat pipes will be tested over a range of operating conditions in order to characterize their performance. The results of this test will be used as a basis for improving the design of these heat exchanger modules on future engines.

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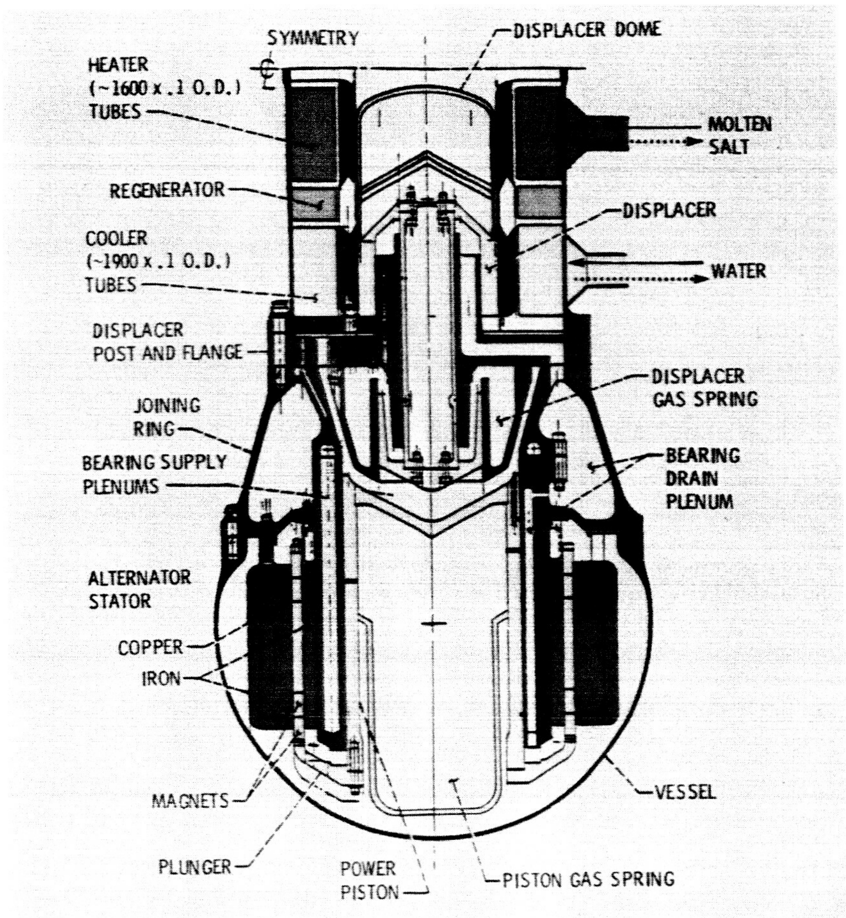

FIGURE 1. - 25 kWe SPDE.

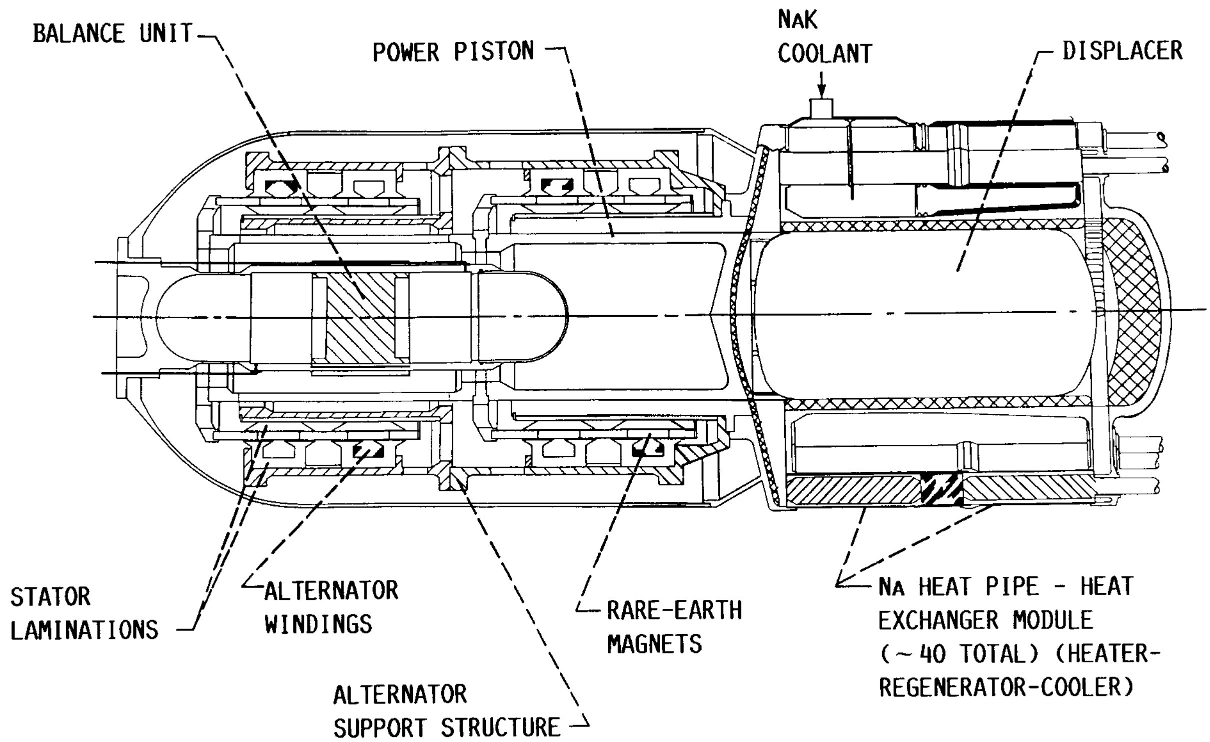

FIGURE 2.- SUPERALLOY STIRLING SPACE ENGINE (SSE) REFERENCE DESIGN.

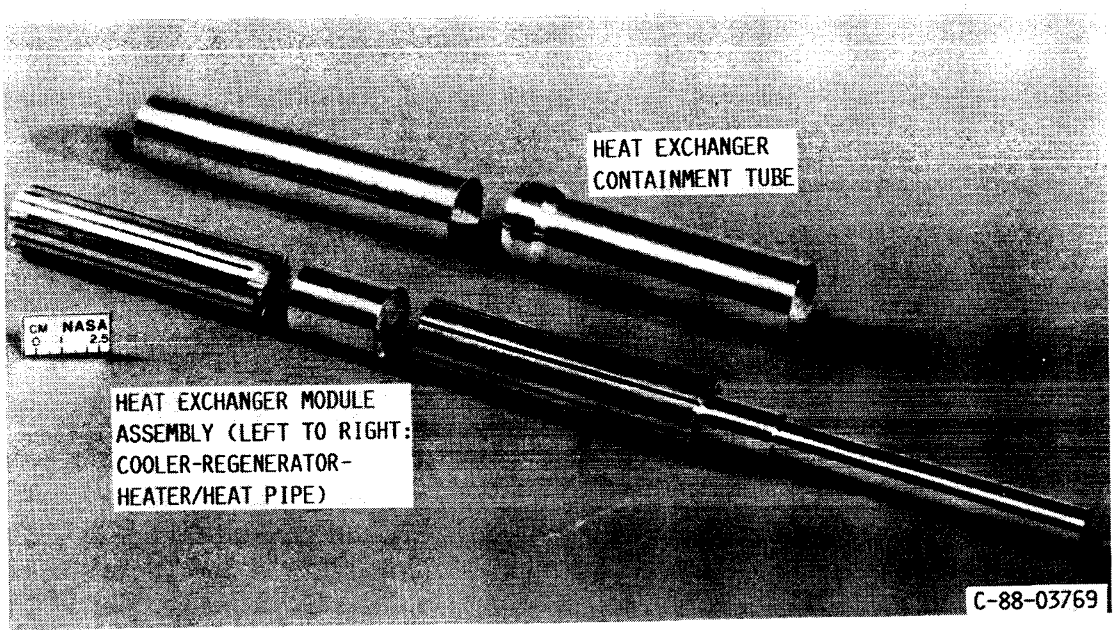

FIGURE 3. - STIRLING MODULAR HEAT EXCHANGER ASSEMBLY.

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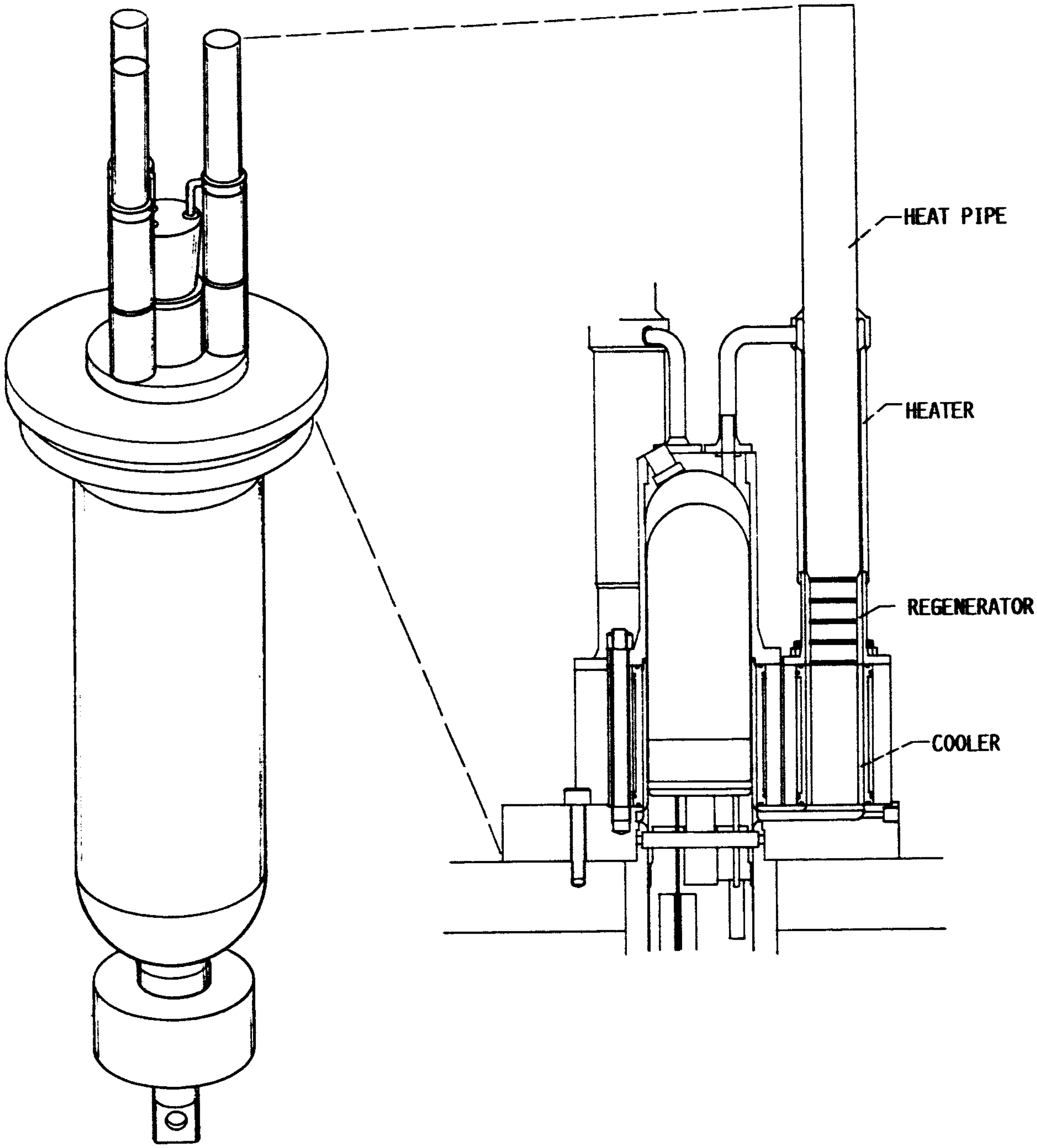

FIGURE 4. - NASA LeRC HEAT PIPE TEST ENGINE.

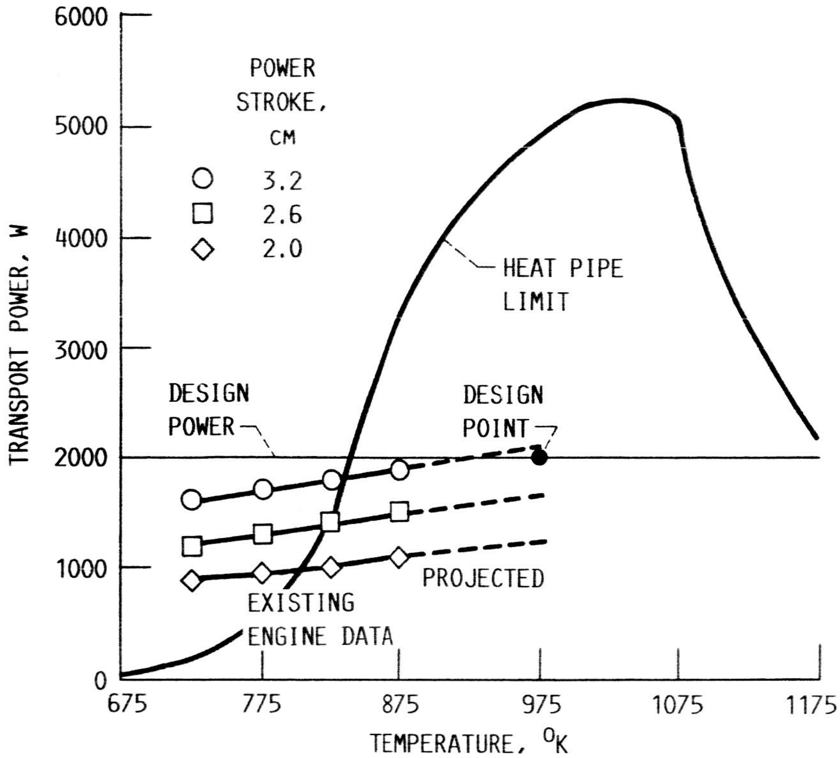

FIGURE 5. - CURVES SHOWING HEAT TRANSPORT LIMITATION OF EACH HEAT PIPE ALONG WITH HEAT DEMAND OF ENGINE PER HEAT PIPE. CURVES REPRESENTING HEAT DEMAND OF ENGINE SHOW EXISTING DATA AND PROJECTED VALUES.

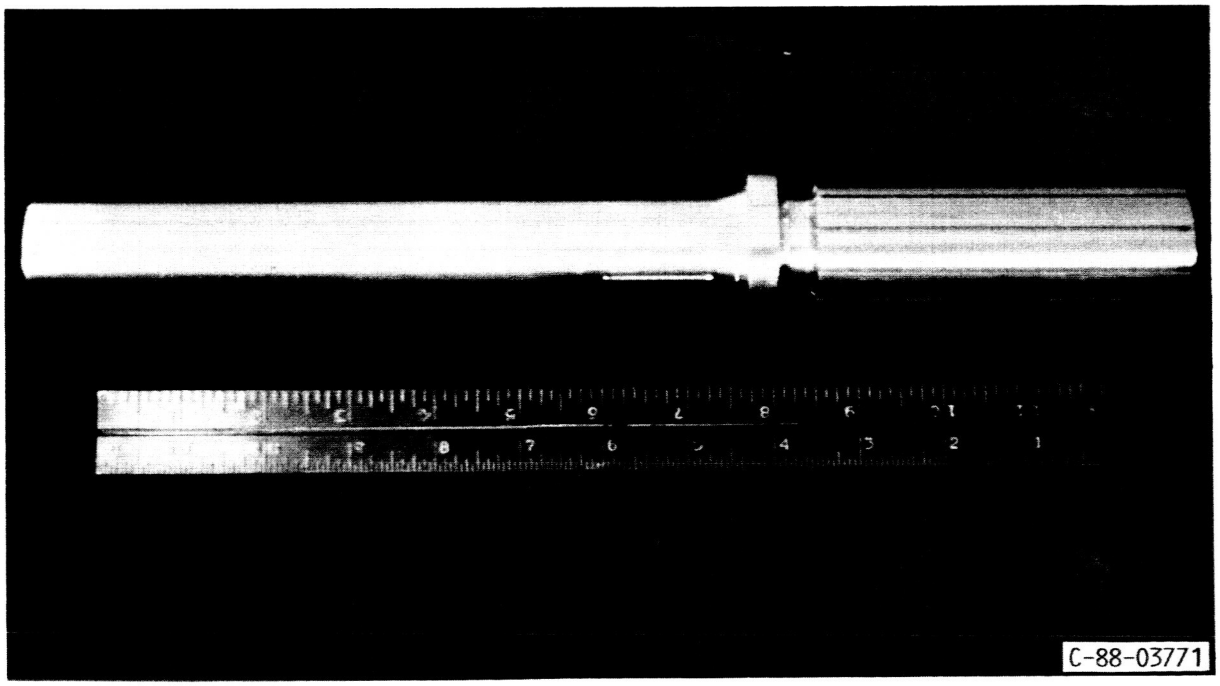

FIGURE 6. - HEAT PIPE WITH ENGINE HEATING FINS.

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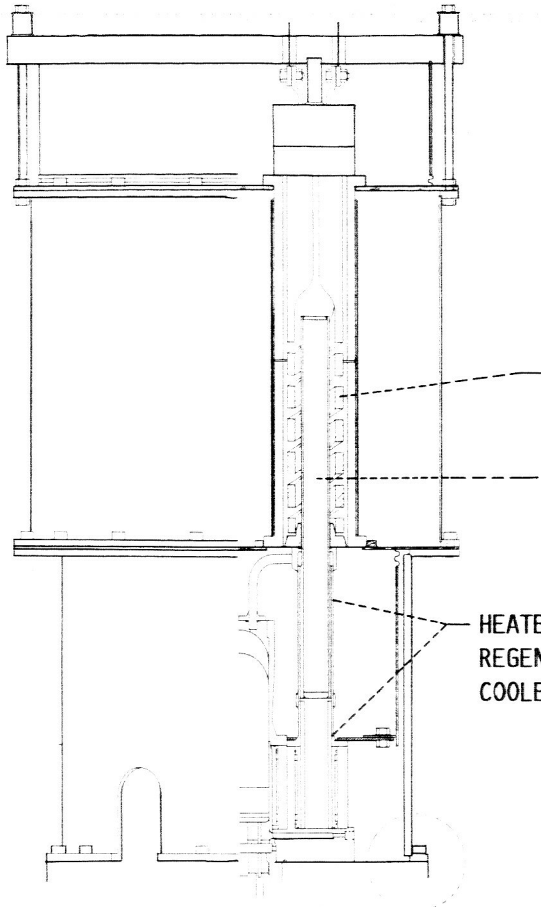

FIGURE 7. - HEAT-PIPE HEATER HEAD WITH HEATING CANISTER.

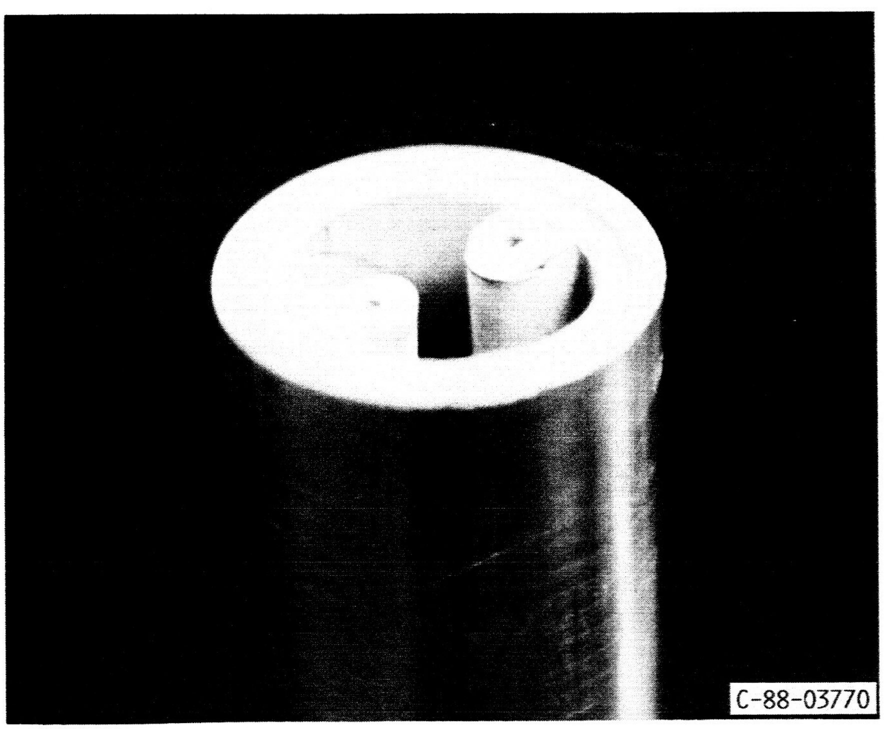

FIGURE 8. - WICK AND ARTERIES IN THE HEAT PIPE EVAPORATOR.

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