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SOLAR POWERED STIRLING CYCLE ELECTRICAL GENERATOR

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ABSTRACT

Under NASA's Civil Space Technology Initiative (CSTI) the NASA Lewis Research Center is developing the technology needed for free-piston Stirling engines as a candidate power source for space systems in the late 1990's and into the next century. Space power requirements include high efficiency, very long life, high reliability, and low vibration. Further, system weight and operating temperature are important. The free-piston Stirling engine has the potential for a highly reliable engine with long life because it has only a few moving parts, non-contacting gas bearings, and can be hermetically sealed.

These attributes of the free-piston Stirling engine also make it a viable candidate for terrestrial applications. In cooperation with the Department of Energy, system designs are currently being completed that feature the free-piston Stirling engine for terrestrial applications. Industry teams have been assembled and are currently completing designs for two Advanced Stirling Conversion Systems utilizing technology being developed under the NASA CSTI Program. These systems, when coupled with a parabolic mirror to collect the solar energy, are capable of producing about 25 kW of electricity to a utility grid. Industry has identified a niche market for dish Stirling systems for worldwide remote power application. They believe that these niche markets may play a major role in the introduction of Stirling products into the commercial market.

INTRODUCTION

The NASA Lewis Research Center, in cooperation with the Department of Energy (DOE), Solar Thermal Technology Program, is currently working with contractor teams designing solar Stirling systems which feature the free-piston Stirling engine for terrestrial applications. Recent studies have concluded that solar dish electric systems utilizing reflux receivers integrated with Stirling engines are a promising candidate as future power sources for remote power applications and ultimately for the utility industry. The free-piston Stirling technology currently being developed by NASA for space applications has the potential to meet DOE's long term goals for performance and cost. (Ref 1)

The Stirling Technology Branch at the NASA Lewis Research Center is responsible for a variety of projects which feature the free-piston Stirling engine. Work is being performed to develop the necessary technologies for free-piston Stirling conversion systems under NASA's Civil Space Technology Initiative (CSTI). Further discussion and description of the NASA CSTI program can be found in reference 2. This paper will overview the NASA managed Advanced Stirling Conversion System (ASCS) project which has the potential to meet DOE's performance and long term cost goals.

FREE-PISTON STIRLING ENGINE

The free-piston Stirling engine was invented in 1962 by William Beale at Ohio University. Beale's early work resulted in small-scale fractional-horsepower free-piston Stirling engines which demonstrated the basic operating principles. The major advantage of the free-piston Stirling engine over the kinematic Stirling engine is that it has only a few moving parts (a displacer piston and power piston), can use noncontacting gas bearings and can be hermetically sealed, thereby increasing the potential for high reliability and very long life. Free-piston engines have no mechanical mechanism coupling the reciprocating elements to each other, rather they are coupled through the forces exerted by the working fluid. The engine will resonate at a frequency determined by the combined dynamics of the piston and displacer. A simplified drawing of the free-piston Stirling engine integrated with a linear alternator is shown in figure 1.

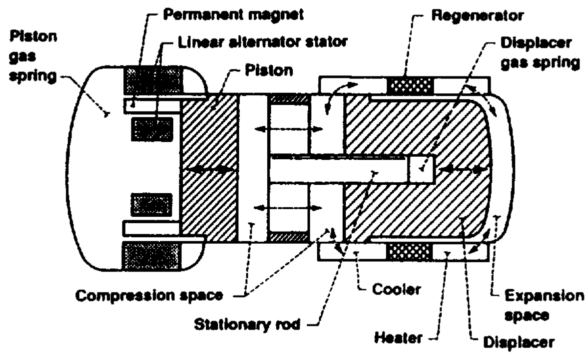

FIGURE 1. - FREE-PISTON STIRLING ENGINE WITH LINEAR ALTERNATOR.

A detailed discussion of the free-piston Stirling engine is contained in reference 3. Only a few organizations in the United States are currently developing free-piston Stirling technology. These include Sunpower Inc. of Athens, Ohio, Mechanical Technology, Inc. (MTI) of Latham, New York, Stirling Technology Company (STC) of Richland, Washington, DOE Oak Ridge National Laboratory and NASA Lewis. Free-piston Stirling engines have been designed and built in power levels ranging from fractional kW up to 25 kW (33 hp). By 1982 a few free-piston engines had been built in the 3- to 4-kW size range. The NASA space power demonstrator engine was designed and built in less than 18 months by MTI, and had delivered more than 22 kW of output power by 1986. Currently, power output of the MTI design is in good agreement with the original predictions at a temperature ratio of 2. Applications of free-piston Stirling systems range from a small implantable heart pumps, to generator sets, heat pumps and cryocoolers.

The major differences between the kinematic and free-piston Stirling engines for the solar application are in the drive and gas systems. The mechanical drive system components (drive shaft, bearings, oil pump, piston rings, crossheads and shaft seals, etc.) and the gas system (the power control system) components (compressor, check valves, storage tank and power control valve, etc.) have wear potential which would reduce engine life in the kinematic configuration. Design life of up to 20 000 hr may be obtained for reciprocating engines such as the kinematic Stirling when modified for a constant speed and load. The free-piston Stirling engine, however has no significant side loads, which minimizes wear mechanisms and allows for long life. The use of noncontacting gas bearings during operation should permit the free-piston conversion system to exceed the 60 000 hr life requirement for the solar application without difficulty. In addition, the free-piston conversion system can be hermetically sealed therefore eliminating the need for a gas makeup system. Further, the free-piston Stirling is oil free, eliminating the problem of the dynamic seals life and concern of regenerator contamination. Analysis has shown the same high brake efficiency as a percentage of Carnot efficiency is expected from either the free-piston or kinematic Stirling configurations. The expected high efficiency, along with the inherently simpler design, make the free-piston Stirling the engine of choice for the long term solar application. These attributes of the free-piston Stirling engine also make it a viable candidate for several terrestrial applications.

Recently Cummins Power Generation (a subsidiary of Cummins Engine Company), of Columbus, Indiana has teamed with Sunpower and Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, has teamed with STC in efforts to commercialize the free-piston Stirling conversion systems. Free-piston Stirling engines are currently under development for the solar terrestrial power application. Both Cummins and Westinghouse have identified a niche market for dish Stirling systems for the worldwide remote electric power applications (Refs. 4 and 5). Power levels required range from 5- to 25- kW. Both organizations believe that successful operation in these niche markets may play a major role in the introduction of Stirling products into the commercial marketplace.

ADVANCED STIRLING CONVERSION SYSTEMS

NASA Lewis is providing management of the ASCS project through a cooperative interagency agreement with the Department of Energy. Cost shared contracts are in place with contractor teams which include manufactures to enhance the free-piston Stirling technology and subsequent commercialization of the ASCS. Contractor teams headed by the Cummins Engine Company and the Stirling Technology Company/Westinghouse completed the preliminary design of each ASCS in late 1989. (Ref. 6)

Each "system" consists of a solar energy receiver, a liquid metal heat transport system, a free-piston Stirling engine, the engine heat rejection system, an alternator or generator either directly or indirectly coupled to the utility grid, and the appropriate controls and power conditioning. The preliminary design completed by the Cummins Team features a heat pipe receiver integrated with a free-piston Stirling engine/linear alternator conversion system (Ref. 7). The STC preliminary design features a reflux boiler receiver integrated with a Stirling engine/hydraulic conversion system (Ref. 8). Each ASCS is designed to mount on, and to receive concentrated solar energy from an 11 m test bed concentrator (TBC) located at the Sandia Test Facility in Albuquerque, New Mexico. The ASCS Project design requirements and the Sandia TBC characteristics are given in reference 9.

DOE's requirements for high efficiency along with long life and high reliability makes the free-piston Stirling engine an ideal candidate for the terrestrial application (Ref. 1). Although the duty cycles for the space and terrestrial applications are quite different, the key technologies are similar. Work is ongoing for the demanding materials requirements which include materials characterization along with and life and reliability predictions for the liquid metal heat transport system and Stirling heater head. Use of noncontacting gas bearings during operation should permit the free-piston Stirling engine to meet or exceed the 60 000 hr life requirement for the solar application. In addition, the conversion system can be hermetically sealed therefore eliminating the need for working gas makeup system typical of kinematic engine systems.

The DOE cost goals are shown in Table I. The receiver and conversion system costs have been combined to provide a total system cost for the ASCS, excluding the concentrator. The ASCS total cost is based on collecting concentrated solar energy into a receiver from an 11 m parabolic dish while providing 25 kW or more electrical power to a utility grid. Based on an independent assessment, both ASCS concepts, have the potential to meet the DOE long term cost goal of $452/kW$_e$ (Ref. 10). A comparison of the Cummins and STC preliminary design is provided in Table II. The expected high efficiency, along with inherently simple design, and potential for lower cost, make the free-piston Stirling the engine of choice for the long term solar application.

CUMMINS ASCS PRELIMINARY DESIGN

Cummins Preliminary Design Team

Cummins Power Generation (CPG), a subsidiary of Cummins Engine Company (CEC), Columbus, IN was responsible for project management and system integration of the free-piston linear alternator concept into the ASCS preliminary design. The Cummins ASCS is shown in Fig. 2. CPG teamed with Thermacore Inc., Lancaster, PA for the heat transport system, and Sanders Associates, Nashua, NH, for the solar receiver. Further, Sunpower Inc., Athens, OH provided the analytical and design experience for the free-piston Stirling conversion system. Cummins Electronic Company, Columbus, IN was responsible for the system controls and power conditioning, while McCord Heat Transfer Corp., Wall Lake, MI, for the external cooling system. Cummins R&D Engineering, Columbus, IN provided expertise for the FMEA, materials and manufacturing technology. Consultants used during the preliminary design process included: Onan Corporation, Minneapolis, MN, (a subsidiary of Cummins) for alternator manufacturing issues and Dr. F. Demofte (University of New Mexico) for gas bearing analysis.

Receiver/Heat Transport System (HTS)

During the conceptual design phase of the ASCS Project, a heat pipe concept was selected to be integrated with the Stirling conversion system. Advantages cited for use of the heat pipe included a small liquid metal inventory along with demonstrated design theory. Concerns identified for the heat pipe technology are high construction cost and the vulnerability of the wicking system to dryout (a single point failure) and subsequent burnout of the receiver.

The receiver/HTS is a single heat pipe on a hemispherical shell as shown in Fig. 3. The heat pipe evaporator is designed to operate continuously, providing heat to the Stirling engine at 700 °C. A nominal insolation of 950 W/m^2 provides about 75 kW of thermal energy while a maximum peak insolation of 1100 W/m^2 provides about 87 kW of thermal energy to the absorber surface. The absorber is a full 180 degree hemisphere with a sintered powder metal wick on the evaporator surface. Inconel 625 was selected as the base material for the absorber and the body of the HTS. The working fluid is high purity sodium. The surface of the evaporator is covered with both a circumferential and a radial artery system. The manufacturing cost at a rate of 10 000 units per year is estimated at $844 in 1984 dollars.

Engine/Linear Alternator System

The Stirling conversion system is a single cylinder free-piston Stirling engine integrated with a linear alternator to directly convert the power generated to electrical energy for the grid. Figure 4 shows a cross section of the engine/linear alternator conversion system. The heater head is designed at operation at 700 °C with an engine operating frequency of 60 Hz. The working fluid is Helium at a mean pressure of 10.5 MPa and the regenerator and cooler have an annular configuration. A single magnet configuration is used for the linear alternator along with internal magnetic springs for centering of the piston. Hydrodynamic gas bearings were designed to allow the use of non-contacting seals which eliminate wear mechanisms during operation. Rotation of the power piston is provided by a induction spin motor at a rotational speed of 30 Hz. A viscous coupling between the power piston and the displacer causes rotation of the displacer. The engine and the linear alternator are contained in a common pressure vessel to allow the conversion system to be hermetically sealed. Neodymium-Iron (28 megagauss) was selected as the permanent magnet material along with oriented silicon steel (M4) for the inner and outer laminations. An active cooling system is incorporated around the stator to assure the proper alternator temperature. A passive cooling system (fluid diodes) has been added to circulate the working gas (helium) around the alternator to insure cooling for the magnets and maintain the cold end of the engine below 80 °C. The linear alternator is connected to a series tuning capacitor and to the grid through an autotransformer. The single phase linear alternator has been designed to provide 26.2 kW_e (nominal) and 31.5 kW_e (peak) to the utility grid. A detailed manufacturing and costing analysis was completed, showing the free-piston Stirling conversion system could be manufactured using existing technology and meeting DOE's current cost goals.

Vibration Absorber

A passive (with no active feedback) vibration absorber was designed for the single piston free-piston Stirling conversion system. The balancer is a spring/mass system with the resonant frequency tuned to the 60 Hz engine operating frequency. The annular mass is coupled to the engine housing with multiple springs.

Cooling System

The heat rejection system is a closed loop system which include a radiator(s), a blower fan(s) and a coolant pump. The circuit is divided into two parallel loops: (1) for the engine cooler and (2) for the alternator stator and uses a single water pump. Based on the ASCS requirements and a trade study by McCord, a cooling system was designed utilizing industrial components which will maximize life and minimize maintenance requirements. The cooling system is dish mounted. A detailed evaluation of the cooling system resulted in a manufacturing cost of $940 per unit in 1984 dollars.

Power Conditioning and Control System

The linear alternator is connected to the utility grid through an autotransformer and a series tuning capacitor. The frequency and autotransformer output voltage are essentially constant and established by the grid. The voltage at the alternator terminals is adjusted to match the changes in power while keeping the heater head temperature (700 °C) at its design point. The series tuning capacitors used to compensate for the internal inductance of the linear alternator assure stable operation of the Stirling conversion system. The controls are designed for fully automatic, unattended operation of the ASCS.

STC ASCS PRELIMINARY DESIGN

STC Preliminary Design Team

STC was responsible for project management, completing the preliminary design of the free-piston Stirling hydraulic concept and system integration. Westinghouse Electric Corporation, Pittsburgh, PA. is the manufacturing partner for STC.

The STC ASCS is shown in Fig. 5. STC teamed with Sanders Associates, Nashua, NH for the solar receiver and Thermacore, Inc., Lancaster, PA for the heat transport system. Westinghouse Electric Corp., Hazard Management Group, Pittsburgh, PA was responsible for an independent FMECA and FTA of the STC ASCS. Consultants used during the preliminary design process were: Saaski Technologies, Inc., Seattle, WA, as a heat transport consultant, Westinghouse Hanford Co, Hanford, WA for the high temperature materials expertise, Gedeon Associates, Athens, OH, for the thermodynamic simulation and General Engineering, Center Line, MI provided an update on the manufacturing and cost analysis for the STC design changes.

Receiver/Heat Transport System (HTS)

During the conceptual design phase of the ASCS Project, STC conducted an extensive trade study for the receiver/heat transport system and selected a reflux boiler. The reflux boiler appears to provide a simple and uniform method for transferring the heat to the Stirling engine (Ref. 11). Disadvantages cited for the pool boiler were the large liquid metal inventory along with the lack of demonstrated design theory. The major technical concern was the inability to predict stable boiling under all operational conditions for this unusual configuration. Subsequent subscale testing by Sandia showed that an enhanced surface could provide nucleation sites resulting in stable boiling (Ref. 12). Recent testing of a full scale boiler by Sandia has shown that stable boiling is achievable (Ref. 12).

The receiver/HTS is a pool boiler as shown in Fig. 6. The reflux boiler evaporator is designed to operate continuously and provides heat to the Stirling engine at 704 °C. A nominal insolation of 950

W/m^2 provides about 75 kW of thermal energy while a maximum peak insolation of 1100 W/m^2 provides about 87 kW of thermal energy to the absorber surface. The working fluid is a eutectic NaK alloy. Inconel 625 has been selected for the absorber and the body of the HTS. Nucleation sites are provided to the evaporator surface by adding a sintered metal wick. Thermacore results are discussed in detail in reference 13. At a production rate of 10 000 units per year the current pool boiler design has the potential to be produced at $459 per unit in 1984 dollars.

Engine/Hydraulic System

The free-piston Stirling hydraulic engine (STIRLIC^{TM}) converts heat delivered to the engine into high pressure hydraulic fluid. A cross section of the STIRLIC^{TM} engine is shown in Fig. 7. The Stirling engine delivers high pressure hydraulic fluid to a commercial pump/motor which is coupled to a commercial induction generator to provide electrical energy to the utility grid. The heater head is designed to operate at 704 °C with an engine operating frequency at 50 Hz. The working fluid is Helium at a mean pressure of 18.3 MPa (2690 psi) which is hermetically sealed through the use of metal bellows seals used in the engine. The metal bellows seals are pressure balanced to ensure long life. The power pistons, the displacer rod and the stabilizer/controller are fully immersed in hydraulic fluid which provides full film lubrication of all sliding parts.

STC and their consultants conducted an extensive materials evaluation and trade study for the heater head assembly. Waspaloy was selected as the heater tube material and Inconel 713LC was selected as the heater head material (Ref. 14) for the prototype engine. Udimet 720 is an alternative material being considered for the heater head. Further, the STIRLIC^{TM} engine conversion system underwent several value engineering improvements to enhance the manufacturability, simplify the design and reduce cost. The Stirling conversion system cost is estimated at $2378 in 1984 dollars.

Hydraulic Pump/Induction Motor

Evaluation of two commercial variable displacement motors resulted in the selection of a high efficiency (93.1 percent) Volvo unit coupled to a commercial rotary induction generator. The three phase induction generator has been sized to provide up to 30.0 kW_e (peak) to the utility grid.

Cooling System

Evaluation of the industrial components required for the cooling system resulted in the selection of a longer life and lower cost heat exchanger (radiator). The conventional (braze joints) radiator which is subject to corrosion from the glycol/water solution is replaced with a commercial radiator (all welded) from Modine Manufacturing Company.

Power Control System and Controls

Automatic regulation of the engine is accomplished via a integral control valve for the hydraulic pump which controls engine speed and balances the heat absorbed from the reflux boiler by the engine. Frequency and voltage are maintained by the utility grid. Power factor (PF) correction has been added to maximize power production at low power levels. Analysis has shown that the addition of 5 KVAR of capacitance to the power conditioning is cost effective for the ASCS and will maintain the PF above 0.85 during all regimes of operation. The ASCS control system will be designed to be fully automatic for unattended operation.

CONCLUDING REMARKS

Both the Cummins and STC Preliminary Designs have met the ASCS Project design requirements. The Cummins ASCS features a heat pipe receiver integrated with a free-piston Stirling engine/linear alternator conversion system. The STC ASCS features a reflux boiler receiver integrated with a free-piston Stirling/hydraulic conversion system. Cummins and Westinghouse have identified a niche market for dish Stirling systems for the worldwide remote electric power applications. Both organizations believe that successful operation in these niche markets may play a major role in the introduction of Stirling products into the commercial marketplace.

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TABLE 1 - DOE COST[a] GOALS

	Current Technology	Long-term Goals
Receiver, dollars/m^2	70	40
Conversion, dollars/kWe	380	300
ASCS total,[b] dollars/kWe	646	452
Energy cost, dollars/kWe	0.13	0.05

a 1984 Dollars.
b Receiver (11-m concentrator) and conversion (nominal 25 kWe) combined.

TABLE II - COMPARISON OF ASCS PRELIMINARY DESIGNS

	CEC	STC
Heat Supplied (peak), kWt	86.8	86.8
Electrical power (peak), kWe	31.5	25.9
Annual Energy, kWh	65 953	57 100
Annual Efficiency, percent	31.8	27.6
Receiver	Heat Pipe	Reflux Boiler
Receiver efficiency, percent	92.0	89.6
Liquid metal	Sodium (Na)	NaK
Heater head temperature, °C (K)	700 (973)	704 (977)
Cooler temperature, °C (K)	60 (333)	54 (327)
Temperature ratio, Th/Tc	2.92	2.99
Efficiency (solar to electric), percent	34.9	29.8
Engine frequency, Hz	60	50
Pressure, MPa (psi)	10.5 (1540)	18.3 (2690)
Working fluid	Helium	Helium
Power conversion	Linear Alternator	Hydraulic pump w/Induction Gen.
Electrical efficiency, percent	94.0	95.0
Electrical output	240 V,1 ϕ	240 V,3 ϕ
Power conditioning	Autotransformer	5 KVAR Capacitance
Controls	Automatic	Automatic
Weight on TBC, kg (lb)	1791 (1740)	864 (1900)
ASCS total cost, 1984 dollars	Under review	6931

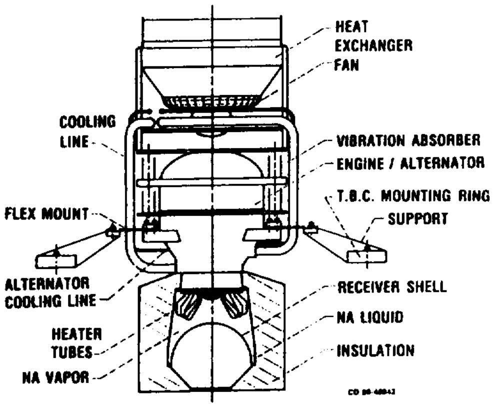

FIGURE 2. - CUMMINS' SINGLE PISTON STIRLING ENGINE ASCS LAYOUT.

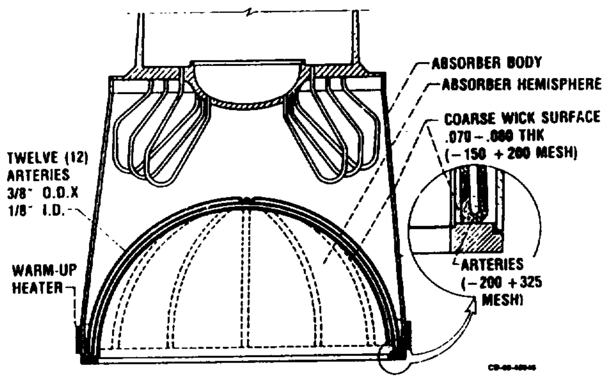

FIGURE 3. - HEAT PIPE RECEIVER/HEAT TRANSPORT SYSTEM.

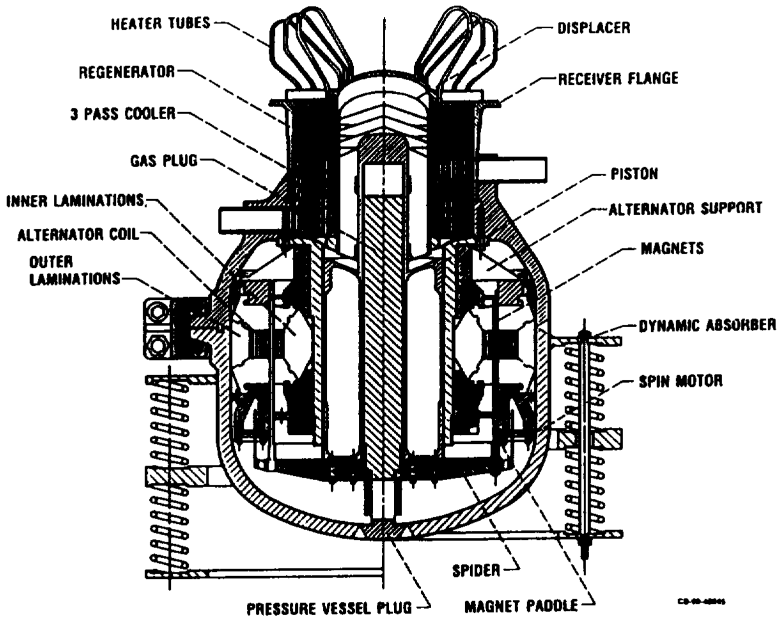

FIGURE 4. - CUMMINS' FREE-PISTON STIRLING/LINEAR ALTERNATOR DETAILS.

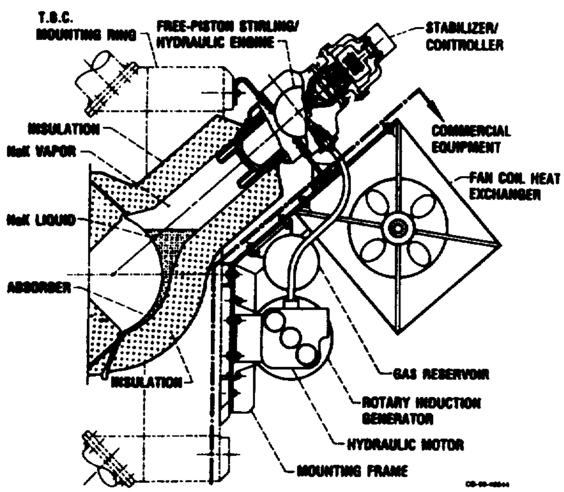

FIGURE 5. - STC'S STIRLING/HYDRAULIC ASCS LAYOUT.

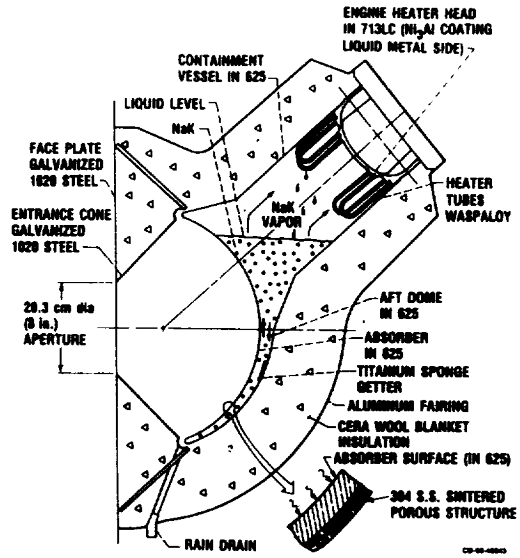

FIGURE 6. - REFLUX BOILER RECEIVER/HEAT TRANSPORT SYSTEM.

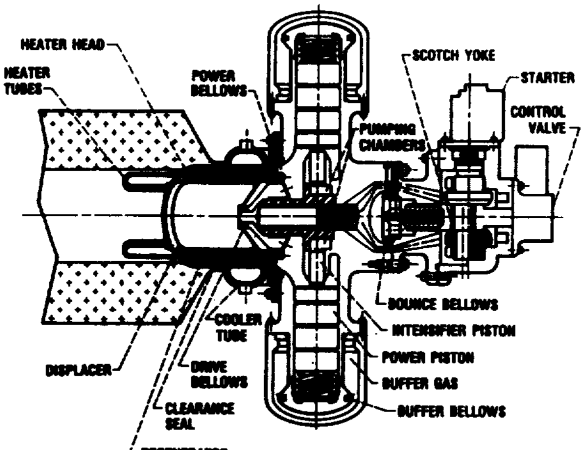

FIGURE 7. - STC'S FREE-PISTON STIRLING/HYDRAULIC DETAILS.