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Preliminary Designs for 25 kWe Advanced Stirling Conversion Systems for Dish Electric Applications

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PRELIMINARY DESIGNS FOR 25 kWe ADVANCED STIRLING CONVERSION SYSTEMS FOR DISH ELECTRIC APPLICATIONS

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SUMMARY

Under the Department of Energy's (DOE) solar thermal technology program, Sandia National Laboratories is evaluating heat engines for terrestrial solar distributed heat receivers. The Stirling engine has been identified by Sandia as one of the most promising engines for terrestrial applications. The Stirling engine also has the potential to meet DOE's performance and cost goals.

The NASA Lewis Research Center is conducting Stirling engine technology development activities directed toward a dynamic power source for space applications. Space power systems requirements include high reliability, very long life, low vibration and high efficiency. The free-piston Stirling engine has the potential for future high power space conversion systems, either nuclear or solar powered. Although both applications appear to be quite different, their requirements complement each other.

NASA Lewis is providing management for the advanced Stirling conversion system (ASCS) project through a cooperative interagency agreement with DOE. Parallel contracts were completed in December 1989 by Cummins Engine Company (CEC), Columbus, IN and Stirling Technology Company (STC), Richland, WA for the preliminary designs of an ASCS. Each design features a free-piston Stirling engine, a liquid metal heat transport system, and a means to provide nominally 25 kW of electric power to a utility grid while meeting DOE's performance and long term cost goals.

The Cummins design incorporates a linear alternator to provide the electrical output, while the STC design generates electrical power indirectly through a hydraulic pump/motor coupled to an induction generator. Both preliminary designs for the ASCS's will use technology which can reasonably be expected to be available in the early 1990's.

INTRODUCTION

The advanced Stirling conversion system (ASCS) project is managed by NASA Lewis Research Center through a cooperative agreement with the Department of Energy. NASA Lewis is currently developing the technology for free-piston Stirling engines for use in space under NASA's civil space technology initiative (CSTI) program (refs. 1 to 3). The free-piston Stirling engine has the potential to be a highly reliable engine with long life because it has few moving parts, noncontacting gas bearings, and can be hermetically sealed. A schematic of the free-piston Stirling engine is shown in figure 1. The discussion in this paper is limited to the ASCS project managed by NASA Lewis.

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. 4). Although the duty cycles for the space and terrestrial applications are quite different, the key technologies are similar. 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. An independent assessment during the conceptual design phase of the ASCS project concluded that free-piston Stirling designs are manufacturable and have the potential to meet DOE's long term cost goals (ref. 5). 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.

ADVANCED STIRLING CONVERSION SYSTEM

NASA Lewis is providing management for the advanced Stirling conversion system (ASCS) project through a cooperative interagency agreement (IAA) with DOE signed in 1985. Two conceptual designs meeting DOE's performance and long term cost goals were completed in 1987 (refs. 6 and 7). Each features a free-piston Stirling engine integrated with liquid metal heat receivers supplying 25 kW of electricity to a utility grid. Cost shared contracts are in place with manufacturers to enhance the free-piston Stirling technology and subsequent commercialization of the ASCS. Contractor teams headed by the Cummins Engine Company (CEC) of Columbus, IN (a free-piston/linear alternator conversion system) and the Stirling Technology Company (STC) of Richland, WA (a free-piston/hydraulic conversion system) completed the preliminary design of each ASCS in November 1989. As part of the PD effort a failure modes and effect analysis (FMEA) was used to identify critical items with their failure modes.

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 the pioneer study, both ASCS concepts, can meet the DOE long term cost goal of $452/kWe (ref. 5).

Each ASCS 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. 8). The STC preliminary design features a reflux boiler receiver integrated with a Stirling engine/hydraulic conversion system (ref. 9).

Both ASCS preliminary designs are considered unique yet complementary to each other. The Cummins design utilizes a heat pipe receiver integrated with the free-piston Stirling conversion system that uses a linear alternator to convert the solar energy to electricity. The STC design uses a reflux boiler receiver integrated with a Stirling hydraulic conversion system generating electricity indirectly using the hydraulic output to a hydraulic/pump motor coupled to a rotating alternator. Each ASCS is being 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, NM. The ASCS project design requirements and the Sandia TBC characteristics are given in reference 10. A comparison of the Cummins and STC preliminary design is provided in table II.

Failure Mode and Effects Analysis (FMEA)

Both contractor teams, Cummins and STC completed FMEA's at the beginning of the preliminary design process. Each ASCS was broken down into general subsystems as follows: (1) the heat transport system, (2) the Stirling conversion system, (3) auxiliaries, (4) controls, and (5) power conditioning. The objective of each analysis was to improve the design by eliminating undesirable characteristics which decrease reliability, life expectancy and increase safety hazards. Additional details on the FMEA's conducted by Cummins and Westinghouse are provided below. In summary, the following general conclusions are offered on the use of FMEA:

(1) The FMEA process is a valuable tool if used early in the design process.

(2) As a result of these analyses numerous constructive recommendations were made for improving manufacturability, reliability, and life expectancy of the developing designs.

(3) A positive interaction resulted from discussions between members (from subsystem and component level) of the designs teams.

(4) The overall system design was improved and recommendations were made which improved the system tolerance to single point failures.

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 figure 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.

Failure Modes, Effects and Criticality Analysis (FMECA)

Cummins conducted a failure modes, effects and criticality analysis (FMECA) on the heat pipe receiver integrated with the free-piston Stirling/linear alternator conversion system. A system (and major subsystems) FMECA was completed during the first month of the PD effort to determine the highest risk(s) which needed to be addressed early in the design phase. Cummins identified five system level failure modes listed below:

(1) Overtemperature of the receiver,
(2) Overpressure of the receiver,
(3) Engine overstroke,
(4) Utility grid contact failure,
(5) Cooling system flow stoppage.

A detailed FMECA at the subsystem and component level was completed during the fifth month of the PD effort completed by the various subcontractors with Cummins providing the training and review of the process. Over 300 failure modes were identified during the detailed evaluation at the component level. Detailed technical issues were identified and corrective actions were implemented during the design process. Cummins asserted that the Solar-Stirling system was amenable to the FMEA process normally utilized with diesel engines and assemblies.

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/heat transport system is a single heat pipe on a hemispherical shell as shown in figure 3. The heat pipe HTS 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° hemisphere with a sintered powder metal wick on the evaporator surface. The absorber diameter has been reduced from 482.4 mm (19.0 in.) to 406.4 mm (16.0 in.). Inconel 625 was selected as the base material for the absorber and the body of the HTS. The working fluid is high purity sodium (less than 10 ppm of O_2). The surface of the evaporator is covered with both a circumferential and a radial artery system. The major change in the HTS is the selection of only one circumferential artery and 12 radial arteries from the conceptual design of two independent and redundant sets (original 8 radial arteries per set). Removal of the redundant artery system was made after a detailed evaluation showed improved structural integrity and reliability, plus manufacturability and cost reduction. While the wick thickness and nickel powder are consistent with the conceptual design, the powered metal pore sizes are different. After detailed analysis, the warmup heater was increased from 160 to 500 W. The manufacturing cost at a rate of 10 000 units per year has increased slightly from $728 to $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 to operation at 700 °C (973 K) 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 MG) 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 kWe (nominal) and 31.5 kWe (peak) to the utility grid.

The major changes from the baseline design include the displacer drive and the linear alternator design. The displacer drive was changed because Cummins manufacturing engineers believe that the baseline displacer tolerances (too tight over the required length) were not practical for low cost manufacturing practices. The linear alternator magnet configuration was changed from an opposed (baseline) magnet to a single magnet based on analysis by Sunpower which showed a significant reduction in fringing fields in vicinity of the alternator for the single magnet configuration. Additional components redesigned include the heater head, regenerator, cooler and linear alternator structure. 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 redesigned 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. The cooling system was evaluated by McCord using the following areas for detailed evaluation: (1) thermal performance, (2) manufacturability, (3) system cost, (4) durability (30 years life), and (5) maintenance requirements. 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 which decreased slightly from $1013 to $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.

The STC ASCS is shown in figure 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.

Failure Mode and Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA)

Westinghouse conducted an independent failure mode and effects and criticality analysis (FMECA) and fault tree analysis (FTA) on the reflux boiler receiver coupled with the free-piston Stirling/hydraulic conversion system. First, a FMECA was performed to identify critical items, their failure modes, as well as identify potential design modifications which might reduce the likelihood of system failure. Over 100 failure modes were identified during the analysis at the component level. Five system level faults were identified by Westinghouse for the STC concept as follows:

(1) Overpressure of the absorber,
(2) Overtemperature of the hydraulic fluid,
(3) Overpressure of the hydraulic system,
(4) Vibration,
(5) Overpressure of the cooling system.

The Westinghouse FTA used the results of the FMECA to identify the event(s) or sequence of events(s) which could result in failure or damage. The FTA evaluated various scenarios which require single and/or simultaneous failures for the identified system events to occur. Design modifications were recommended which improved the system tolerance to single-point failures.

The Westinghouse FMECA and FTA provided valuable data early in the design process which will improve the confidence of the STC prototype ASCS.

Receiver/Heat Transport System

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 from the seven candidate systems evaluated. The reflux boiler appears to provide a simple and uniform method for transferring the heat to the Stirling engine (ref. 7). 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. 11). Recent testing of a full scale boiler by Sandia has shown that stable boiling is achievable (ref. 12). These on-Sun tests were performed for a full scale pool boiler with sodium as the working fluid at temperatures up to 800 °C at the Sandia Test Facility.

The receiver heat transport system is a pool boiler as shown in figure 6. The reflux boiler HTS 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 was changed from potassium to a eutectic NaK alloy, with a melting temperature of -11 °C. The relatively low melting temperature of NaK indicates that auxiliary heaters will be rarely needed to keep the NaK liquid. The absorber is a 508 mm (20.0 in.) diameter, 140° spherical segment. 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. The choice of the alkali metal and the enhanced surface are a result of subscale testing conducted by Thermacore and should result in stable boiling for the current pool boiler design. 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) converts heat delivered to the engine into high pressure hydraulic fluid. A cross section of the

STIRLIC engine is shown in figure 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 (977 K) 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. Reevaluation of the annular and canister regenerator configurations resulted in an annular configuration. Further, the STIRLIC engine conversion system underwent a number of value engineering improvements to enhance the manufacturability, simplify the design and reduce cost. A major change simplified the heater head casting by changing materials from XF818 to Inconel 625 which resulted in lower weight and reduced cost. Other examples of simplification include the power piston which was conceptually a five piece assembly is now a single component, and the main housing which combined three pieces (two cylinders and the pump housing) into a single casting. Evaluation of over 30 proposed changes by General Engineering has resulted in a reduction of the Stirling conversion system cost from $3269 to $2378 in 1984 dollars.

Hydraulic Pump/Induction Motor

Reevaluation 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 kWe (peak) to the utility grid.

Cooling System

Reevaluation 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. A failure mode and effects analysis (FMEA) was completed during the design process of each ASCS. Use of the FMEA during the design process improved the overall system design and tolerance to single-point failures. Each ASCS design underwent value engineering changes to improve manufacturability, simplify the design and reduce cost.

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TABLE I. - 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 kW_e) 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, V	240, 1 ϕ	240, 3 ϕ
Power conditioning	Autotransformer	5 kvar capacitance
Controls	Automatic	Automatic
Weight on TBC, kg (lb)	791 (1740)	864 (1900)
ASCS total cost, 1984 dollars	Under review	6931

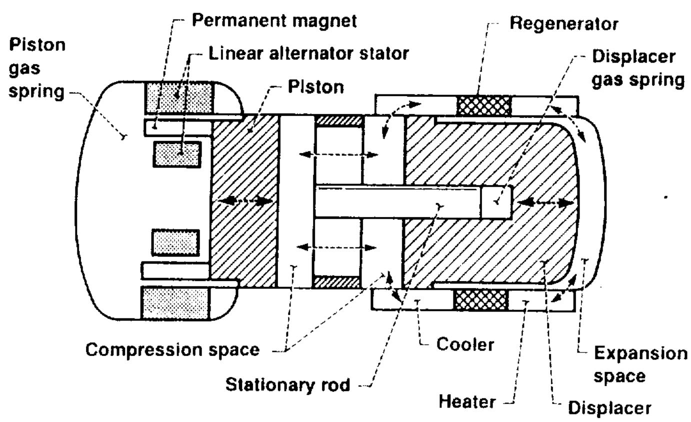

FIGURE 1. - FREE-PISTON STIRLING ENGINE WITH LINEAR ALTERNATOR.

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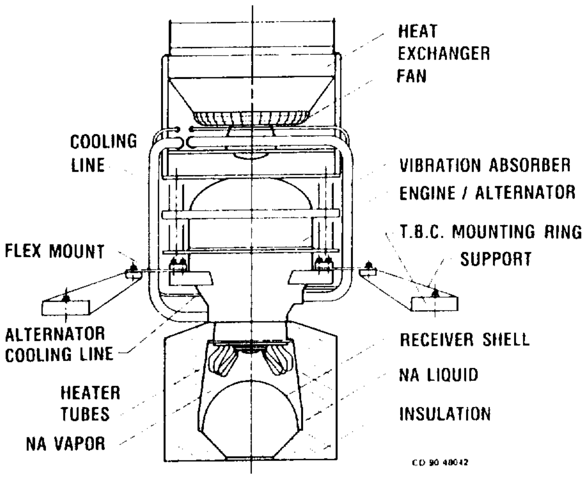

FIGURE 2. - CUMMINS' SINGLE PISTON STIRLING ENGINE ASCS LAYOUT.

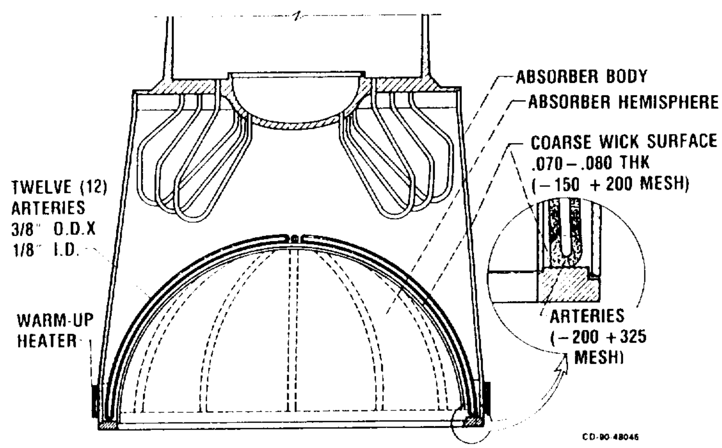

FIGURE 3. - HEAT PIPE RECEIVER/HEAT TRANSPORT SYSTEM.

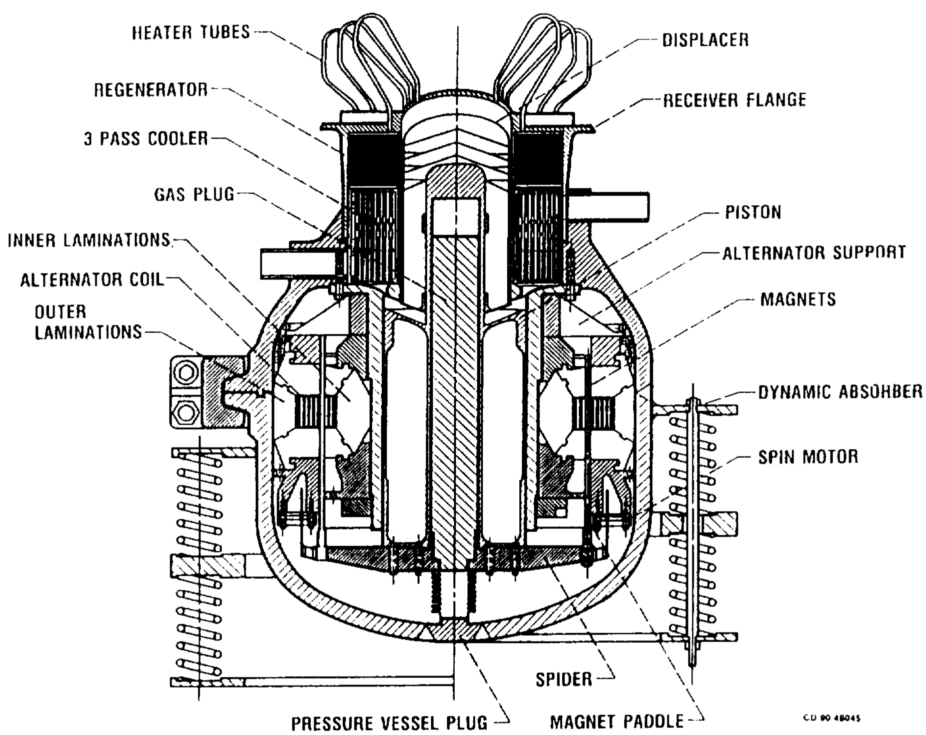

FIGURE 4. - CUMMINS' FREE-PISTON STIRLING/LINEAR ALTERNATOR DETAILS.

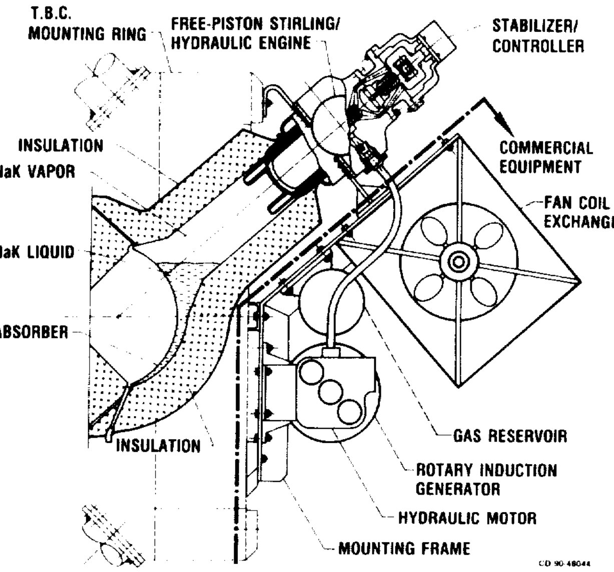

FIGURE 5. - STC'S STIRLING/HYDRAULIC ASCS LAYOUT.

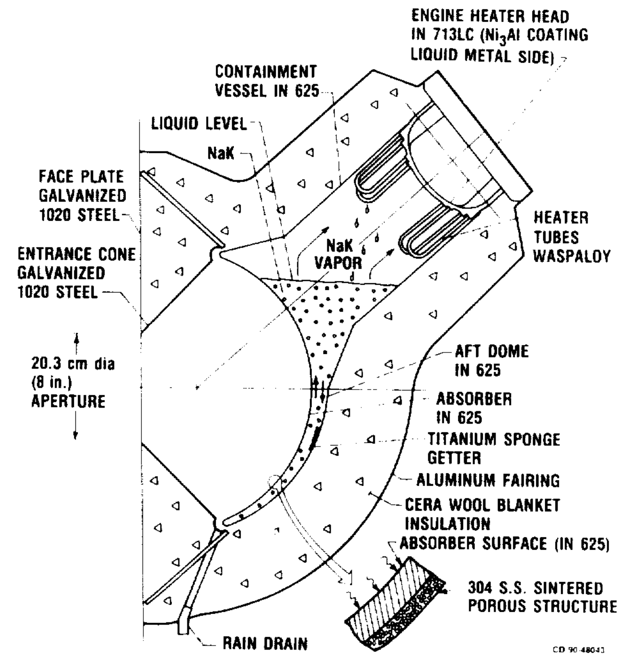

FIGURE 6. - REFLUX BOILER RECEIVER/HEAT TRANSPORT SYSTEM.

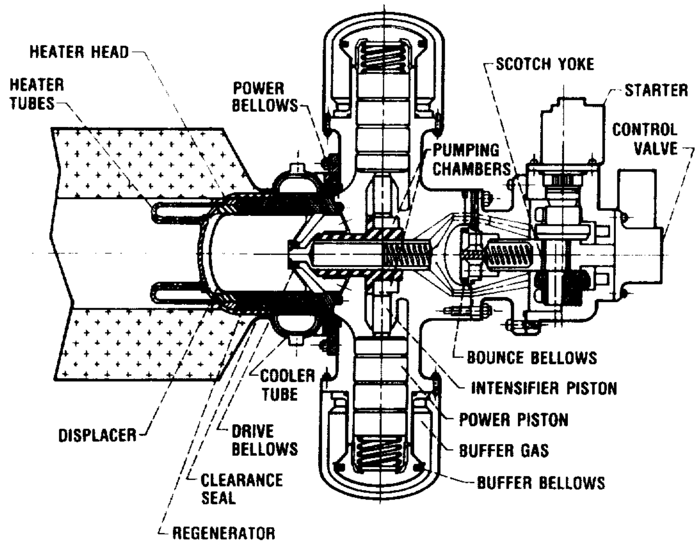

FIGURE 7. - STC'S FREE-PISTON STIRLING/HYDRAULIC DETAILS.

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16. Abstract

Under the Department of Energy's (DOE) Solar Thermal Technology Program, Sandia National Laboratories is evaluating heat engines for terrestrial Solar Distributed Heat Receivers. The Stirling engine has been identified by Sandia as one of the most promising engines for terrestrial applications. The Stirling engine also has the potential to meet DOE's performance and cost goals. The NASA Lewis Research Center is conducting Stirling engine technology development activities directed toward a dynamic power source for space applications. Space power systems requirements include high reliability, very long life, low vibration and high efficiency. The free-piston Stirling engine has the potential for future high power space conversion systems, either nuclear or solar powered. Although both applications appear to be quite different, their requirements complement each other. NASA Lewis is providing management for the Advanced Stirling Conversion System (ASCS) Project through a cooperative Interagency Agreement with DOE. Parallel contracts were completed in December 1989 by Cummins Engine Company (CEC), Columbus, Indiana and Stirling Technology Company (STC), Richland, Washington for the preliminary designs of an ASCS. Each design features a free-piston Stirling engine, a liquid metal heat transport system, and a means to provide nominally 25 kW of electric power to a utility grid while meeting DOE's performance and long term cost goals. The Cummins design incorporates a linear alternator to provide the electrical output, while the STC design generates electrical power indirectly through a hydraulic pump/motor coupled to an induction generator. Both preliminary designs for the ASCS's will use technology which can reasonably be expected to be available in the early 1990's.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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