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CONFERENCE

# **Status of the Advanced Stirling Conversion System Project for 25 kW Dish Stirling Applications**

Richard K. Shaltens and Jeffrey G. Schreiber  
National Aeronautics and Space Administration  
Lewis Research Center

Work performed for  
**U.S. DEPARTMENT OF ENERGY**  
**Conservation and Renewable Energy**  
**Office of Solar Energy Conversion**

Prepared for  
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Boston, Massachusetts, August 4-9, 1991

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# STATUS OF THE ADVANCED STIRLING CONVERSION SYSTEM PROJECT FOR 25 kW DISH STIRLING APPLICATIONS

Richard K. Shaltens and Jeffrey G. Schreiber  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

## 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 heat engines for terrestrial applications. The Stirling engine also has the potential to meet DOE's performance and cost goals (ref. 1).

The NASA Lewis Research Center is conducting technology development for Stirling convertors directed toward a dynamic power source for space applications. Space power requirements include high reliability with very long life, low vibration and high system 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 of the Advanced Stirling Conversion System (ASCS) Project through an Interagency Agreement (IAA) with the DOE. Parallel contracts continue with both Cummins Engine Company (CEC), Columbus, Indiana and Stirling Technology Company (STC), Richland, Washington for the designs of an ASCS. Each "system" design features a solar receiver/liquid metal heat transport system, and a free-piston Stirling convertor with 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 free-piston Stirling convertor incorporates a linear alternator to directly provide the electrical output, while the STC design generates electrical power indirectly through a hydraulic pump/motor coupled to an induction generator. Both the Cummins and STC ASCS designs 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 an Interagency Agreement (IAA) with the Department of Energy (DOE). NASA Lewis is currently developing the technology for Stirling convertors for use in space (ref. 2). The Stirling convertor, which features a free-piston engine directly integrated with a linear alternator, has the potential to be a highly reliable machine with long life because it has only a few moving parts, uses noncontacting clearance seals, and can be hermetically sealed. Free-piston engines have no mechanical coupling of the reciprocating components (the displacer piston and the power piston); rather they are coupled through the forces exerted by the working fluid. The moving components resonate at a frequency determined by the combined dynamics of the convertor and load. No significant side loads exist for the moving components, which minimizes potential wear mechanisms, and allows for the use of the noncontacting clearance seals, and enhances the capacity for long life. Further, the free-piston Stirling is oil free, eliminating the

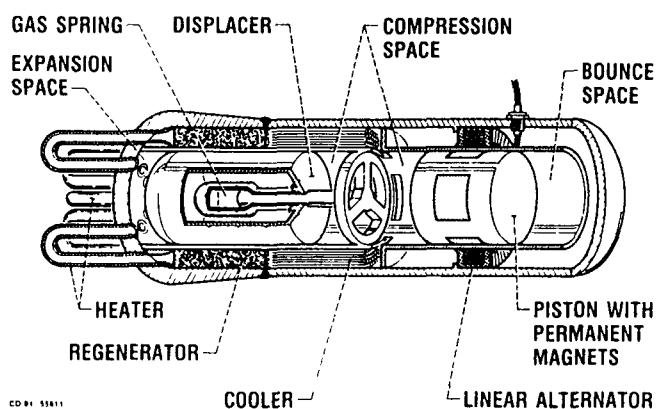


Figure 1.—Free-piston Stirling engine with linear alternator.

problem of dynamic oil seals and concern of regenerator contamination. A simplified drawing of a Stirling convertor showing a free-piston engine integrated with a linear alternator is shown in figure 1. A detailed discussion of the free-piston Stirling engine is contained in reference 3. The discussion of this paper is limited to the ASCS Project managed by NASA Lewis.

## Advanced Stirling Conversion System (ASCS) Project

NASA Lewis is providing management of the ASCS Project through an IAA with the DOE. Cost shared contracts are in place with contractor teams which include manufacturers to enhance the free-piston Stirling convertor technology with subsequent commercialization of the ASCS for the solar thermal market. Two preliminary designs meeting DOE's performance and cost goals were completed in 1989 (ref. 4). The contractor teams headed by Cummins Engine Company and the Stirling Technology Company/Westinghouse partnership continue with each of the ASCS designs.

Each ASCS consists of an overall "system" design which includes the following major subsystems: (1) a solar receiver, (2) a liquid metal heat transport system, (3) a free-piston Stirling convertor with an alternator or generator either directly or indirectly driven, and coupled to the utility grid, (4) a heat rejection system, and (5) appropriate controls and power conditioning. The Cummins ASCS design integrates a heat pipe receiver with a Stirling convertor which features a free-piston engine/linear alternator system. The STC ASCS design integrates a reflux boiler receiver with a Stirling convertor which features a free-piston engine/hydraulic output system. 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 solar receiver is designed for a nominal insolation value of 950 W/m<sup>2</sup> providing about 75 kW of thermal energy, while a peak insolation value of 1100 W/m<sup>2</sup> provides about 87 kW of thermal energy to the absorber surface. The ASCS Project design requirements and the Sandia TBC characteristics are given in reference 5.

DOE's requirements for high "system" efficiency, along with the potential for high reliability and long life makes, the free-piston Stirling convertor 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 life and reliability predictions for the liquid metal heat transport system and the Stirling heater head. Use of noncontacting clearance seals during operation eliminates potential wear problems of conventional seals, and should permit the free-piston Stirling convertor to meet or exceed the

60 000 hr life requirement for the solar thermal application. Further, the Stirling convertor can be hermetically sealed, eliminating the need for a working gas make-up system typical of kinematic Stirling systems.

The DOE cost goals are shown in table I. The receiver and the conversion systems costs have been combined to provide a total *system* cost for the ASCS, excluding the concentrator. The ASCS total *system* cost includes all the major subsystems previously described above which result in a minimum overall cost for converting solar energy to electricity for the utility grid. 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 into a utility grid. Based on an independent assessment, both ASCS concepts, have the potential to meet DOE's "long-term" cost goal of \$452/kWe (ref. 6). The expected high efficiency coupled with the inherently simple design of the free-piston Stirling convertor and the potential for lower first cost and elimination of operation and maintenance (O&M) costs, make the free-piston Stirling convertor the system of choice for the long term solar application.

TABLE I. - DOE COST<sup>a</sup> GOALS

	Technology	
	Current	Long-term
Receiver, dollars/m <sup>2</sup>	70	40
Conversion, dollars/kWe	380	300
ASCS total, <sup>b</sup> dollars/kWe	646	452
Energy cost, dollars/kWe	0.13	0.05

<sup>a</sup>1984 dollars.

<sup>b</sup>Receiver (energy from a 11-m concentrator) and conversion systems (nominal 25 kWe) combined.

## Cummings ASCS Design

### Cummins ASCS Design Team

Cummins Power Generation (CPG), a subsidiary of Cummins Engine Company, Columbus, Indiana is responsible for project management and system integration of the free-piston Stirling convertor for the ASCS design. During 1990 the Cummins Team, under the technical direction of Cummins Electronics Company (CEL), continued work on the preliminary design phase (updating the November 1989 preliminary design (PD) (ref. 7)) of the Cummins ASCS, with focus on value engineering and manufacturing changes along with cost reduction for the Stirling convertor, power conditioning and control systems (ref. 8). The receiver, heat transport system and external cooling system designs remained unchanged during the 1990 update. The Cummins ASCS is designed to operate at 700 °C and deliver about 24 kW of single phase electrical power to a utility grid. The ASCS is shown in figure 2 and key parameters are shown in table II. Further, the Cummins design is manufacturable, and the ASCS when

produced at the rate of 10 000 units per year is estimated at \$11 200 (about \$450/kWe) in 1984 dollars.

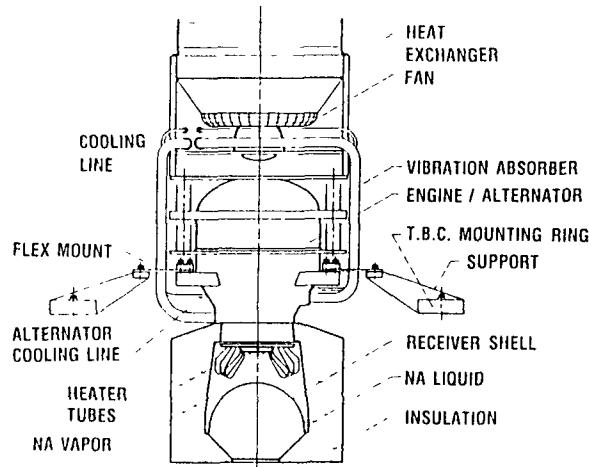


Figure 2.—Cummins' ASCS layout with free-piston Stirling convertor.

TABLE II.—CUMMINS ASCS “UPDATED” PRELIMINARY DESIGN REVIEW

Heat pipe receiver free-piston/linear alternator convertor	
Heat supplied (peak), kWt	86.8
Electrical power (peak), kWe	28.1
Heat supplied (nominal), kWt	75.0
Electrical power (nominal), kWe	23.9
Heater head temperature, °C (K)	700 (973)
Cooler temperature, °C (K)	60 (333)
Engine frequency, Hz	.60
Pressure, MPa (psi)	10.5 (1520)
Working fluid	Helium
Weight on TBC, kg (lb)	713 (1570)
Annual energy, kWh	59 958
ASCS total cost, 1984 dollars	11 193

CPG teamed with Sanders Associates, Nashua, NH, for the solar receiver and Thermacore Inc. Lancaster, PA for the heat pipe technology and the heat transport system. Further, Clever Fellows Innovation Consortium (CFIC), Melrose, NY provided the analytical, design and hardware experience for the free-piston Stirling engine. The thermodynamic simulation model used was GLIMPS 3.0 from Gedeon Associates, Athens, OH. Cummins Power Generation, Columbus, IN provided expertise for the manufacturing technology, cost analysis and FMEA. Two subsidiaries of Cummins contributed to the ongoing design effort: Cummins Electronics Company (CEL), Columbus, IN, was responsible for overall system controls and the power conditioning, while McCord Heat Transfer Corp., Wall Lake, MI, was responsible for the external cooling system. Consultants used during the design process included: Onan Corporation, Minneapolis, MN (a subsidiary of Cummins), for alternator manufacturing issues, Dr. S. Nasar, University of Kentucky for the linear alternator analysis, power conditioning and controls and Dr. F. Demofte, Magnebit, Inc., San Diego, CA., for a gas bearing model and analysis.

## Heat Pipe Receiver and Heat Transport System (HTS)

The earlier design for the heat pipe receiver and heat transport system (HTS), reported at the November 1989 PDR, remains unchanged. Figure 3 shows a single heat pipe with a

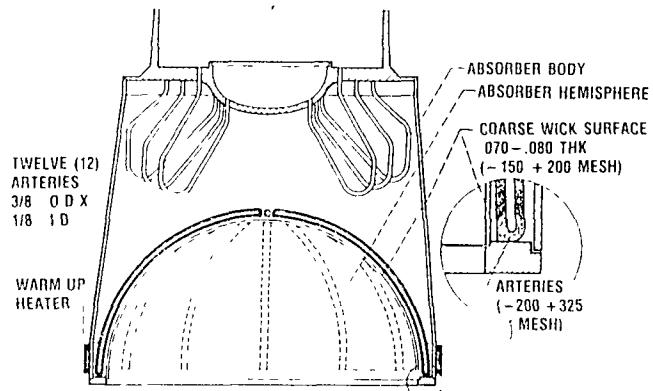


Figure 3.—Heat pipe receiver/heat transport system

hemispherical absorber (or evaporator). The heat pipe evaporator is designed to operate continuously, providing heat to the Stirling convertor at 700 °C (973 K). The absorber is a full 180° 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 evaporator wick utilizes both a circumferential and a radial artery system. While the use of a heat pipe receiver for the heat transport system should minimize local hot spots and provide more uniform heating to the Stirling heater head, concerns remain for the structural integrity and reliability (potential of a single point failure) of the artery system. A warmup heater is included to maintain the sodium in a liquid state prior to startup. The manufacturing cost at a rate of 10 000 units per year is estimated at \$844 in 1984 dollars for the preliminary design reviewed in November 1989 (ref. 7).

Use of Inconel 625 as the base material will have to be reexamined due to the potential for structural instability of Inconel 625 when exposed to elevated temperatures for long durations. Further, based on reports from Cummins with their “on-sun” heat pipe receiver experience, delamination of the wicking structure and artery radial system remains a concern, and alternatives need to be evaluated (ref. 9).

Thermacore is conducting long term tests to evaluate various candidate combinations of heat pipe materials and to establish reliability for the wick and artery structure with Sodium environment at 700 °C (973 K). The radial heat flux to each test capsule is estimated at 8 W/cm<sup>2</sup>. Material combinations include Inconel 601 and 713LC with two candidate braze alloys (BNi-2 and BNi-5) to a nickel wick structure. The baseline (10 hr) and 1000 hr tests have been completed and are being evaluated by Lewis materials specialists. The long term 10 000 hr tests are expected to be complete early in 1992 (ref. 10).

## Stirling Convertor - Free-piston Stirling/Linear Alternator System

The Cummins Stirling convertor is a single cylinder free-piston Stirling engine integrated with a linear alternator to directly convert the thermal energy (in the Stirling cycle) into electrical energy for the grid. The heater head is designed to operate 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 with the regenerator and cooler having annular type configurations. The cooler temperature is 60 °C (333 K). Hydrodynamic gas bearings were designed to allow use of noncontacting clearance seals which eliminate wear mechanisms during operation to ensure long life.

As shown in figure 4, the free-piston/linear alternator convertor consists of two major components: the displacer and

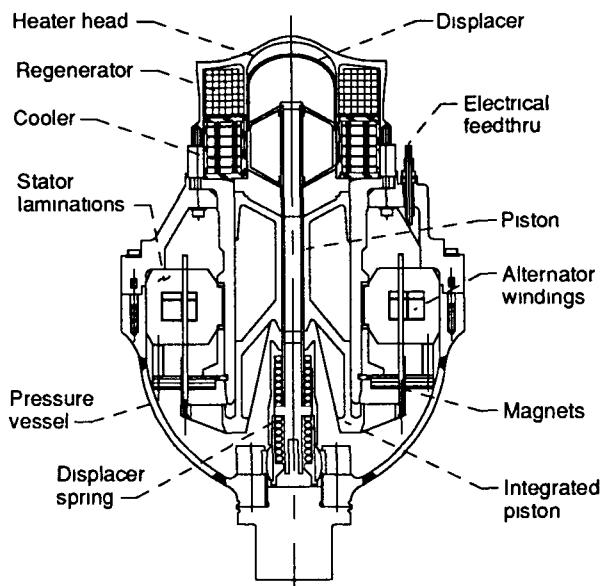


Figure 4 —Cummins' free-piston Stirling with linear alternator output

power piston. The displacer has a central rod extending through the power piston with mechanical springs attached in the bounce space. The stiffness of these springs is sufficient to resonate the displacer while also performing the task of conventional centering ports. This feature eliminates losses associated with the displacer gas spring hysteresis and centering port pumping while also reducing cost. During operation, the displacer is subject to damping which originates primarily from the heat exchanger losses. Displacer damping added by the control system is in addition to this inherent damping, and is used to modulate the displacer stroke. Varying the dynamics of the displacer allows the control system to vary the convertor power output.

The Stirling convertor, which contains the free-piston engine and linear alternator in a common pressure vessel, is hermetically sealed. Neodymium-Iron (28 mg) was previously selected as the permanent magnet material along with

oriented silicon steel (M4) for the inner and outer lamination (ref. 7). Additional analysis by Cummins has shown that the net circulation of the internal working fluid (helium) that passes by the alternator is sufficient to insure cooling of the permanent magnets. Heat is removed from the alternator by the engine cooler with the compression space temperature being increased by about 1 °C. The linear alternator is connected to a series tuning capacitor which in turn is connected to the grid. The Stirling convertor, with the single phase linear alternator has been designed to provide 23.9 kWe (nominal) and 28.1 kWe (peak) to the utility grid. However, the Stirling convertor was not optimized due to a NASA requirement to maintain the overall pressure vessel dimensions and linear alternator configuration from the November 1989 PD. Cummins completed a detailed manufacturing and cost analysis, showing the Stirling convertor could be manufactured using existing technology while meeting DOE's long term cost goals. The manufacturing rate for the Stirling convertor (including the engine and linear alternator) at 10 000 units per year is estimated at \$8135 per unit in 1984 dollars.

## Cooling System

The earlier design for the heat rejection system, reported at the November 1989 PDR, remains unchanged. The closed loop external cooling system includes: a radiator(s), a blower fan(s) and a coolant pump. The cooling circuit is divided into two parallel loops: (1) for the engine cooler and (2) for the alternator stator and uses a single pump. The cooling system is dish mounted. Based on the ASCS requirements and a trade study by McCord, the cooling system was designed utilizing industrial components which will maximize life and minimize maintenance requirements. A detailed evaluation of the cooling system resulted in a manufacturing cost of \$940 per unit in 1984 dollars (ref. 7).

Because of the Cummins analysis during the PD update of the internal cooling of the linear alternator permanent magnets, a change for the cooling system specifications has resulted, and a redesign is required.

## Power Conditioning and Control System

During the updated preliminary design phase of the ASCS, conducted in 1990, an extensive trade study for the power conditioning and the control system was conducted. Three cases were examined by CEL: (1) a motorized transformer (baseline), (2) a solid state invertor, and (3) internal power modulation with displacer damping. System analysis was completed for each case to evaluate cost, efficiency, failure modes and reliability. The internal power modulation control system was selected where the linear alternator is connected to the utility grid through a series tuning capacitor. Further, system modeling and simulation were completed for the motorized transformer to evaluate the dynamic behavior of

the receiver and convertor in response to perturbations in insulation or, grid voltage, and to electromagnetic noise in the control system (ref. 11).

The controls are fully automatic, to allow unattended operation for the ASCS. The controls and power conditioning system cost was significantly reduced from \$3353 to \$676 per unit in 1984 dollars when produced at a rate of 10 000 per year.

## STC/Westinghouse ASCS Design

### STC/Westinghouse ASCS Design Team

Stirling Technology Company (STC), Richland, WA is responsible for project management and completing the final design of the ASCS with a Stirling convertor which features the free-piston/hydraulic system. The final design of the "engineering prototype" for STC's ASCS was completed in February 1991. Specifications for the "engineering prototype" to be operated on the Sandia TBC include 5000 hr of operation with 1000 start/stop cycles and the capability to operate at 800 °C (1073 K) for up to 100 hr. Manufacturing, value engineering and cost analysis task for the "production" ASCS was deferred (refs. 12 and 13). Westinghouse Electric Corp., Pittsburgh, PA, is the manufacturing and marketing partner for STC. The STC/Westinghouse ASCS is designed to operate at 704 °C (977 K) and to deliver about 22 kW of three phase electrical power to a utility grid. The STC ASCS is shown in figure 5 with the key parameters shown in table III.

STC teamed with Kesseli Associates, Mount Vernon, NH for the solar receiver and Thermacore, Inc. Lancaster, PA for the pool boiler and heat transport system design. Consultants used during the final design process were: Saaski Technologies, Seattle, WA, as a heat transport consultant, Westinghouse Hanford Co., Hanford, WA for high temperature

TABLE III STC/WESTINGHOUSE ASCS "ENGINEERING PROTOTYPE" FINAL DESIGN REVIEW

Reflux boiler receiver free-piston/hydraulic output convertor	
Heat supplied (peak), kWt	86.8
Electrical power (peak), kWt	26.7
Heat supplied (nominal), kWt	75.0
Electrical power (nominal), kWt	22.1
Heater head temperature, °C (K)	704 (977)
Cooler temperature, °C (K)	54 (327)
Engine frequency, Hz	26.2
Pressure, MPa (psi)	18.3 (2650)
Working fluid	Helium
Weight on TBC, kg (lb)	1130 (2490)
ASCS total cost, 1984 dollars	Not applicable

materials expertise, Westinghouse Electric Corp., Pittsburgh, PA for system controls and power conditioning design, and Gedeon Associates, Athens, OH, for the thermodynamic simulation model using GLIMPS 3.0.

### Reflux Boiler Receiver and Heat Transport System (HTS)

The STC design for the reflux boiler receiver is integrated with the HTS as shown in figure 6. The refluxing evaporator is designed to operate continuously and provides heat to the Stirling convertor at 704 °C (977 K). The absorber is a 140° spherical segment, with nucleation sites being provided to the evaporator surface by the addition of a sintered metal structure. The maximum heat flux is estimated at 46 W/cm<sup>2</sup>. Inconel 625 was replaced with Inconel 617 for the absorber and the body of the HTS. It has been reported by Carpenter Technology Corp. that Inconel 625 and Inconel 625 PLUS when exposed [to temperatures] at 650 to 760 °C for extended periods of time has "resulted in extensive grain boundary precipitation and a large reduction in Charpy V-notch impact energy" accompanied by a "smaller reduction in tensile du-

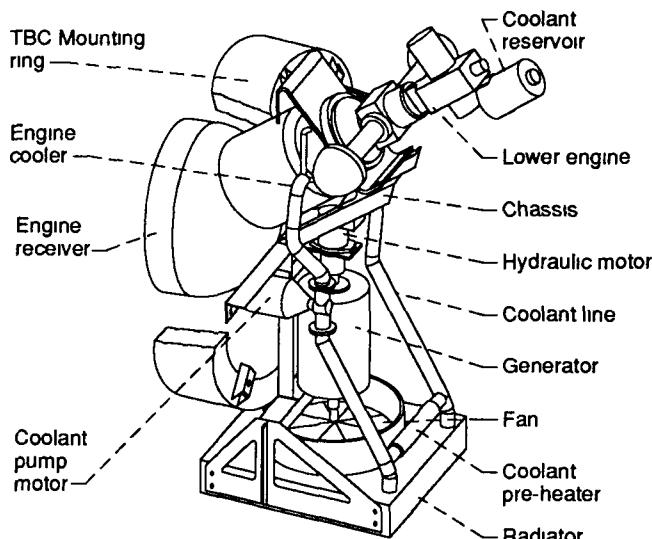


Figure 5 —STC's ASCS with free-piston Stirling convertor

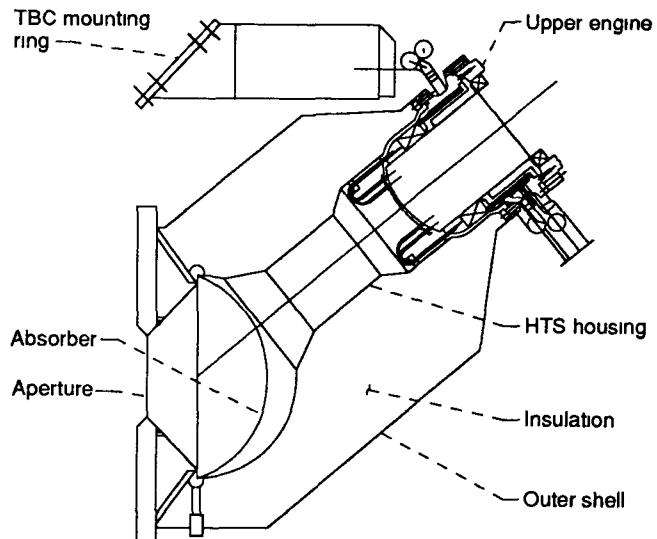


Figure 6 —STC's reflux boiler receiver/heat transport system

tility" (ref. 14). STC's final design for the reflux boiler receiver and heat transport system are discussed in detail by Thermacore in reference 15.

An 800 hr subscale life test was conducted by Thermacore to verify that the pool boiling remained stable as the HTS aged. The subscale pool boiler was operated at about 700 °C (973 K) with NaK as the working fluid. The test apparatus used an enhanced boiling surface, a stainless steel mesh (-100, +400) with representative heat fluxes at the evaporator of between 40 and 60 W/cm<sup>2</sup>. The life test included a total of 82 cold starts, to simulate start-up each morning, and 60 warm restarts, to simulate cloud cover transients. No observable changes were noted by Thermacore during the 800 hr life test as reported in reference 16.

### Stirling Convertor - Free-piston Stirling/Hydraulic Output

The STC Stirling convertor, is a free-piston Stirling engine which converts heat into high pressure hydraulic fluid. The Stirling convertor delivers the high pressure hydraulic fluid to a commercial rotary pump/motor which is coupled to a commercial induction generator to provide electrical power to the utility grid. The working fluid is helium at a mean pressure of 18.3 MPa. The working gas volume is hermetically sealed through the use of metal bellows seals used in the engine. The engine was optimized to operate at 704 °C (977 K) and a frequency of 26.2 Hz. The metal bellows seals are pressure balanced to ensure long life. Udimet 720 has been selected for the "engineering prototype" heater head with Waspaloy for the 60 tubes. Brunswick Random Fiber (wire diameter 0.001 in.) was selected for the annular regenerator. The cooler temperature is 54 °C (327 K). The annular cooler is a tube and shell configuration and has 192 tubes. A clearance seal is utilized for the displacer, to eliminate the potential of seal wear, and provide for long life. The displacer rod, power pistons, and the stabilizer/controller are fully immersed in hydraulic fluid which provides full film lubrication of all sliding parts.

As shown in figure 7, the free-piston/hydraulic convertor consists of three major components: the displacer, the stabilizer module, and the power pistons. The displacer is coupled to the stabilizer module (a Scotch yoke/gas spring assembly) by a hydraulic link. The Scotch yoke provides control of the displacer amplitude with power being transmitted through the mechanism only during start-up. A flow control valve has been placed in the hydraulic circuit to regulate the power output of the engine. The control valve induces damping on the displacer in addition to that derived from the heat exchanger flow losses. Unlike a typical free-piston/linear alternator convertor, the free-piston/hydraulic convertor operates at a frequency significantly below the resonant frequency of the power piston. Variation of the displacer damping will alter the operating frequency of the free-piston/hydraulic

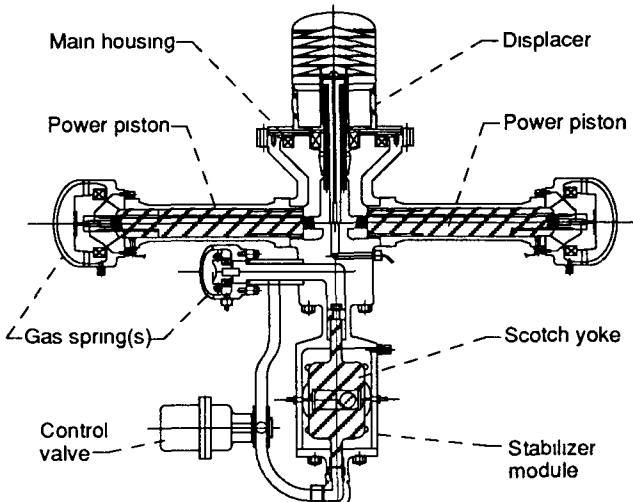


Figure 7 —STC'S free-piston Stirling with hydraulic output.

convertor and the power piston amplitude, with the displacer amplitude remaining fixed.

STC is conducting long term compatibility tests to evaluate various candidate combinations of heater head and tube materials in a NaK environment at 700 °C (973 K). The heat flux to each test capsule is estimated at 32 W/cm<sup>2</sup>. Material combinations include 713LC, coated with nickel aluminide and uncoated, and Udimet 720CR uncoated, each with Waspaloy and Nicrobraze 130, respectively. A unique braze joint, designed by STC to minimize the corrosion of the braze material, was incorporated in the test capsules. The six long term 10 000 hr tests are expected to be completed during the summer of 1991. The baseline (10 hr) and three 1000 hr tests have been completed by STC and evaluated by Lewis materials specialists and reported to have little or no corrosion as discussed in reference 17.

### Hydraulic Pump/Induction Motor

Commercial equipment has been identified for the hydraulic and electrical system for the STC ASCS. A highly efficient (over 93 percent) Volvo bent-axis variable displacement motor is coupled directly to a Kato rotary induction generator. The STC ASCS has been designed to provide 22.1 kWe (nominal) and 26.7 kWe (peak) to the utility grid. The three phase induction generator has been sized to deliver up to 30 kWe (peak) to the utility grid.

### Cooling System

The dish mounted cooling system is a closed loop system, consisting of the following commercial components: a Young radiator and fan/motor, a Teel coolant pump/motor, and a Young pumped oil heat exchanger, a coolant pre-heater and an expansion tank. Temperature control is independently pro-

vided to three parallel circuits which share the common radiator and pump as follows: (1) the upper engine (internal Stirling cooler), (2) the lower engine (external hydraulic cooler), and (3) the external hydraulic oil heat exchanger. The coolant is a 50/50 water glycol mixture and is maintained at a slight pressure to prevent evaporation.

### Power Conditioning and Control System

Automatic regulation of the engine is accomplished via an integral control valve in the displacer drive circuit. This valve controls engine speed to match the heat absorbed from the reflux boiler with the heat requirements of the engine. Frequency and voltage regulation are maintained by the electric utility grid. Power factor (PF) correction has been added to maximize power production at the low power levels. Analysis has shown that the addition of 5 kvar of capacitive reactance for 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 is designed to be fully automatic for unattended operation.

### Concluding Remarks

Both the Cummins and STC/Westinghouse ASCS designs are continuing. The Cummins ASCS features a heat pipe receiver coupled with a free-piston Stirling engine integrated with a linear alternator. The STC ASCS features a reflux boiler receiver coupled with includes a free-piston Stirling engine integrated with a hydraulic output. The free-piston Stirling convertor, which can be hermetically sealed, and uses noncontacting clearance seals, has the potential to meet or exceed the 60 000 hr life requirement for the solar thermal application. The expected high efficiency coupled with the inherently simple design of the free-piston Stirling convertor and the potential for lower cost and elimination of O&M costs, make the free-piston Stirling convertor the system of choice for the long term solar application.

Cummins and Westinghouse have identified a niche market for dish Stirling systems for worldwide remote power applications and for the future electric utility market. Both organizations believe that successful operation in these remote niche markets may play a major role in the introduction of Stirling products into the commercial marketplace.

### References

1. Stein, W.B.: Progress in Parabolic Dish Technology. SERI/SP-220-3237, 1989.
2. Dudenhoefer, J.E.: Programmatic Status of NASA's CSTI High Capacity Power Stirling Space Converter Program. NASA TM-103142, 1990.

3. Walker, G.: Stirling Cycle Machines. Clarendon Press, Oxford, 1973, pp. 121-127.
4. Shaltens, R.K.; and Schreiber, J.G.: Preliminary Designs for 25 kWe Advanced Stirling Conversion Systems for Dish Electric Applications. NASA TM-103188, 1990.
5. Shaltens, R.K.: Advanced Stirling Conversion System for Terrestrial Applications. NASA TM-88897, 1987.
6. Shaltens, R.K.; and Schreiber, J.G.: Comparison of Conceptual Designs for 25 kWe Advanced Stirling Conversion Systems for Dish Electric Applications. NASA TM-102085, 1989.
7. Cummins Engine Company, Preliminary Design Review held at the NASA Lewis Research Center, Cleveland, Ohio. Nov. 2 & 3, 1989.
8. Cummins Engine Company, "Updated" Preliminary Design Review held at the NASA Lewis Research Center, Cleveland, OH, Apr. 9 & 10, 1991.
9. Heat Transport System Workshop, held at Thermacore, Inc., Lancaster, PA., Nov. 13-14, 1990.
10. Letter from Thermacore, Inc., Lancaster, PA. (J. R. Hartenstein), to NASA Lewis Research Center (R. K. Shaltens) dated Jan. 31, 1991.
11. Rosswurm, M.A.: "Modeling and Simulation of the Thermal Control System for the 25 KW Advanced Stirling Conversion System," Vol. 5, 26th IECEC, Boston, MA, Aug. 4-9, 1991, pp. 331-336.
12. Stirling Technology Company, Final Design Review for "Engineering Prototype" held at the NASA Lewis Research Center, Cleveland, OH, Feb. 20-22, 1991.
13. Wallace, D.A., et al.: Final Design of an Free-piston Hydraulic Advanced Stirling Conversion System. Vol. 5, 26th IECEC, Boston, MA, Aug. 4-9, 1991, pp. 349-354.
14. Letter from Carpenter Technology Corp., Reading, PA. (Dr. J.M. Dahl) to NASA Lewis Research Center, Cleveland, OH, (Dr. T. Grobstein), dated Feb. 18, 1991.
15. Anderson, W.A., et al.: Design of a Pool Boiler Heat Transport System for a 25 kWe Advanced Stirling Conversion System. Vol. 5, 26th IECEC, Boston, MA, Aug. 4-9, 1991, pp. 343-348.
16. Anderson, W.G., et al.: Alkali Metal Pool Boiler Life Tests for a 25 kWe Advanced Stirling Conversion System. Vol. 5, 26th IECEC, Boston, MA, Aug. 4-9, 1991, pp. 376-381.
17. Noble, J.E. et al., "Alkali Compatibility Testing of Candidate Heater Head Materials for a Stirling Engine Heat Transport System," Vol. 6, 26th IECEC, Boston, MA, August 4-9, 1991, pp. 166-170.



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## Report Documentation Page

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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 heat 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 technology development for Stirling convertors directed toward a dynamic power source for space applications. Space power requirements include high reliability with very long life, low vibration and high system 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 of the Advanced Stirling Conversion System (ASCS) Project through an Interagency Agreement (IAA) with the DOE. Parallel contracts continue with both Cummins Engine Company (CEC), Columbus, Indiana and Stirling Technology Company (STC), Richland, Washington for the designs of an ASCS. Each "system" design features a solar receiver/liquid metal heat transport system, and a free-piston Stirling convertor with 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 free-piston Stirling convertor incorporates a linear alternator to directly provide the electrical output, while the STC design generates electrical power indirectly through a hydraulic pump/motor coupled to an induction generator. Both the Cummins and STC ASCS designs will use technology which can reasonably be expected to be available in the early 1990's.			
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