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Comparison of Stirling Engines for Use With a 25-kW Dish-Electric Conversion System

Richard K. Shaltens
National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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Prepared for the
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E-3655

SUMMARY

The Department of Energy's (DOE) Solar Thermal Technology Program, Sandia National Laboratories (SNLA), is evaluating heat engines for terrestrial solar distributed heat receivers. The Stirling engine has been identified by SNLA as one of the most promising engines for terrestrial applications. The potential to meet DOE's goals for performance and cost can be met by the free-piston Stirling engine.

NASA Lewis Research Center is conducting Stirling activities directed toward a dynamic power source for the space application. 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, terrestrial and space power, appear to be quite different, their requirements complement each other.

NASA Lewis is providing technical management for an Advanced Stirling Conversion System (ASCS) through a cooperative Interagency Agreement with DOE. Parallel contracts have been awarded to Mechanical Technology, Inc. (MTI) of Latham, New York, and Stirling Technology Company (STC) of Richland, Washington, for the conceptual designs of an ASCS. Each design will feature a free-piston Stirling engine, a liquid-metal heat pipe receiver, and a means to provide about 25 kW of electric power to a utility grid while meeting DOE's long-term performance and cost goals.

The MTI design incorporates a linear alternator to directly convert the solar energy to electricity while STC generates electrical power indirectly by using a hydraulic output to a ground-based hydraulic pump/motor coupled to a rotating alternator. Both designs for the ASCS's will use technology which can reasonably be expected to be available in the 1980's. Both the MTI and STC concepts will be evaluated by the same, but independent, contractor to provide a manufacturing and cost analysis including life cycle cost. The ASCS designs using a free-piston Stirling engine, a heat transport system, a receiver, and the methods of providing electricity to the utility grid will be discussed.

INTRODUCTION

Under DOE's Solar Thermal Technology Program, Sandia National Laboratories (SNLA) is evaluating heat engines for terrestrial solar distributed heat receivers. Of the available heat engine technologies, SNLA has identified the Stirling to be one of the most promising candidates to meet the DOE goals for both performance and cost.

NASA Lewis has pursued the Stirling cycle as a candidate dynamic power converter for future high-power space conversion systems since the 1960's. Unique Stirling expertise and a technology base gradually developed at Lewis during the 1970's. The need to develop automotive powerplant alternatives in the late 1970's initiated the U.S. Department of Energy's Automotive Stirling Engine (ASE) Program which was planned and implemented by Lewis. A consequence of the ASE Program was an accelerated effort which has provided significant expansion in the research and technology of Stirling engines. This has resulted in a synergetic technology base at Lewis and its contractors.

The Stirling Engine Project Office at Lewis is responsible for a variety of projects including both kinematic and free-piston Stirling engines. Testing and evaluating a wide variety of these engines have included the GPU-3 (3 kW), P-40 (40 kW), Mod I ASE (60 kW), and RE-1000 (1 kW) with a dashpot load. Engine performance has been mapped to provide data for computer code validation. Lewis is currently testing the RE-1000 with a hydraulic output and has started testing a 12.5-kW space power research engine (SPRE) as a test bed for further evaluation of larger free-piston Stirling engines for space.

Current projections for space power requirements are shown in figure 1. Space power system requirements include high efficiency, high reliability, very long life, and low vibration. In addition, system weight and operating temperatures are important parameters. Unlike the kinematic Stirling engine, which was invented by the Reverend Robert Stirling in 1816, the free-piston Stirling engine (FPSE) concept is a very recent invention. The FPSE has the potential to be the future dynamic power source for space power applications, either nuclear or solar powered. An overview of the free-piston activities at Lewis is contained in reference 1.

The free-piston Stirling engine was invented in 1962 by William Beale at Ohio University. Early work by Beale resulted in small-scale fractional-horsepower free-piston engine. The major advantage of the FPSE over the kinematic Stirling engine in that it has only two moving parts, noncontacting gas bearings, and can be hermetically sealed, thereby increasing the potential for high reliability and very long life. A simplified drawing of a FPSE with a linear alternator is shown in figure 2. A detailed discussion of the Beale FPSE is contained in reference 2. Only a few organizations in the United States are currently developing the FPSE. These include Sunpower Inc. of Athens, Ohio, Mechanical Technology, Inc. (MTI) of Latham, New York, Stirling Technology Company (STC) (formerly University of Washington) of Richland, Washington, DOE Oak Ridge National Laboratory (ORNL), and NASA Lewis. The FPSE's designed and built have ranged from fractional hp to 33 hp (25 kW). Scaling studies are currently being conducted for Lewis by MTI to determine whether it is feasible to design a single-cylinder FPSE in the 100- to 150-kW range. The design and development of the space power demonstration engine (SPDE) built by MTI for NASA has demonstrated power in excess of 25 kW (17 kW_e), nearly seven times the power produced by earlier FPSE's. The SPDE is shown in figure 3.

ADVANCED STIRLING CONVERSION SYSTEM

DOE signed a cooperative Interagency Agreement (IAA) in 1985 with Lewis to provide technical management for the Advanced Stirling Conversion System (ASCS). Under this IAA, the ASCS Project is providing DOE/SNLA with conceptual engine to electrical power via a linear alternator using permanent magnets. An all-welded pressure vessel has been designed to provide hermetic sealing. A vibration absorber on the mounting ring is used to meet the dynamic balancing specifications. The cooler subsystem is mounted on the ground and is similar to a water-glycol automotive cooling system. The MTI ASCS, designed for unattended safe operation, will be capable of automatic startup and shutdown of the system. The MTI ASCS is designed for a 30-year life and has no planned maintenance for the components mounted on the dish. The MTI design is shown in figure 7.

STC CONCEPTUAL DESIGN

STC is the prime contractor and is responsible for both project management and the Stirling engine/hydraulic output design and system integration. STC has teamed with Sanders Associates for the receiver design, Gedeon Associates for analytical code validation, and Technology Dynamics, Inc., to augment STC's in-house heat pipe experience. The University of Washington provides the dynamic simulation and system design. Pioneer Engineering and Manufacturing Company will provide a manufacturing and cost analysis with a life cycle cost analysis of the conceptial design.

STC proposed using 25-kW, single-piston, Stirling hydraulic engine (STIRLIC[a]) as the baseline design. This concept uses a Stirling hydraulic engine, shown in figure 8, mounted directly on the TBC while the remainder of the system is based on the ground. Use of developed commercial components were proposed for the ground based hardware to minimize development costs and reduce maintenance. The STIRLIC design is based on a 15-kW free-piston Stirling engine with an hydraulic output (described in ref. 6).

During the initial ASCS conceptual design phase the STC team reviewed a number of design options to meet the long-term cost and performance goals of DOE. Areas reviewed were -

- Optimum array size
- Conventional heater head (brazed) versus advanced annular heater head (welded)
- Reflux boiler versus heat pipe
- Material selection for long life
- Single-power piston versus opposed-power pistons
- Engine dynamic, scaling, and thermodynamic parameters
- Starter motor versus no starter motor

The STC "preliminary" conceptual design review was held in February 1987 at Lewis. The STC team presented a design which featured a Stirling engine with hydraulic output mounted on a TBC. A receiver concentrates the solar

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[a] Owner, Stirling Technology Company, Richland, Washington.

energy received from the collector and transfers it by conduction through a reflux boiler to the Stirling engine heater head operated at 800 °C. The engine is located off axis from the receiver cavity in order to maintain the heater tubes in vapor regardless of orientation. The liquid metal chosen for the reflux boiler is sodium. A conventional tubular heater head with an annular regenerator and cooler are used in this design. The helium working gas is hermetically sealed using a pair of nested bellows seals on the displacer. A scotch yoke-counter balance is used to maintain a precision top and bottom position of the displacer while significantly reducing the associated dead volumes. A starter motor is incorporated with the scotch yoke mechanism. The thermal energy is converted directly by the Stirling engine to hydraulic power through a pair of hermetically sealed power bellows. The two power bellows are identical and opposed for self-balancing. STC has demonstrated the potential for long life of the proposed pressure-balanced bellows systems in rigs and in their long-life artificial heart systems which are discussed in reference 7. The hydraulic power is transmitted on lines mounted directly on a TBC strut and routed to the ground-based conversion system. The STC design approach is to use an array of TBC's each mounted with a Stirling hydraulic engine capable of providing the necessary hydraulic power for 25 kW of electrical power on the ground. Four TBC's are used for a single array which provides hydraulic power to the common ground based system as shown in figure 9. The ground-based system includes a common accumulator with a single variable displacement hydraulic pump/motor, a rotary induction alternator with the necessary switch gear, and a common heat rejection system. The four Stirling hydraulic engines will be controlled by a common microprocessor. The STC Stirling hydraulic engine has been designed for a 30-year life and presently has no planned maintenance for the components mounted on the dish. The STC ASCS is designed for automatic startup and shutdown and is capable of unattended safe operation. The STC design is shown in figure 10.

STATUS

"Preliminary" conceptual designs of each ASCS have been completed by MTI and STC. A comparison of the ASCS designs are provided in table V. Both contractors are reviewing their designs to eliminate or reduce any unproven technologies. Also, each contractor is reducing the hot-end temperature from 800 to about 700 °C. The temperature reduction will increase material life and minimize potential liquid-metal capability problems. This temperature reduction may effect both power and efficiency for their ASCS.

The design changes will emphasize manufacturability and the potential for low cost while using existing technology available during the late 1980's. After completing each ASCS design in June, both conceptual designs will be frozen. Pioneer will make an independent evaluation of each design to assess manufacturability and provide a cost analysis using Pareto's Law (detailed costs of 20 percent of the ASCS critical parts). The Pioneer analysis is expected to be complete in September 1987 at which time DOE, SNLA, and NASA will make a selection of the ASCS for follow-on competitive procurement in late 1987 or early 1988.

CONCLUDING REMARKS

The Stirling engine has been identified by SNLA as one of the most promising heat engines for terrestrial applications. Free-piston technology currently being developed at Lewis for space and terrestrial applications has the potential to meet DOE's goals for both performance and cost. Common requirements for the space and terrestrial applications include high efficiency, high reliability, and very long life. Conceptual designs by STC and MTI each feature a Stirling engine, a receiver, and a means to provide about 25 kW of electric power to a utility grid while meeting DOE's long-term cost and performance goals. The MTI and STC conceptual designs are both unique and complementary. The MTI proposal incorporates a linear alternator to directly convert the energy to electricity, while STC generates electrical power indirectly by use of a hydraulic output to a ground-based hydraulic motor coupled to a rotating alternator. Both the MTI and STC concepts will be evaluated by the same but independent contractor to provide a manufacturing and cost analysis including life cycle cost. One of the conceptual designs will be selected for a competitive final design, hardware procurement, assembly, and test of the ASCS at the SNLA test facilities in Albuquerque, New Mexico, by 1990.

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TABLE I - DOE COST[a] GOALS

	Current technology	Long-term goals
Receiver	\$70/m^2	\$40/m^2
Transport	\$70/m^2	\$7/m^2
Conversion	\$380/kW$_e$	\$300/kW$_e$
Energy cost	0.13/kW$_e$	0.05/kW$_e$

[a] 1984 dollars.

TABLE II - SNLA TEST BED CONCENTRATOR (TBC) CHARACTERISTICS

Collector diameter, m	11.0
Focal length, m	6.6
Parabolodial mounting structure, f/D	0.6
Reflectivity	0.89
Slew rates, deg/hr:	
Azimuth	2000
Elevation	200
Slope error, mrad	2
Input	75 kW$_{th}$ at 950 W/m^2

TABLE III - ASCS DESIGN REQUIREMENTS

Heat engine - free-piston Stirling:
  Engine/alternator system, < \$300/kW$_e$ (1984 \$)
  Heater head (metal) temperature, 800 °C
Thermal transport system - heat pipe integral part of receiver:
  Receiver aperture, 8.0 in.
Technology available in the late 1980's
Solar insulation, 950 W/m^2:
  Survival to 1100 W/m^2 for 15 min
ASCS weight: Not to exceed 2000 lb (907 kg)
Dynamic balance:
  Maximum force not to exceed 150 lb (667 N)
ASCS design life:
  30 yr (60,000 hr) with major overhaul
Engine design life with major overhaul:
  30 yr (60,000 hr) with major overhaul at 20 yr (40,000 hr)
ASCS temperature range:
  33 to -6.6 °C (92 to 20 °F)
Elevation:
  5310 ft above sea level
Electrical output:
  25 kW$_e$
  120 V, 1 phase, 60 Hz or
  240 V, 3 phase, 60 Hz
  Power factor, not to exceed 0.85
  Harmonic distortion, < 2.5 percent
System efficiency (solar to electric):
  > 33 percent
Controls:
  Fully automatic, unattended

TABLE IV - COMPARISON OF THE ASCS PROPOSALS

	MTI	STC
Heat supplied, kW_{th}	75	75
Electric power, kW_e	25.0	24.8
Efficiency (solar to electric), percent	33.3	33.1
Heat pipe heater	Yes	Yes
Heater tempeature (metal), K(°C)	1073(800)	1073(800)
Cooler temperature K(°C)	346(73)	323(50)
Temperature ratio, T_h/T_c	3.1	3.3
Working fluid	Helium	Helium with Freon buffer
Working pressure, bar	100	138
Weight (on TBC), kg(lb)	907(2000)	82(181)
Annual power, kW-hr	58,666	61,940

TABLE V - COMPARISON OF ASCS CONCEPTS

(MARCH 1987)

	MTI	STC
Heat supplied, kW_{th}	75	75
Electric power, kW_e	26.5	26.8
Efficiency (solar to electric), percent	35.3	35.7
Efficiency engine (Q_{in} to PWR_{out}), percent	45.2	44.3
Receiver/liquid metal	Heat pipe/ sodium	Reflux boiler/ sodium
Heater head temperature, K (°C)	1073(800)	1073(800)
Cooler temperature, K (°C)	333(60)	323(50)
Temperature ratio, T_h/T_c	3.2	3.3
Working fluid	Helium	Heium with Freon buffer
Annual power (est.), kW-hr	70,000	62,000

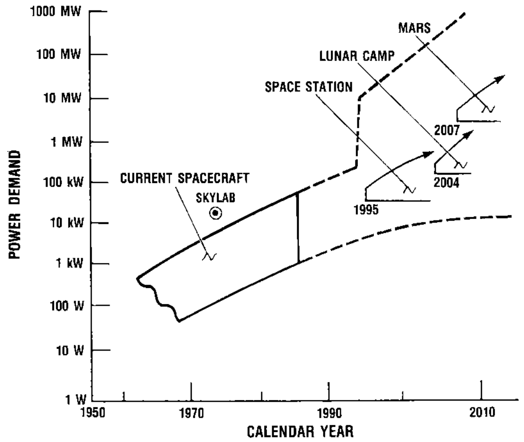


FIGURE 1. - PLANNED SPACE POWER PROGRAMS ADDRESS GROWTH.

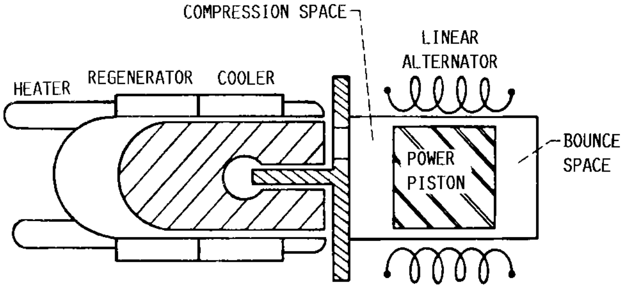


FIGURE 2. - FREE-PISTON STIRLING ENGINE WITH LINEAR ALTERNATOR.

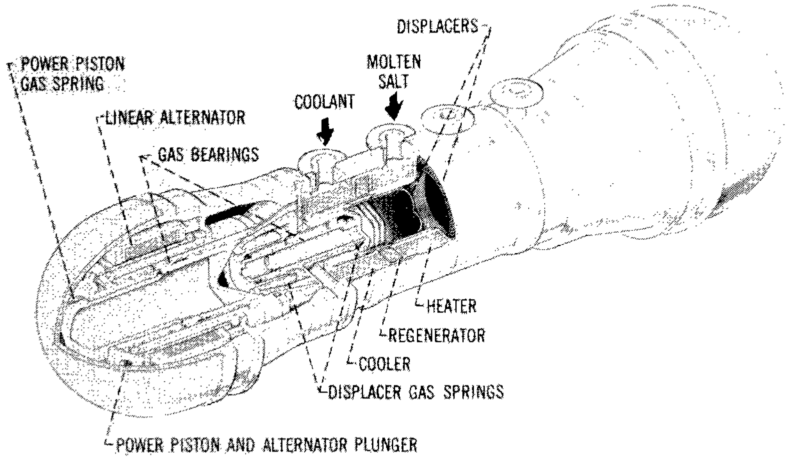


FIGURE 3. - 25-kW_E SPACE POWER DEMONSTRATOR ENGINE.

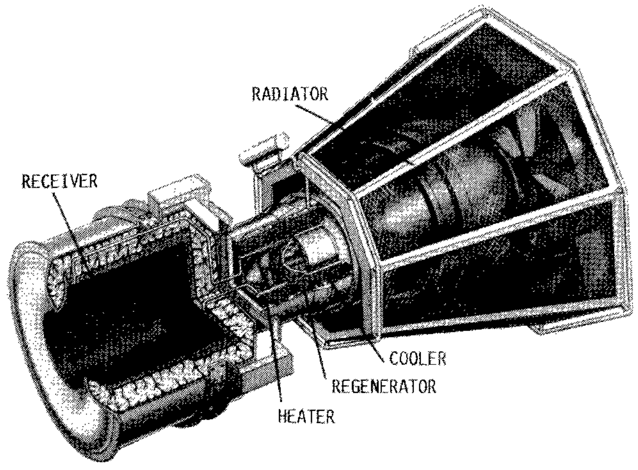
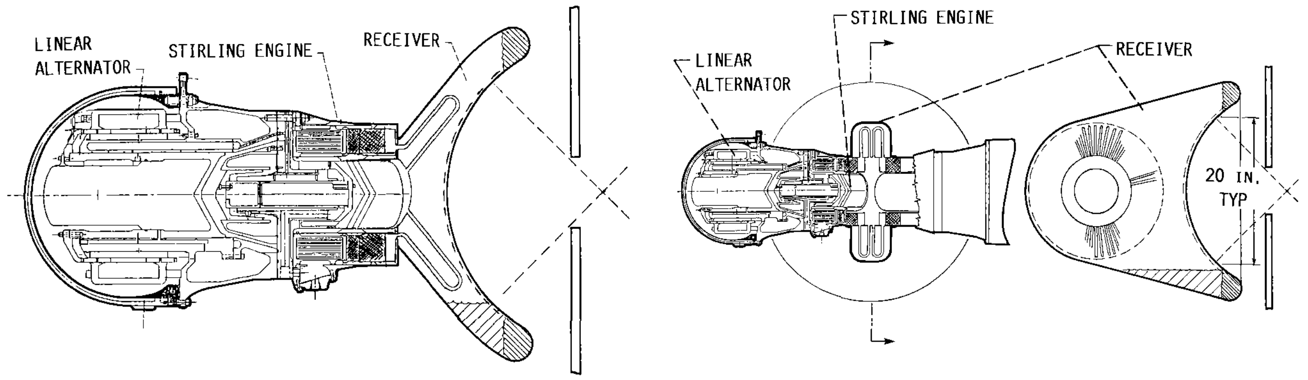


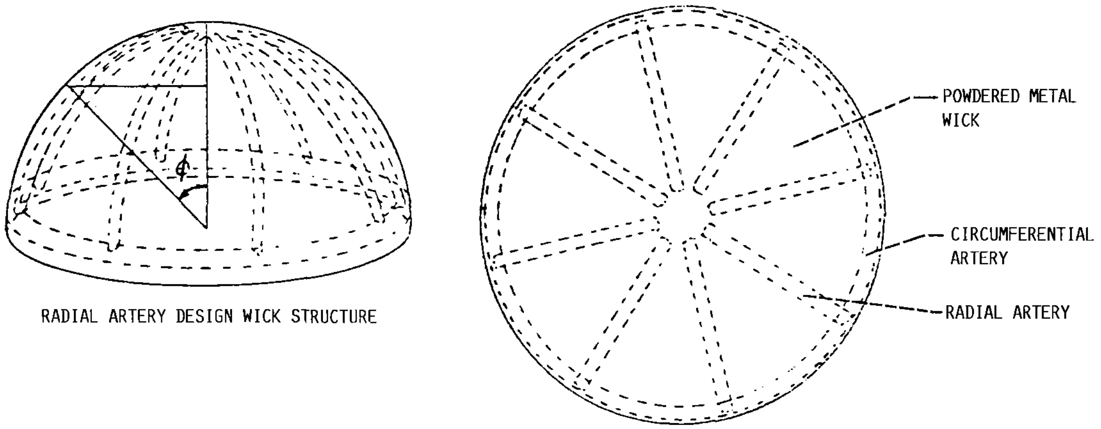
FIGURE 4. - CONCEPTUALIZED FREE-PISTON STIRLING ENGINE CONVERSION SYSTEM.



(A) SINGLE ENGINE CONFIGURATION.

(B) OPPOSED ENGINE CONFIGURATION.

FIGURE 5. - MTI'S PROPOSED CONCEPTS.



RADIAL ARTERY DESIGN WICK STRUCTURE

FIGURE 6. - MIT'S DISH SHAPED HEAT PIPE WITH ARTERIES.

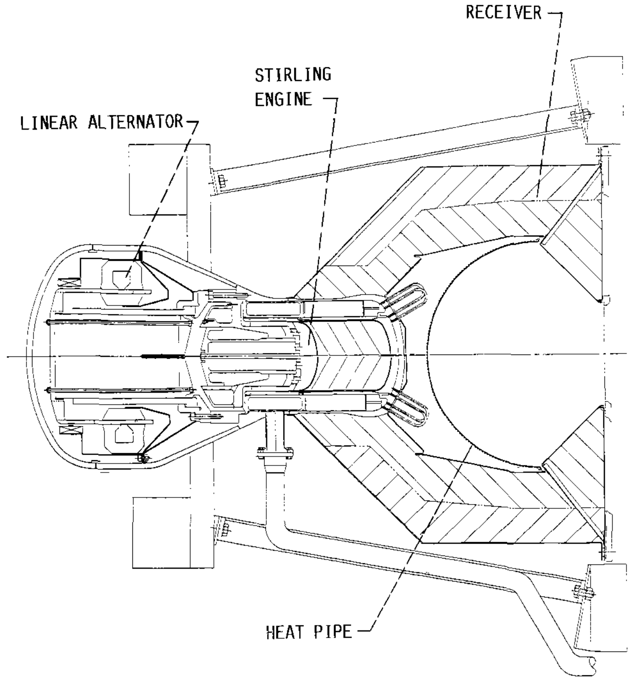


FIGURE 7. - MTI'S SINGLE-PISTON STIRLING ENGINE CONFIGURATION.

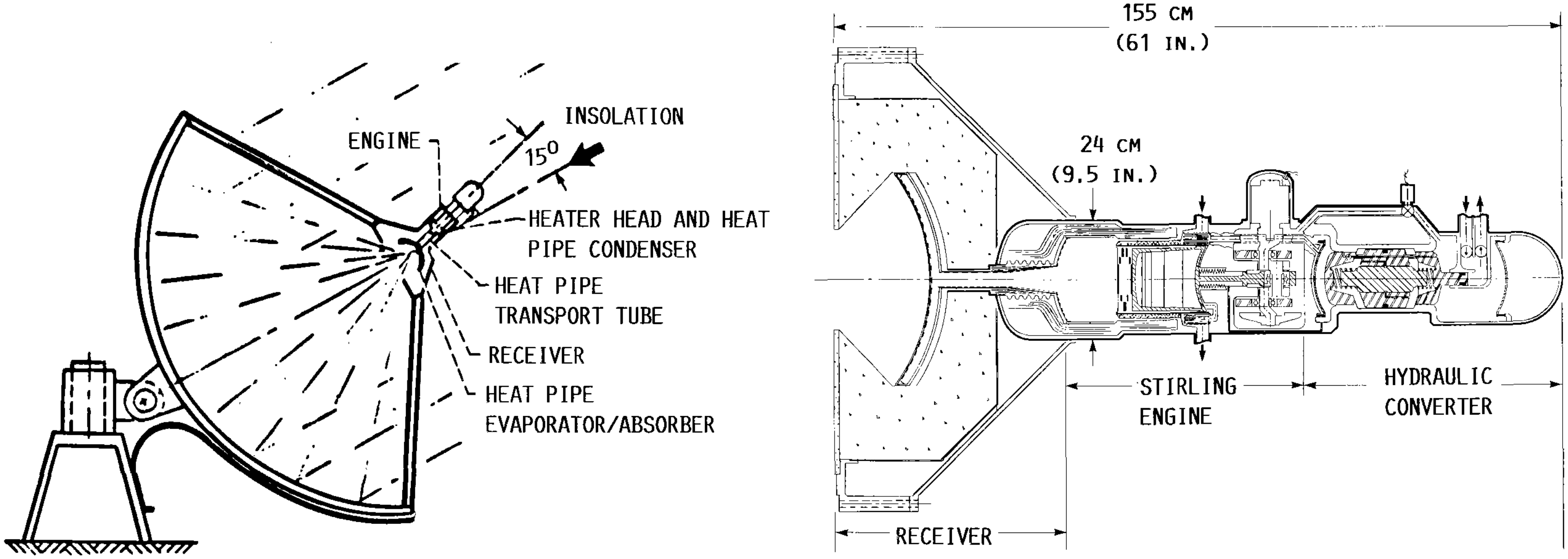


FIGURE 8. - STC'S PROPOSED DESIGN ON THE TBC.

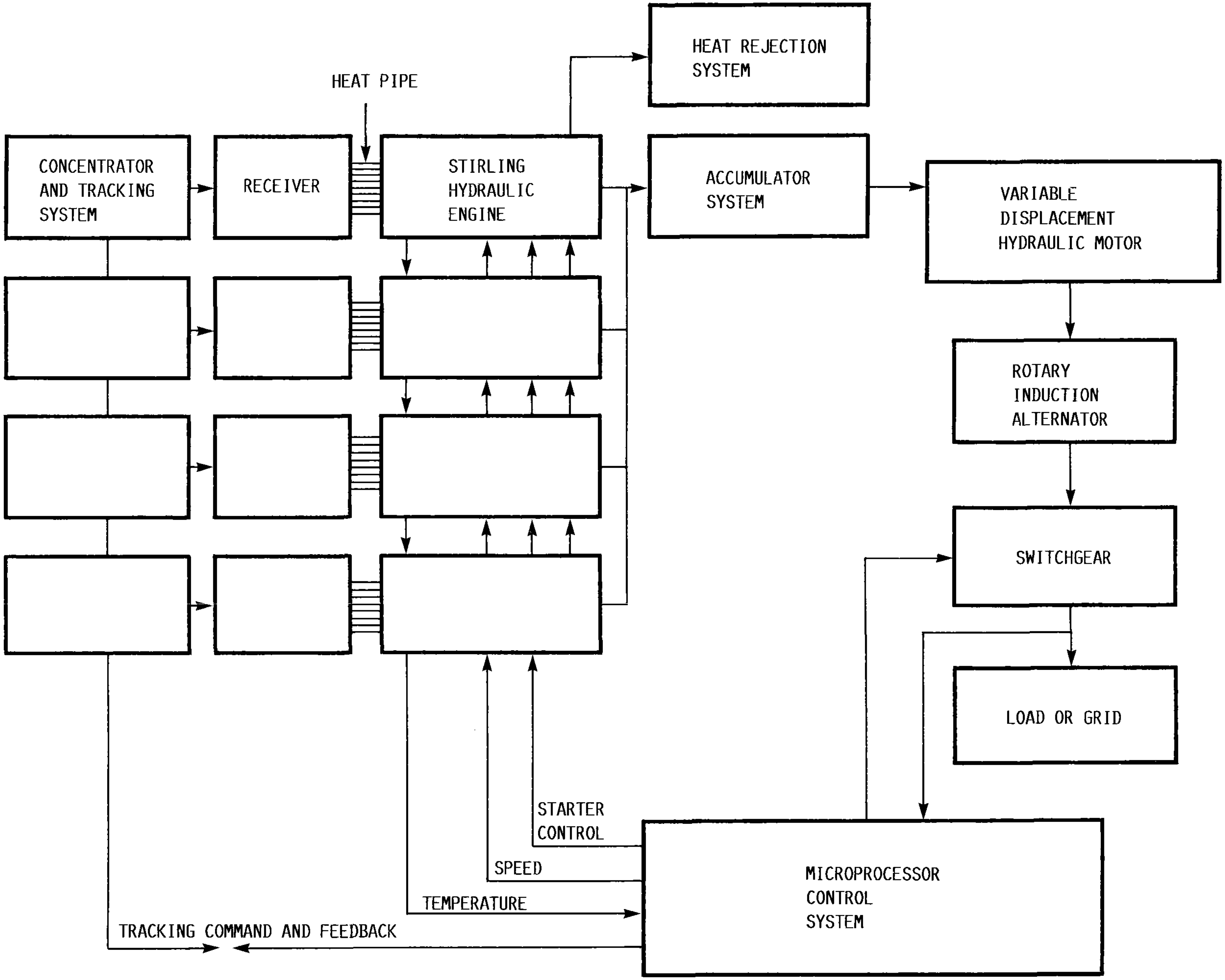


FIGURE 9. - STC'S BLOCK DIAGRAM FOR A SINGLE ARRAY.

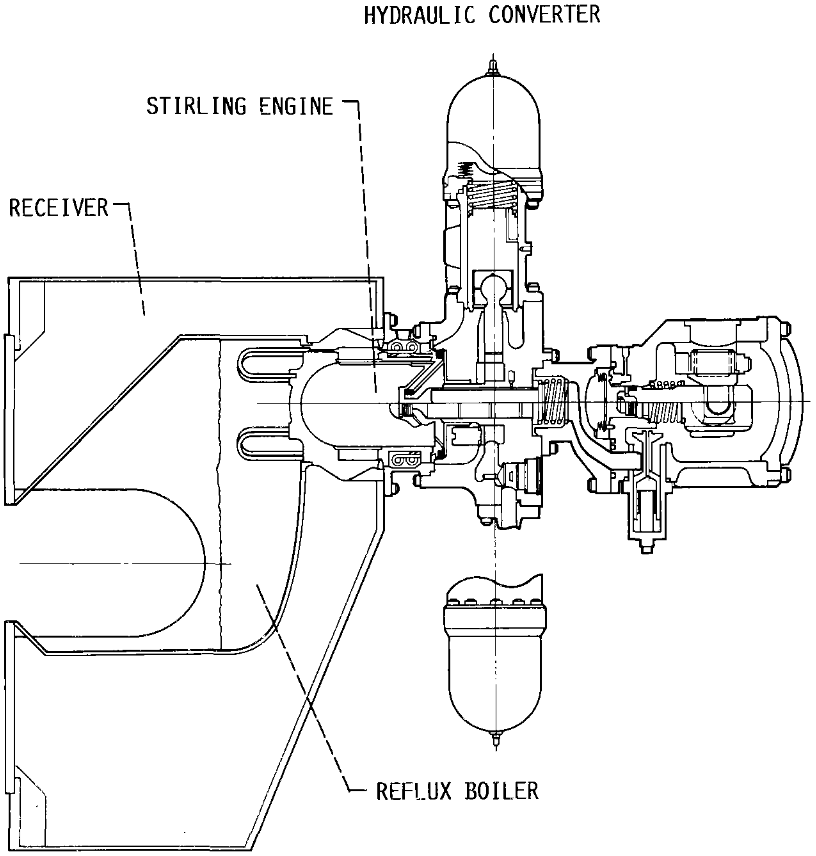


FIGURE 10. - STC'S STIRLING ENGINE WITH HYDRAULIC OUTPUT.

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