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Advanced Stirling Conversion Systems for Terrestrial Applications

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

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

Prepared for
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SUMMARY

Under the Department of Energy's (DOE) Solar Thermal Technology Program, Sandia National Laboratories (SNLA) is developing heat engines for terrestrial Solar Distributed Heat Receivers. SNLA has identified the Stirling to be one of the most promising candidates for the terrestrial applications. The free-piston Stirling engine (FPSE) has the potential to meet the DOE goals for both performance and cost.

The National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) is conducting free-piston Stirling activities which are directed toward a dynamic power source for the space application. Space power system requirements include high efficiency, very long life, high reliability and low vibration. The FPSE has the potential for future high power space conversion systems, either solar or nuclear powered.

Generic free-piston technology is currently being developed by LeRC for DOE/ORNL for use with a residential heat pump under an Interagency Agreement. Since 1983, the SP-100 Program (DOD/NASA/DOE) is developing dynamic power sources for space. Although both applications (heat pump and space power) appear to be quite different, their requirements complement each other.

A cooperative Interagency agreement (IAA) was signed in 1985 with NASA Lewis to provide technical management for an Advanced Stirling Conversion System (ASCS) for SNLA. Conceptual design(s) using a free-piston Stirling (FPSE), and a heat pipe will be discussed. The ASCS will be designed using technology which can reasonably be expected to be available in the 1980's.

Also, an overview is presented of proposed conceptual designs for the ASCS using a free-piston Stirling engine and a liquid metal heat pipe receiver. Power extraction includes both a linear alternator and hydraulic output capable of delivering approximately 25 kW of electrical power to the electric utility grid. Target cost of the engine/alternator is 300 dollars per kilowatt at a manufacturing rate of 10,000 units per year. The design life of the ASCS is 60,000 hr (30 yr) with an engine overhaul at 40,000 hr (20 yr). Also discussed are the key features and characteristics of the ASCS conceptual designs.

INTRODUCTION

Under DOE's Solar Thermal Technology Program, Sandia National Laboratories (SNLA) is developing 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 Research Center (LeRC) has pursued the Stirling cycle as a candidate dynamic power source for future high power space conversion systems since the 1960's. Unique Stirling expertise and the technology base developed gradually at Lewis during the 70's. The need to develop automotive powerplant alternatives in the late 70's triggered the U. S. Department of Energy's Automotive Stirling Engine (ASE) Program which was planned and implemented by LeRC. 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 of LeRC is responsible for a variety of projects as shown in figure 1. A complete description of the ASE Program in contained in reference 1, while an overview of the Free-Piston activities at Lewis is contained in references 2 to 4. Testing and evaluation of the Sunpower RE-1000 FPSE at Lewis are discussed in reference 5. Engine performance has been mapped to provide data for computer code validation. Testing of the modified RE-1000 FPSE with a hydraulic output was recently begun. Details of this FPSE configuration is contained in reference 6. The LeRC advanced technology program is a long range broadly based program supporting technology areas listed in table I.

Current projections for space power requirements are shown in figure 2. Space power system requirements include high efficiency, very long life, high reliability 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 solar or nuclear powered.

In 1962, the Free-Piston Stirling Engine was invented by William Beale at Ohio University. Beale's early work resulted in small-scale fractional-horsepower engines which demonstrated the operating principles of the basic free-piston engine. The FPSE has a major advantage 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 3. A detailed discussion of the Beale FPSE is contained in reference 7. 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/LeRC. FPSE's have been designed and built ranging from fractional hp up to 33 hp (25 kW). Scaling studies are currently being advertised for LeRC 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 20 kW, nearly seven times the power produced by earlier FPSE's. The SPDE is shown in figure 4. Although resources for these programs have been limited, FPSE technology continues to make good progress. This progress is in part credited to the ability to take advantage of the fact that much of the basic operational characteristics and the generic technology, which have already been developed for the kinematic, are also common to both the kinematic and Free-Piston Stirling engines as shown in figures 5 and 6. Specific technology areas include analytical code and materials development which have been developed to resolve specific Stirling issues. These are reviewed in references 8 to 13.

Generic free-piston technology is currently being developed for DOE/ORNL for use with a residential heat pump under an Interagency agreement with Lewis. Since 1983, the SP-100 Program (DOD/NASA/DOE) has developed dynamic power sources for space. Although both applications appear to be quite different, their requirements complement each other. The research resulting from this program covers generic Free-Piston Stirling technology applicable for both space and terrestrial applications.

Advanced Stirling Conversion System

A cooperative Interagency agreement (IAA) was signed by DOE and NASA-LeRC in 1985 with LeRC to provide technical management for an Advanced Stirling Conversion System (ASCS). Under this IAA, the ASCS Project will provide DOE/SNLA with conceptual designs of free-piston Stirling engine systems which have the potential of meeting DOE's long-term performance and cost goals. Objectives of the ASCS Project are shown in table II. Competitive contracts for the conceptual designs and cost and manufacturing studies for the ASCS were awarded to both MTI and STC in late 1986. The proposals from MTI and STC were judged to be unique and complementary to each other. Each conceptual design will feature the Stirling engine, a liquid metal heat pipe receiver, a means to provide electric power,the necessary auxiliaries and a control system. The ASCS will be designed to mount to and receive concentrated solar energy from an 11 meter diameter Test Bed Concentrator (TBC) located at the SNLA test facility. The TBC characteristics are shown in table III. Also, the conceptual designs will predict ASCS performance over a range of solar inputs, estimate system and major component weights, define engine and electrical power conditioning and control requirements. Each conceptual design shall include existing technology, available by the late 1980's. The goal of the ASCS is to generate a conceptual design capable of generating about 25 kW of electric power to an electric utility grid at an engine/alternator target cost of 300 dollars per kilowatt at the manufacturing rate of 10,000 units per year. The design life of the engine/alternator is 60,000 hr which includes an engine overhaul at 40,000 hr. The ASCS design requirements are shown in table IV. At the completion of the conceptual design studies by MTI and STC an independent manufacturing and cost analysis will be completed by Pioneer Engineering and Manufacturing Company of Warren, Michigan. One design will be selected for a follow on procurement to complete a final design, hardware procurement, assemble and test the ASCS at the SNLA test facilities in Albuquerque, NM by the late 1980's. An artist's conceptualization of the ASCS showing the solar receiver, heat transport system, Stirling engine/linear alternator, and heat rejection system is shown in figure 7.

As stated earlier, the MTI and STC concepts are both unique and complementary. The major difference is the method to generate the electrical power. MTI is using the NASA 25 kWe SPDE as their baseline which incorporates a linear alternator to directly convert the energy to useful electricity on the utility grid. STC has chosen a 25 kWe FPSE which generates electrical power indirectly by use of a hydraulic output to a ground based fluid pump coupled to a rotating induction generator. Both the MTI and STC concepts will produce 25 kWe at a heater head (metal) temperature of 800° C with Helium as the working fluid. A temperature ratio of T_H/T_C of 3 for the ASCS, results in a system efficiency (solar input to electrical output) of 33 percent. Estimates of about 60,000 kW-hr per year were provided for both the STC and MTI proposed concepts. A comparison of the MTI and STC proposals is provided in table V.

MTI Conceptual Design

MTI has teamed with Thermacore, Inc., and Sanders Associates to provide an integrated conceptual design of the ASCS. The design combines expertise in three areas: Stirling engine systems (MTI), solar receivers (Sanders) and liquid metal thermal transport systems (Thermacore). A manufacturing and cost analysis with a life cycle cost analysis of the conceptual design will be conducted by Pioneer Engineering and Manufacturing Company.

MTI proposed using the NASA SPDE, a 25 kWe, two opposed-piston Stirling engine/linear alternator system as the baseline design (see fig. 8). Major changes required to solarize the SPDE included: reducing frequency from 105 to 60 Hz, removing light weight Beryllium materials and replacing with more conventional materials (lightweight is required for space, but too expensive for the terrestrial application) and increasing the temperature ratio (T_H/T_C) from 2.0 to 3.1.

However, the MTI team will focus on a larger single piston Stirling engine/linear alternator system as the prime concept (see fig. 9). The receiver will receive concentrated solar energy from the collector and transfer it by conduction through a liquid metal heat pipe to the Stirling engine heater tubes. A dish-shaped receiver element has been proposed and is shown in figure 10. The thermal energy is then converted directly by the Stirling engine to electrical power via a linear alternator whose output is connected directly to the utility grid. A water-glycol cooler subsystem will remove waste heat from the engine/alternator system and reject it to atmosphere. The complete system will be mounted on the TBC. The control system will provide unattended safe operation, and will be capable of automatic startup and shutdown of the system.

System performance, initial cost and life-cycle costs will be evaluated for the proposed concept to minimize costs for a potential commercial product. Impact of a number of design options on life-cycle cost wil be considered during the design process. These include:

- External versus internal heater tube geometry.
- High-performance regenerators versus lower cost regenerator,
- Hydrodynamic versus hydrostatic versus Piezoelectric bearings.
- Clearance seals versus piston rings,
- Permanent magnet-versus saturated plunger alternator,
- High-inductance alternator with tuning capacitor versus Low-inductance alternator without tuning capacitor.

A further discussion of the MTI's solarized Free-piston Stirling Engine Design is contained in reference 14.

STC Conceptual Design

STC has teamed with Sanders Associates, Inc., for receiver design, Gedeon Associates for analytical validation and Technology Dynamics, Inc. to augment STC's in-house heat pipe experience. STC and the University of Washington will provide expertise in Stirling engine systems with a hydraulic output designed to operate with reliable, long-life bellows systems. Pioneer Engineering and Manufacturing Company will provide a manufacturing and cost analysis with a life cycle cost analysis of the conceptual design.

STC has proposed using a 25 kWe, single-piston, Stirling hydraulic engine STIRLIC^{TM} as the baseline design. A sketch of the proposed design is shown in figure 11. The receiver and Stirling hydraulic engine will be mounted directly on the TBC (shown in fig. 12), while the remainder of the system is based on the ground. A receiver will intercept the solar insolation from the SNLA collector and transfer the energy through a liquid metal heat pipe boiler to the Stirling engine heater head. Wicking and arteries are required to distribute the fluid from the condenser to the evaporator section. An advanced heater head design, the Pressure Stabilized^{TM} Heater Head (PSHH) will be evaluated. It is an annular design, made of fewer and simpler components, an integral heat pipe, and all welded construction amenable to automated mass production techniques. In addition to the advanced PSHH STC will also evaluate a conventional tubular heater head. The thermal energy is converted directly by the Stirling engine through an hermetically sealed power bellows to hydraulic power. Hydraulic lines will be mounted on a TBC strut and routed to the ground based hydraulic system. The hydraulic system includes commercially available "off the shelf" components which include a hydraulic motor which directly operates a rotary induction alternator providing electricity to the utility grid. Recirculating the hydraulic fluid is being considered to remove waste heat from the engine and reject it to atmosphere. A control system will provide unattended safe operation and will be capable of automatic startup, shutdown and power conditioning of the system.

Maximum utilization of developed commercial components are proposed to minimize development risks and life cycle costs. Components include: hydraulic motors, accumulators, rotary alternators and the switchgear which are all ground based for easy maintenance. This also results in a low weight system which is mounted directly on the TBC. Trade studies considered during the design process will include:

- Optimization of concentrator modules in an array to a central ground based hydraulic unit (one versus four or more).
- Conventional heater head (brazed) versus advanced annular heater head (welded).
- Water/glycol versus hydraulic fluid for cooling system.
- Induction versus synchronous alternators.
- No starter motor versus starter motor.
- Material selection for long life.
- Validation of analysis and codes with two sources.
- Optimization of appendix gap and displacer seal clearances.
- Regenerator matrix materials.

The concept proposed by STC is based on a conceptual design for a 15 kW free-piston Stirling engine with a hydraulic output which is described in

Ref. 15. Modifications have been made to the engine to improve power density, simplicity, and stability while reducing cost.

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 by LeRC 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 application, include high efficiency, very long life and high reliability. Conceptual designs by STC and MTI each feature a Stirling engine, a liquid metal heat pipe receiver, and a means to provide about 25 kW of electric power to an 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, NM by the later 1980's.

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TABLE I. - LEWIS ADVANCED TECHNOLOGY PROGRAM

SUPPORTS KEY TECHNOLOGY AREAS NEEDED FOR:

- GAS BEARINGS
- LINEAR ALTERNATORS
- ALTERNATIVE POWER EXTRACTION
- CODE VALIDATION AND ANALYSIS
- OSCILLATING FLOW
- PERFORMANCE PREDICTIONS
- SCALING
- HEAT EXCHANGERS
- MATERIALS
- POWER CONDITIONING INTERFACE
- LONG LIFE VALIDATION

TABLE II. - ADVANCED STIRLING CONVERSION SYSTEM

CONCEPTUAL DESIGN OBJECTIVES

O DEFINE THE ASCS CONFIGURATION

O PREDICT ASCS PERFORMANCE OVER A RANGE OF SOLAR INPUTS

O ESTIMATE SYSTEM & MAJOR COMPONENT WEIGHT

O DEFINE ENGINE & ELECTRICAL POWER CONDITIONING & CONTROL REQUIREMENTS

O DEFINE KEY TECHNOLOGY NEEDS NOT READY BY THE LATE 1980'S IN MEETING GOALS

O PROVIDE A MANUFACTURABILITY AND COST EVALUATION FOR THE ENGINE-ALTERNATOR

TABLE III. - SNLA TEST BED CONCENTRATOR (TBC) CHARACTERISTICS

- 0 COLLECTOR - NOMINAL 11.0 METER DIAMETER
- 0 FOCAL LENGTH - 6.6 METER
- 0 PARABOLODIAL MOUNTING STRUCTURE - f/d = 0.6
- 0 REFLECTIVITY - 0.89
- 0 SLEW RATES -
  - AZIMUTH 2,000 DEG/HR
  - ELEVATION 200 DEG/HR
- 0 SLOPE ERROR - 2 MILLIRAD
- 0 INPUT - 75 kWth @ 950 W/m^2

TABLE IV. - ASCS DESIGN REQUIREMENTS

0 HEAT ENGINE - FREE-PISTON STIRLING

ENGINE/ALTERNATOR SYSTEM LESS THAN $300/kWe (1984 $)
HEATER HEAD (METAL) TEMPERATURE - 800° C

0 THERMAL TRANSPORT SYSTEM - HEAT PIPE INTEGRAL PART OF RECEIVER

RECEIVER APERATURE - 8.0 INCHES

0 TECHNOLOGY AVAILABLE IN THE LATE '80's

0 SOLAR INSOLATION - 950 W/m^2

SURVIVAL TO 1100W/m^2 FOR 15 MIN.

0 ASCS WEIGHT - NOT TO EXCEED 2000 POUNDS (907 kg)

0 DYNAMIC BALANCE -

MAX FORCE NOT TO EXCEED 150 POUNDS (667 NEWTONS)

0 ASCS DESIGN LIFE - 30 YR (60,000 HR)
WITH MAJOR OVERHAUL

0 ENGINE DESIGN LIFE WITH MAJOR OVERHAUL AT - 30 YR (60,000 HR)
WITH MAJOR OVERHAUL AT 20 YR (40,000 HR)

0 ASCS TEMPERATURE RANGE -

33° C (92° F) TO - 6.6° C (20° F)

0 ELEVATION - 5310 FT ABOVE SEA LEVEL

0 ELECTRICAL OUTPUT -

25 kWe
120 VOLT, 1 PHASE, 60 Hz or 240 VOLT, 3 PHASE, 60 Hz
POWER FACTOR NTE 0.85
HARMONIC DISTORTION LESS THAN 2.5%

0 SYSTEM EFFICIENCY, (SOLAR TO ELECTRIC) - GREATER THAN 33%

0 CONTROLS
FULLY AUTOMATIC, UNATTENDED

TABLE V. - COMPARISON OF THE ASCS PROPOSALS

		MTI	STC
0	HEAT SUPPLIED (kWt)	75	75
0	ELECT POWER (kWe)	25.0	24.8
0	EFFICIENCY (SOLAR TO ELECT)	33.3%	33.1%
0	HEAT PIPE HEATER	YES	YES
	HEATER TEMP (METAL) K	1073	1073
0	COOLER TEMP K	356	323
0	RATIO Th/Tc	3.1	3.3
0	WORKING FLUID	He	He w/ Freon Buffer
0	WORKING PRESSURE (bar)	100	138
0	WEIGHT (ON TBC)	907 kg	82 kg
		2000 lb	181 lb
0	ANNUAL POWER (kW-hr.)	58,666	61,940

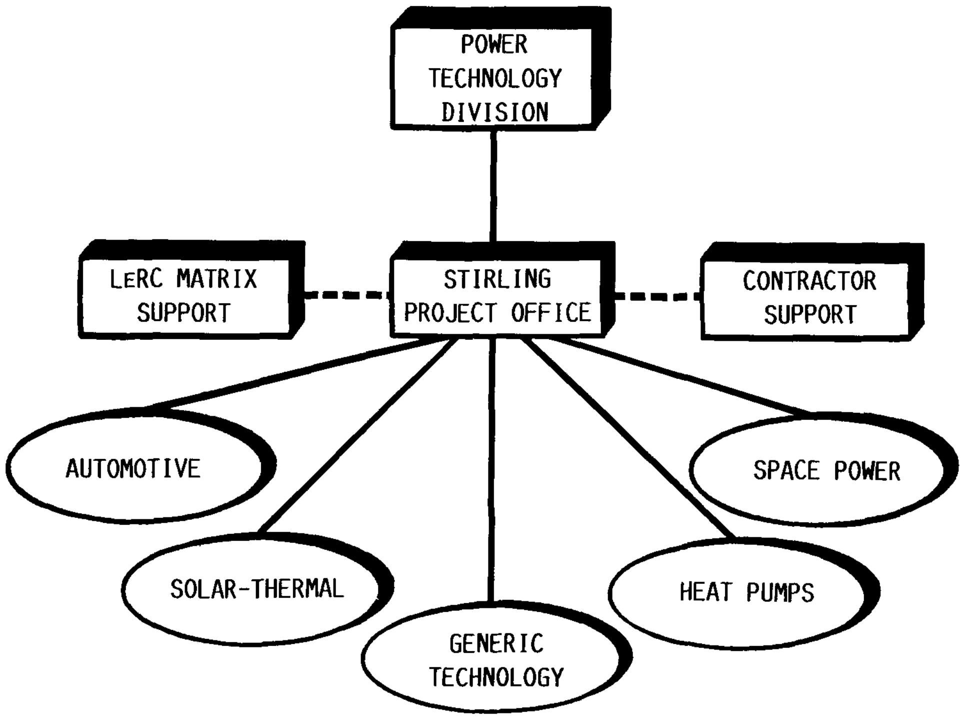

FIGURE 1. - ORGANIZATION AND ACTIVITIES OF STIRLING ENGINE PROJECT OFFICE.

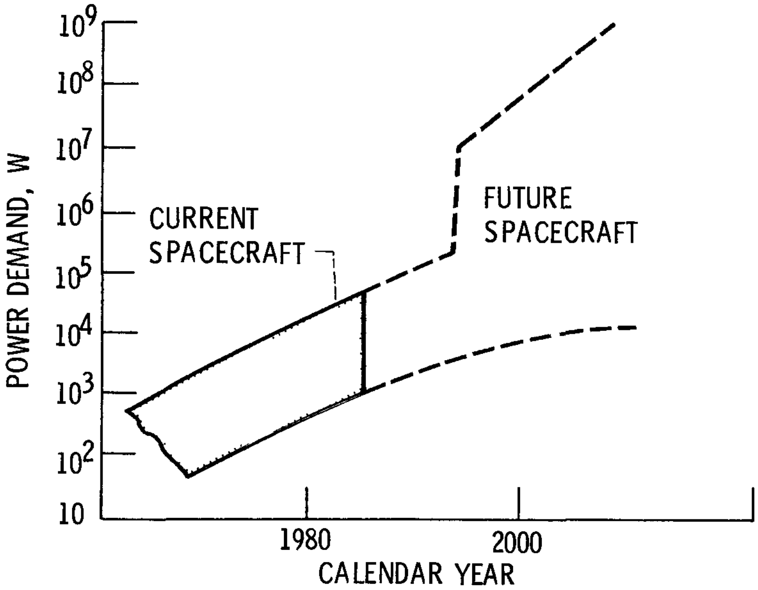

FIGURE 2. - PLANNED SPACE POWER PROGRAMS ADDRESS SPACECRAFT GROWTH.

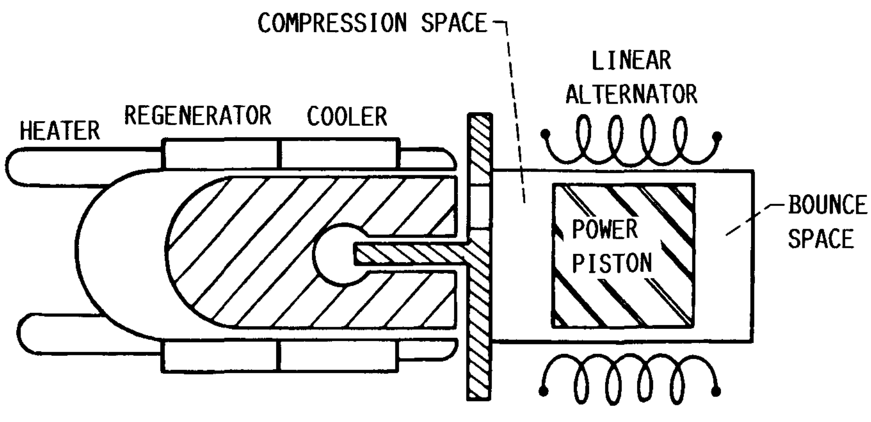

FIGURE 3. - FREE-PISTON STIRLING ENGINE WITH LINEAR ALTERNATOR.

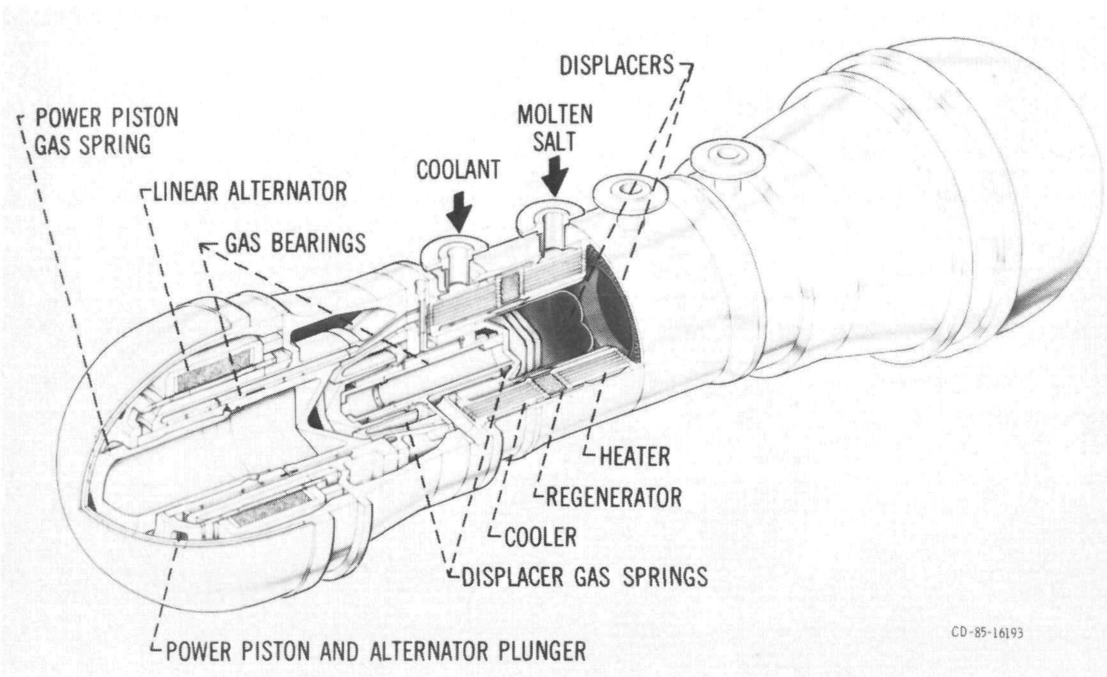

FIGURE 4. - 25 KWE SPACE POWER DEMONSTRATOR ENGINE.

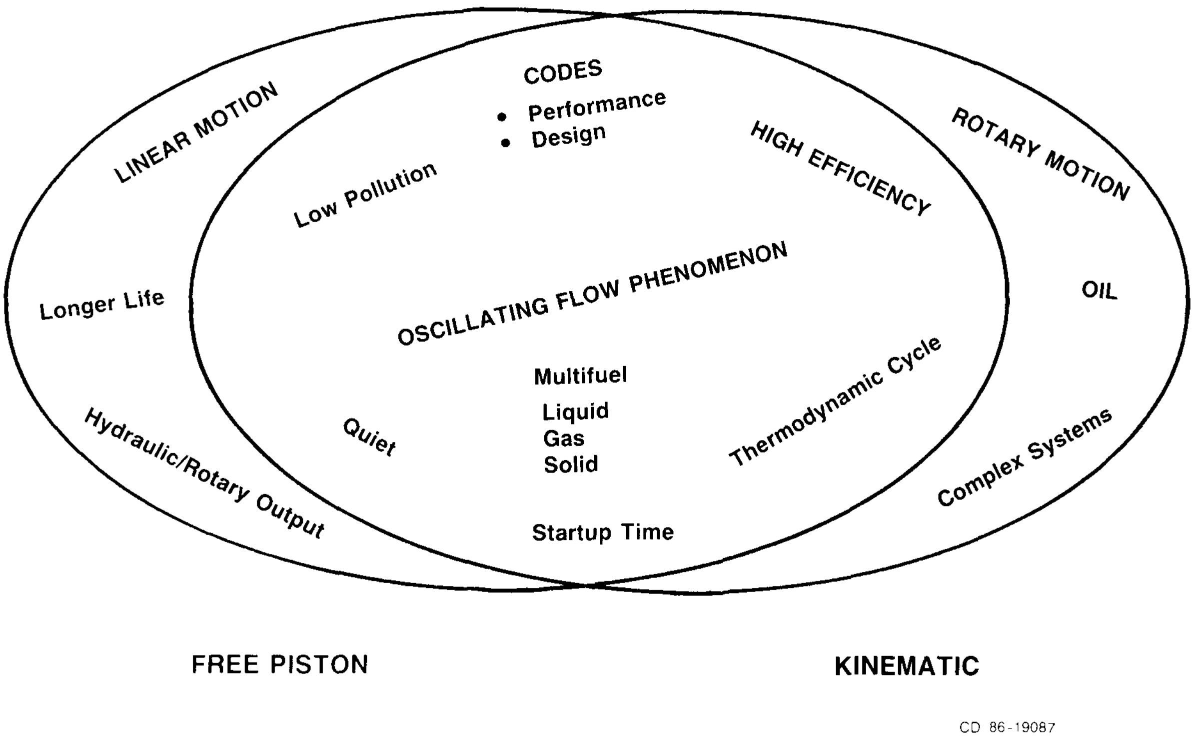

FIGURE 5. - COMMON STIRLING OPERATIONAL CHARACTERISTICS.

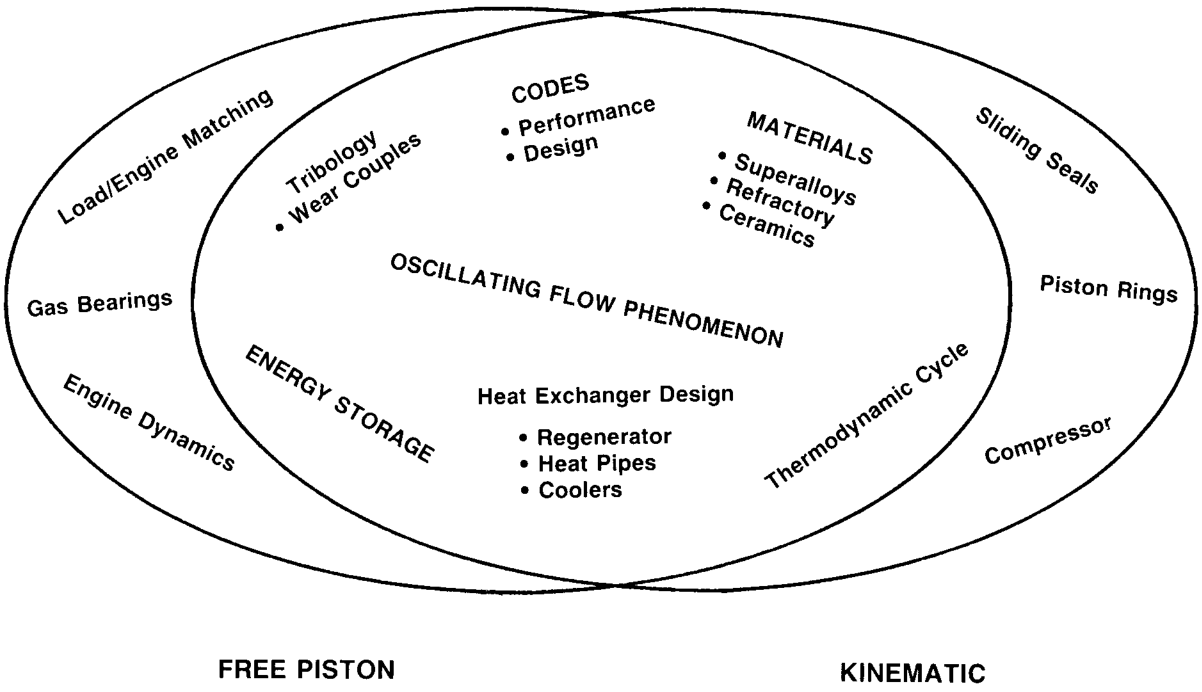

FIGURE 6. - COMMON STIRLING TECHNOLOGIES.

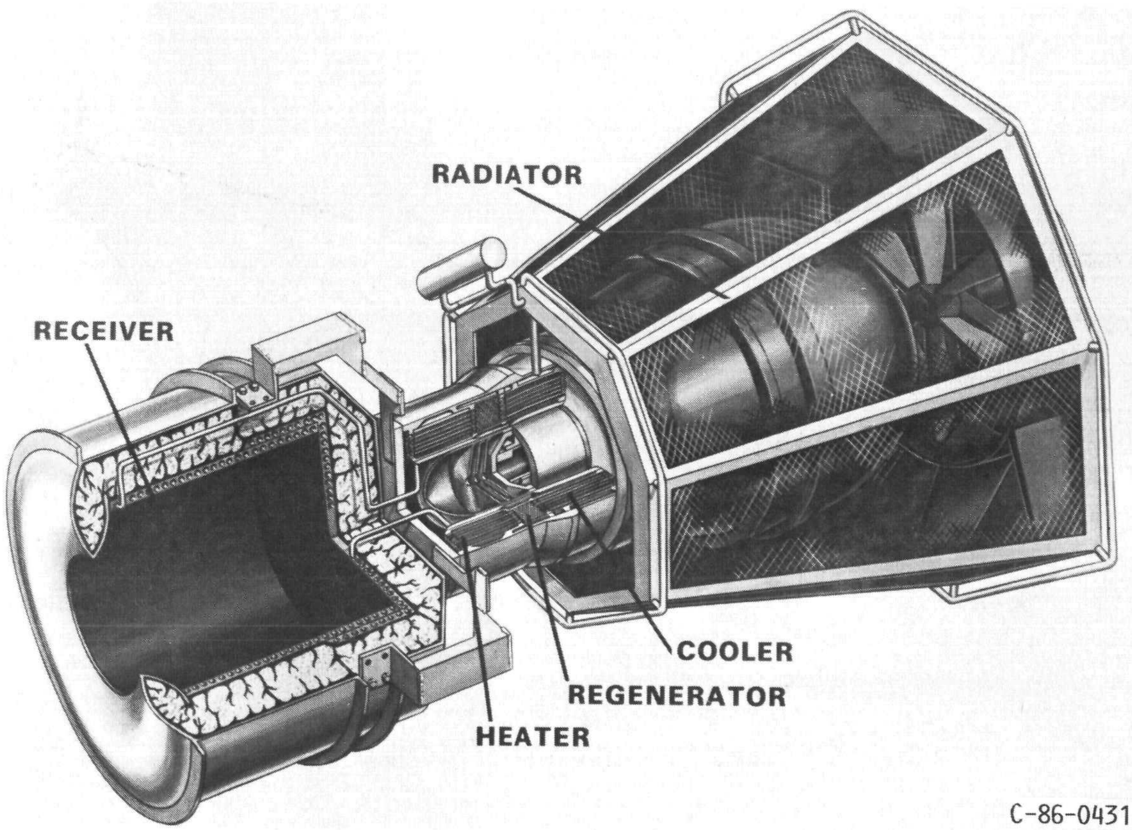

FIGURE 7. - CONCEPTUALIZED FREE-PISTON STIRLING ENGINE CONVERSION SYSTEM.

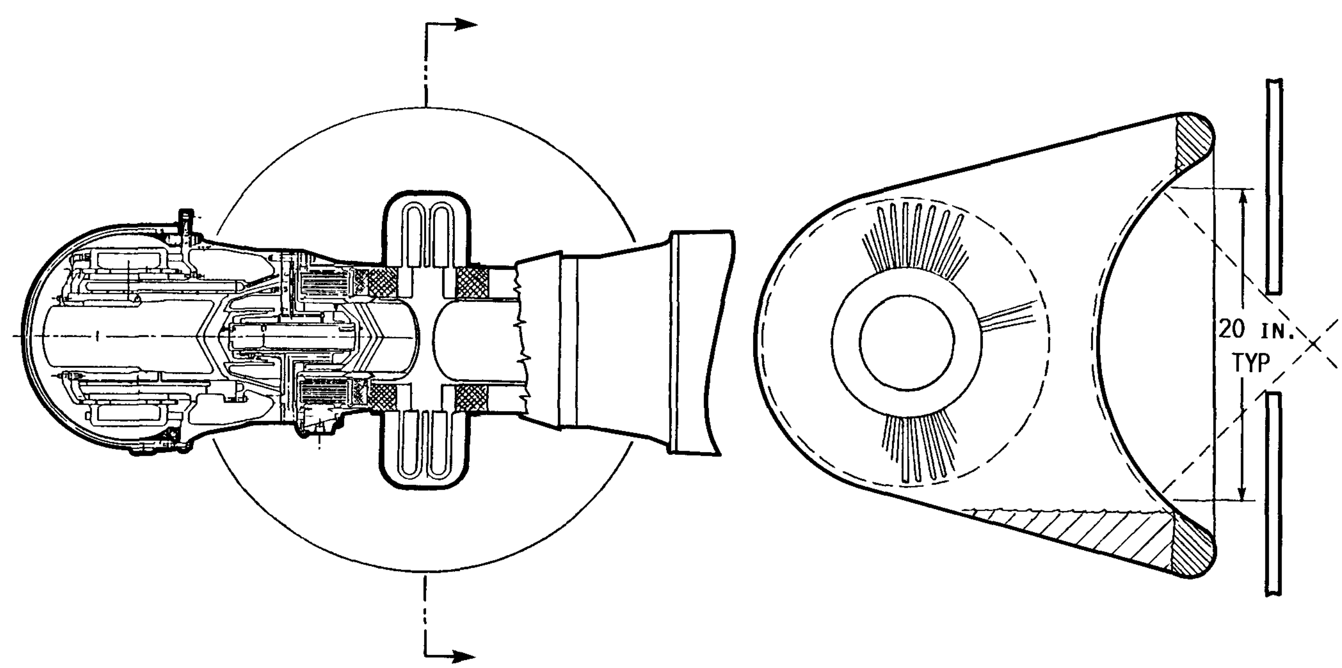

FIGURE 8. - MTI'S OPPOSED - PISTON STIRLING ENGINE CONFIGURATION.

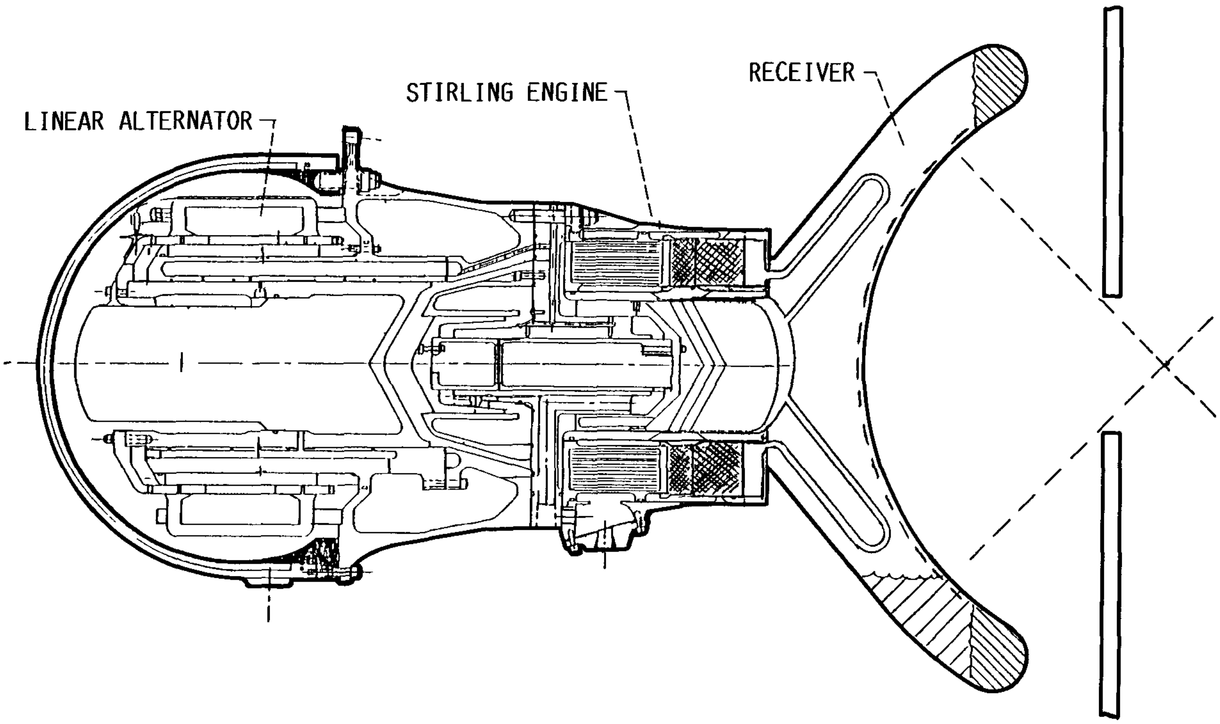

FIGURE 9. - MTI'S SINGLE-PISTON STIRLING ENGINE CONFIGURATION.

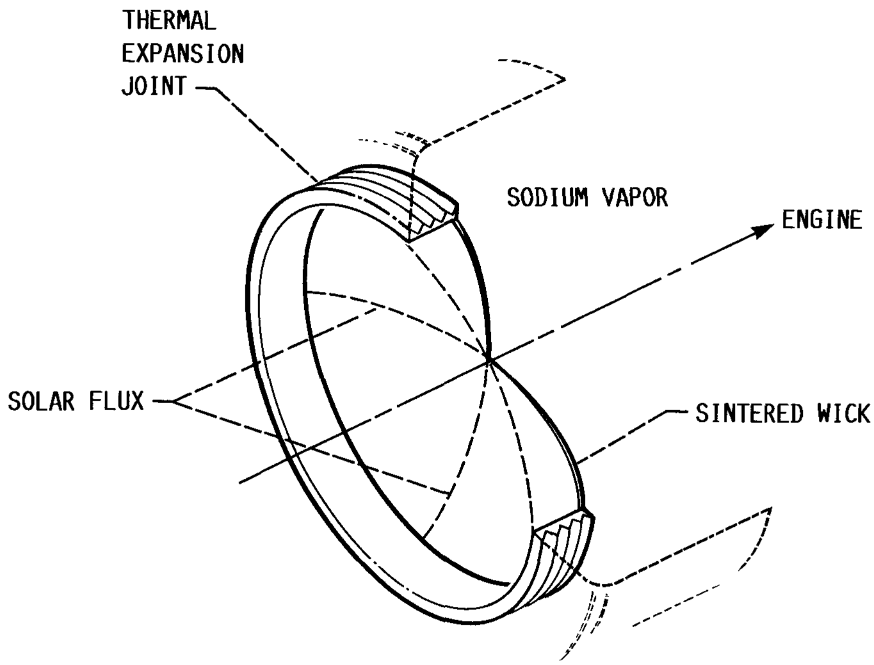

FIGURE 10. - MTI'S DISH-SHAPED RECEIVER ELEMENT.

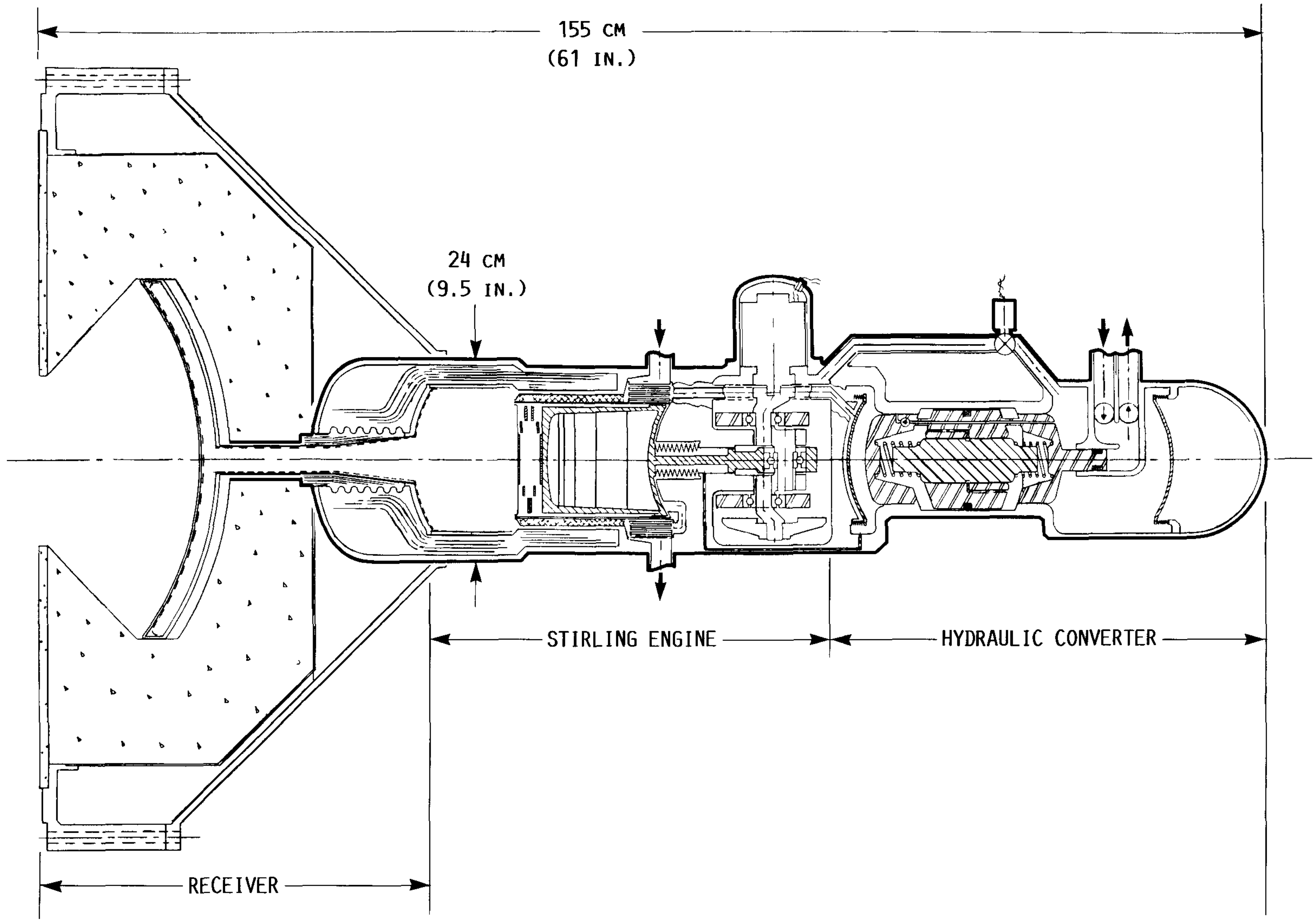

FIGURE 11. - SEC'S SINGLE-PISTON STIRLING ENGINE WITH HYDRAULIC OUTPUT.

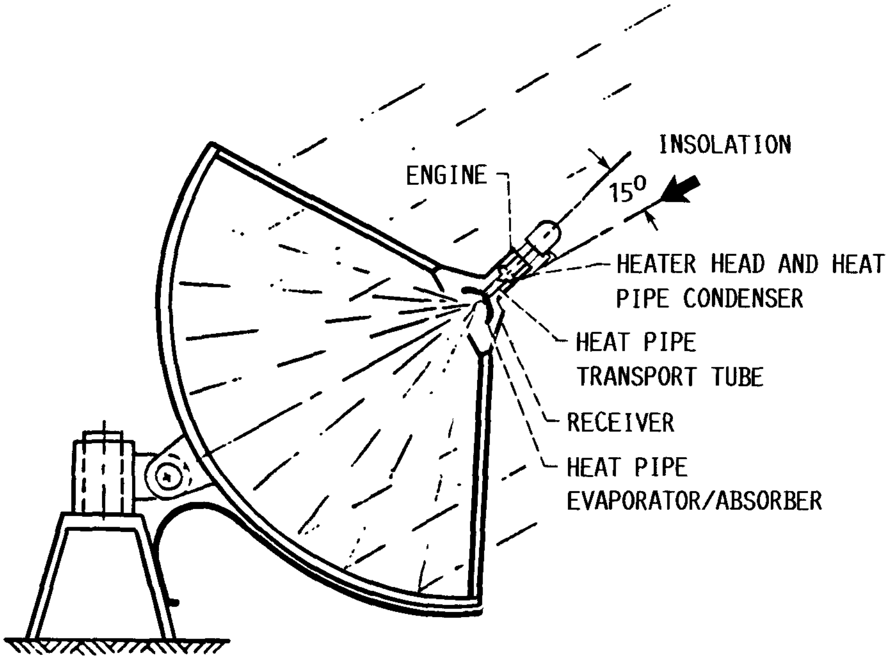

FIGURE 12. - STC'S PROPOSED DESIGN ON THE TBC.

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16 Abstract

Under the Department of Energy's (DOE) Solar Thermal Technology Program, Sandia National Laboratories (SNLA) is developing heat engines for terrestrial Solar Distributed Heat Receivers. SNLA has identified the Stirling to be one of the most promising candidates for the terrestrial applications. The free-piston Stirling engine (FPSE) has the potential to meet the DOE goals for both performance and cost. The National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) is conducting free-piston Stirling activities which are directed toward a dynamic power source for the space application. Space power system requirements include high efficiency, very long life, high reliability and low vibration. The FPSE has the potential for future high power space conversion systems, either solar or nuclear powered. Generic free-piston technology is currently being developed by LeRC for DOE/ORNL for use with a residential heat pump under an Interagency Agreement. Since 1983, the SP-100 Program (DOD/NASA/DOE) is developing dynamic power sources for space. Although both applications (heat pump and space power) appear to be quite different, their requirements complement each other. A cooperative Interagency agreement (IAA) was signed in 1985 with NASA Lewis to provide technical management for an Advanced Stirling Conversion System (ASCS) for SNLA. Conceptual design(s) using a free-piston Stirling (FPSE), and a heat pipe will be discussed. The ASCS will be designed using technology which can reasonably be expected to be available in the 1980's.

17 Key Words (Suggested by Author(s))

Advanced Stirling conversion systems; Terrestrial solar distributed heat receivers; Free-piston Stirling engine

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