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Heat Engine Development for Solar Thermal Dish-Electric Power Plants

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Abstract

The Department of Energy's (DOE) Solar Thermal Program has as one of its program elements the development and evaluation of heat engine technologies that are applicable to Distributed Receiver Systems. The primary research and development activities, for the past several years, have involved the so-called dish-electric concept in which a heat engine, solar receiver, and generator are coupled and located at the focus of a parabolic dish concentrator. Power conversion assemblies (PCA) would be deployed at the size of about 25 to 50 kWe, which is consistent with concentrator development in the 11-15 m diameter range. This report describes various heat engine cycles, outlines the status of their development, presents test data and performance evaluation from experimental work to date, and discusses the strategy for future development efforts.

SOLAR THERMAL TECHNOLOGY

FOREWORD

The research and development described in this document was conducted within the U. S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low temperature troughs to over 1500°C in dish and central receiver systems

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

This report outlines the heat engine development program for Distributed Receiver Systems. Heat engines are being developed to meet DOE's near-term and long-term goals so that the technology can be commercialized.

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1. INTRODUCTION

In 1976 Jet Propulsion Laboratory proposed to the Department of Energy (DOE) the concept of mounting a heat engine at the focus of a parabolic dish. Subsequently, the distributed dish-electric idea was born, and JPL became the lead lab for developing heat engines to suit this new application. In 1983 Sandia National Laboratories Albuquerque (SNLA) assumed the lead lab responsibility to further develop heat engines. SNLA has continued with JPL's original heat engine development and testing as well as investigating new engines for the program.

To date, several heat engine cycles have undergone development and testing. These include: Open and Semi-Open Brayton Cycles, Organic Rankine Cycle, and Kinematic Stirling. Two other engines, the Free-Piston Stirling and a Liquid Metal Thermoelectric Converter, are being developed for eventual hardware testing.

2. STIRLING CYCLE

The Stirling engine is unique among the available thermodynamic cycles in that it offers several features that make it an excellent match for the solar application. These include:

- High thermal efficiency, 30 to 45%
- Silent operation
- Completely closed cycle and potential for extended engine life
- High specific power
- Multi-fuel capability; allowing hybrid operation of a solar engine with available fuel sources

From basic thermodynamics the Stirling engine can be idealized on a P-V and T-S plot (Figure 1) as an isothermal expansion process c-d in which heat is added to the engine and an isothermal compression process a-b in which heat is removed. The cycle is completed with process b-c and d-a, which are constant-volume displacement on shuttle process whereby the working fluid is passed through the regenerator. A simple mechanical device that emulates this cycle is shown on the left side of Figure 1.

The engine consists of a closed system with a compression space, expansion space, displacer, and power piston. During the compression stroke a-b the displacer occupies the expansion space and the power piston moves from left to right compressing the working fluid and rejecting heat through the cooler. From b-c the displacer moves to the compression space thus transferring the working fluid to the expansion space. From c-d heat is added to the fluid causing the gas to expand and drive the power piston from right to left during process d-a. Net power is produced because the fluid pressure acting on the power piston is larger in its right-to-left motion than in its left-to-right motion. An integral part of the Stirling cycle is the method for extracting power from the engine. Several types of configurations exist for arranging the displacer and power piston. Stirling engines can be separated in to two basic groups: kinematic and free-piston. The kinematic engine is fixed or constrained by the drive mechanism. A free-piston machine has a displacer and power piston that are free to move within the engine and are not physically attached to each other.

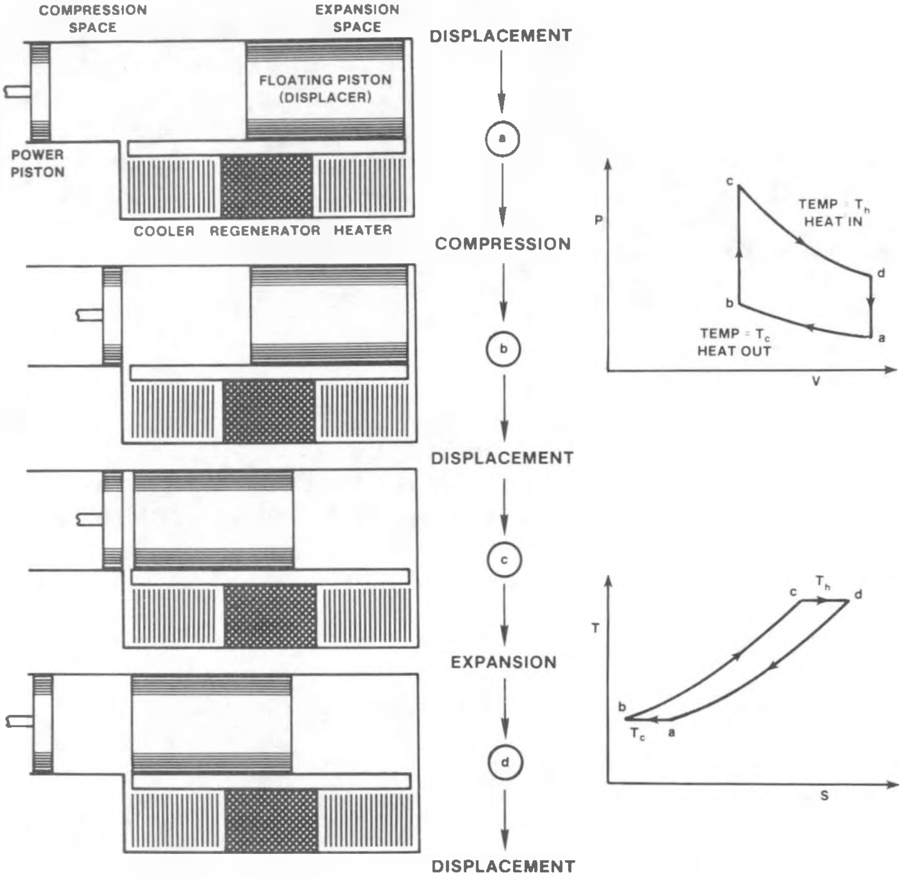

Figure 1. Stirling Cycle

The first modern solarized kinematic Stirling Power Conversion Assembly (PCA) was developed by United Stirling (USAB) with Fairchild Industries Stratos Division (FSD) beginning in 1979 under a contract with JPL. Under this contract, USAB redesigned their 4-95 double-acting Stirling kinematic engine to operate as a solar engine. The output mechanism uses twin crankshafts coupled through gears to a single output drive shaft. FSD was the prime contractor and was also responsible for a hybrid solar/natural gas receiver for the USAB 4-95 (Figure 2). The USAB 4-95 demonstrated 350 hours of successful bench testing. At 1500 rpm and a heater temperature of 1328°F (720°C), the measured efficiency was 38%* at 22 kWe output using helium as the working fluid. This engine was then integrated with the FSD receiver. The USAB 4-95 engine was never tested extensively on-sun because the receiver tubes leaked helium, which caused loss of engine operating pressure [1]. However, this engine was the basis for the very successful Vanguard project.

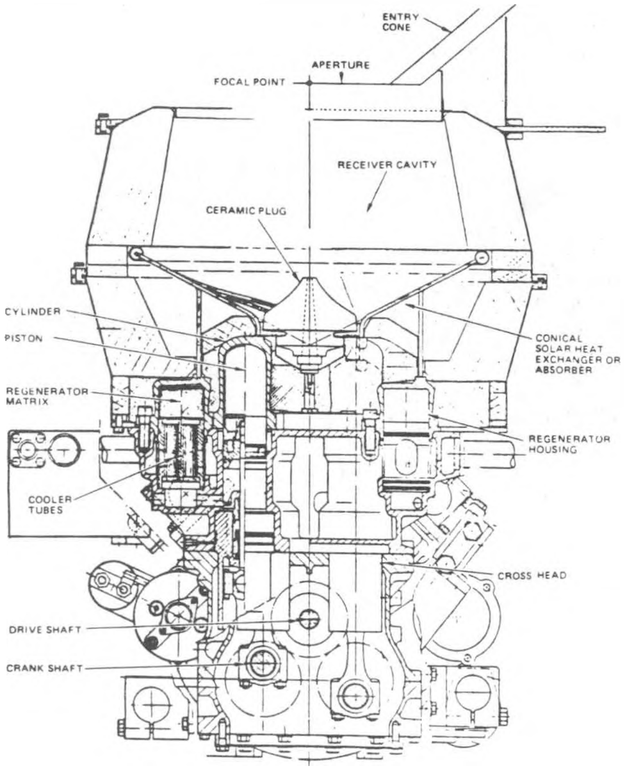

Figure 2. USAB 4-95

In May 1982 Advanco Corporation entered into a cooperative agreement with DOE to design, fabricate, and test a 25 kWe Stirling engine on a parabolic dish called the Vanguard. Based on the previous work by USAB, Advanco chose the USAB 4-95 as the baseline engine. An up-dated version of this engine labeled the 4-95 Mk II Solar Engine was actually used. Advanco

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*Note: efficiency is defined as electrical power output divided by heat input to the engine.

completed the design and assembly of the Vanguard module in November 1983 at a specially constructed test site in Rancho Mirage, California (Figure 3). Between February 1984, when the module began operation, and during September 1984 the Vanguard produced 13,822 kWh of electricity. In addition, a net conversion efficiency of 29.4% from solar insolation to electricity was obtained [2]. As a follow-on effort, Advanco operated the Vanguard for another 1,372 hours from October 1984 through July 1985 and produced 15,789 kWh [3,4]. Vanguard operations were completed in July 1985.

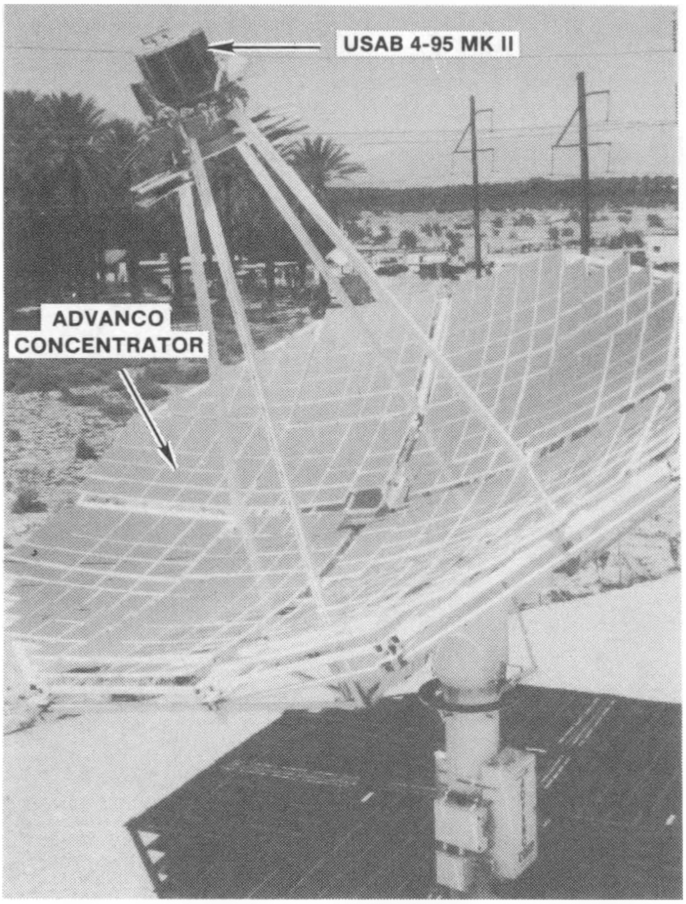

Figure 3. Vanguard Module

Another kinematic engine which shows strong possibilities for the solar application in the near future is being developed by Stirling Thermal Motors [5]. This is a double-acting system which uses a variable swashplate drive to deliver the shaft power (Figure 4). A variable swashplate has two advantages: first, the swashplate converts the reciprocating motion of the pistons to rotating motion, and second, the variable swashplate allows the swept volume of the piston to be controlled very easily, thereby controlling output power.

The swashplate drive allows the engine to be physically quite small, thus giving it a favorable specific power.

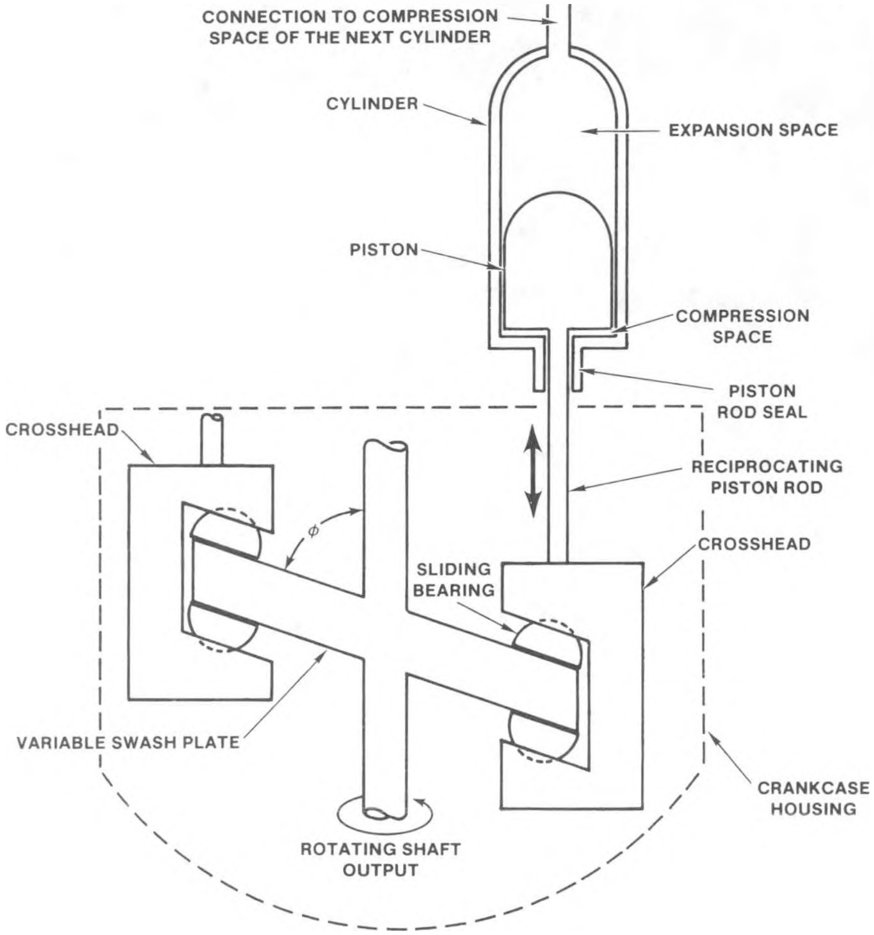

Figure 4. Swashplate

In addition to the variable swashplate the STM4-120 features a pressurized crankcase and heat pipe inputs to the heater head. The pressurized crankcase allows the piston rod seal to act only as an oil scraper instead of a combination oil scrapper/ pressure seal. The heat pipe input makes this engine heat source independent. Any number of energy sources may be used to vaporize sodium in the evaporator section of a heat pipe (Figure 5). This type of heat input allows flexibility in the design of solar receivers.

During FY87 SNLA will take delivery of an STM4-120 engine for demonstration experiments. A solar receiver, radiator, and control system will be integrated with the engine by SNLA. By mid FY88 it is anticipated that the STM4-120 PCA will be mounted to a TBC for solar testing.

The free-piston Stirling engine (FPSE) is a relatively new concept relative to other Stirling engine designs. This method of power extraction was first discovered in the early 1960s [6].

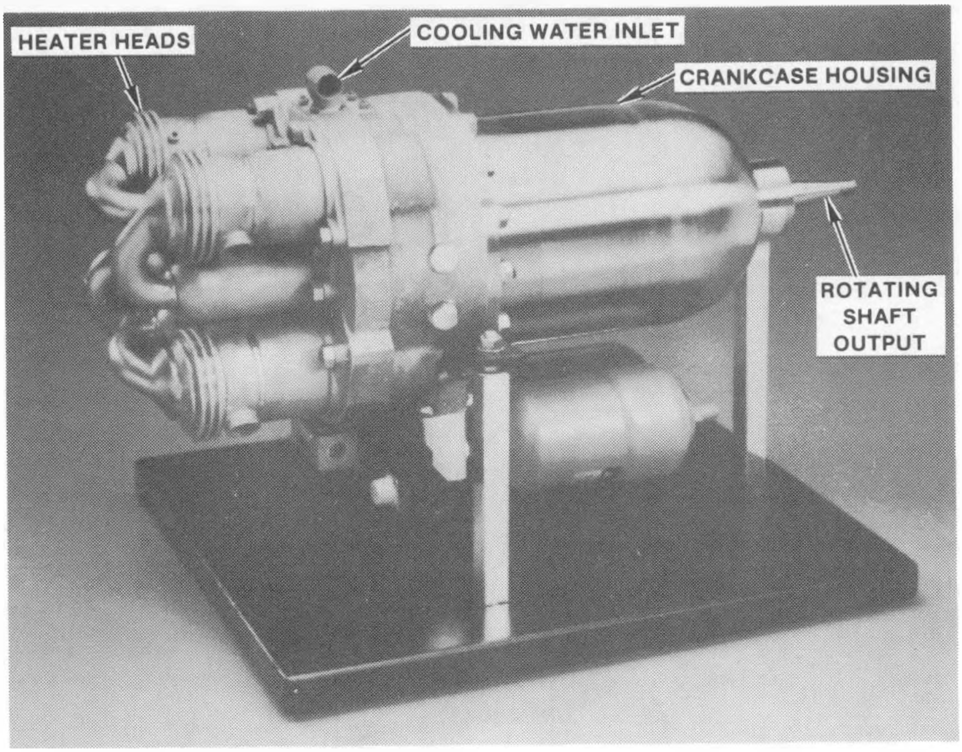

Figure 5. STM4-120

Figure 6 shows a detailed cross section of a FPSE, in particular, the Space Power Demonstrator Engine (SPDE), designed and built by Mechanical Technology, Inc. (MTI). This engine is designed for 25 kWe, 25% efficiency, and an operating frequency of 105 Hz at a temperature ratio of T(high)/T(low) = 2.0.

During 1978-79 JPL, with the help of NASA/Lewis Research Center (LeRC), analyzed the FPSE for solar thermal application. The FPSE was considered because it offers the potential for high reliability, high cycle efficiency, long life, low maintenance, and low production costs. As a result, a 15 kWe FPSE with a linear alternator and hydraulic converter for a rotary alternator were proposed [1]. It was projected that a 15 kWe FPSE could be 38% efficient. However, lack of funding and the immaturity of the technology at that time resulted in a decision to defer further development.

In September 1985 SNLA teamed with NASA/LeRC to develop an Advanced Stirling Conversion System (ASCS) using the FPSE. The first phase of the ASCS will be a conceptual design as well as a cost and manufacturing study. A second phase would consist of a detailed design, fabrication, and field test. The ASCS conceptual design objectives are

- Define the ASCS configuration
- Predict ASCS performance over range of solar input
- Estimate system weight
- Define engine and electrical power conditioning controls
- Define key technologies needed for the ASCS
- Provide a manufacturability and cost evaluation for the ASCS

In September 1986 LeRC placed contracts with Stirling Technology Company (STC) and MTI for Phase I of the ASCS. Their proposed systems are

MTI	STC
Single Stirling with dynamic balance and linear alternator 120V-1Ø	Single Stirling with hydraulic output and ground based hydraulic system with a rotary induction generator 240V-3Ø or 120V-1Ø

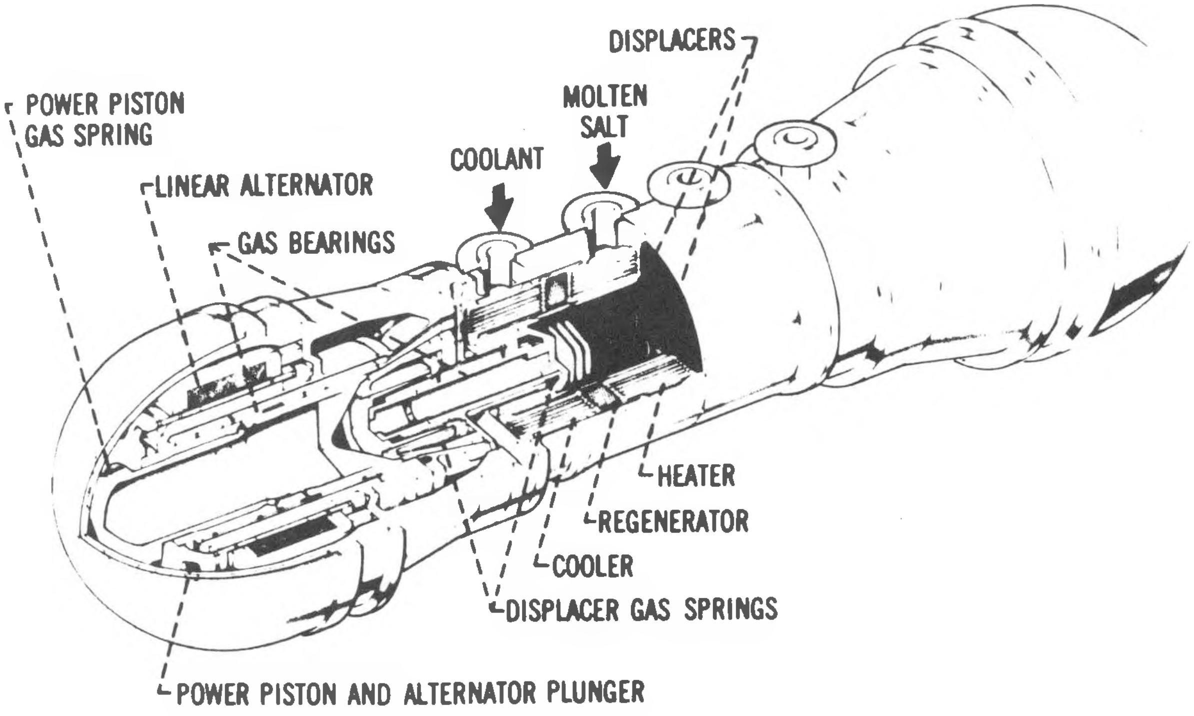

Figure 6. Space Power Demonstrator Engine

Table 1

CHARACTERISTICS OF THE PROPOSED ASCS

	MTI	STC
Heat Supplied (kWt)	75	75
Electric Power (kWe)	25.0	24.8
Efficiency (Solar to Electric)	33.3%	33.1%
Heat Pipe Heater	YES	YES
Heater Temperature (Metal) K	1073	1073
Cooler Temperature K	356	323
Ratio Th/Tc	3.0	3.3
Working Fluid	He	He with Freon Buffer
Working Pressure (bar)	100	138
Weight (on TBC)	907 kg 2000 lb	82 kg 181 lb

Figure 7 and Figure 8 detail the proposed system by MTI and STC, respectively.

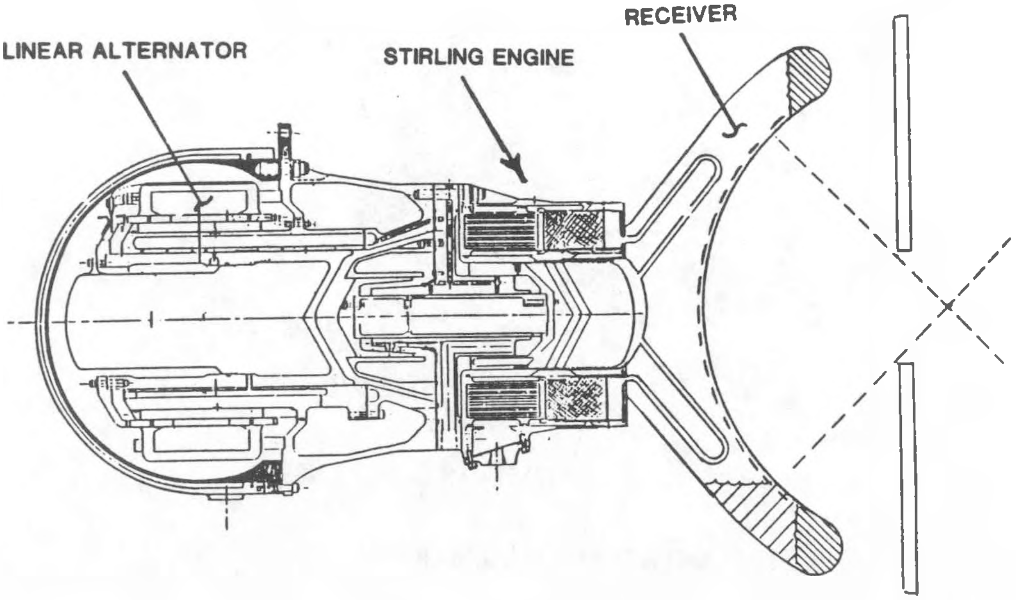

Figure 7. MTI Conceptualized ASCS

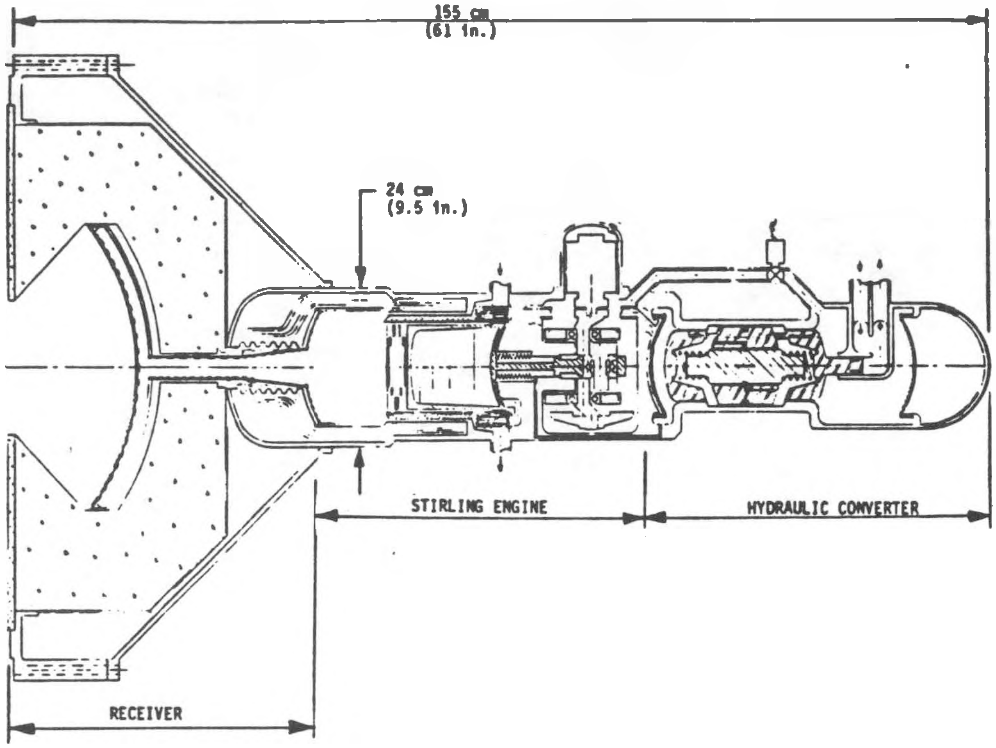

Figure 8. STC Conceptualized ASCS

3. LIQUID METAL THERMAL ELECTRIC CONVERTER

In 1984 SNLA embarked on the development of a Liquid Metal Thermal Electric Converter (LMTEC). The LMTEC is based on a Sodium Heat Engine (SHE) developed at the Ford Scientific Laboratory (Ford Motor Company). At the Ford Motor Company, the SHE has demonstrated an efficiency of 19% and produced 22 watts of electrical energy at 1472°F (800°C) [7,8].

The LMTEC offers several potential advantages for its use in a solar application:

- No moving parts except a simple electromagnetic pump
- Very low maintenance
- High efficiency
- Light weight
- Long life and High reliability
- Silent operation
- Simple design

Production costs for high volume production could be reasonable because there are no inherently expensive parts.

The LMTEC is a electrochemical "heat engine" that directly converts thermal energy to electrical energy. LMTEC uses a liquid metal such as mercury, sodium, or potassium as the working fluid. The liquid metal is vaporized with solar energy and is expanded through a Beta Alumina Solid Electrolyte (BASE). The BASE material allows only cations to pass. The electrons which are removed are routed through an external circuit and recombined with the cations which have passed through the BASE. The vapor is then condensed, and the liquid metal is then pumped back via an electromagnetic pump to the high temperature region, "boiler," where it begins the cycle again (Figure 9).

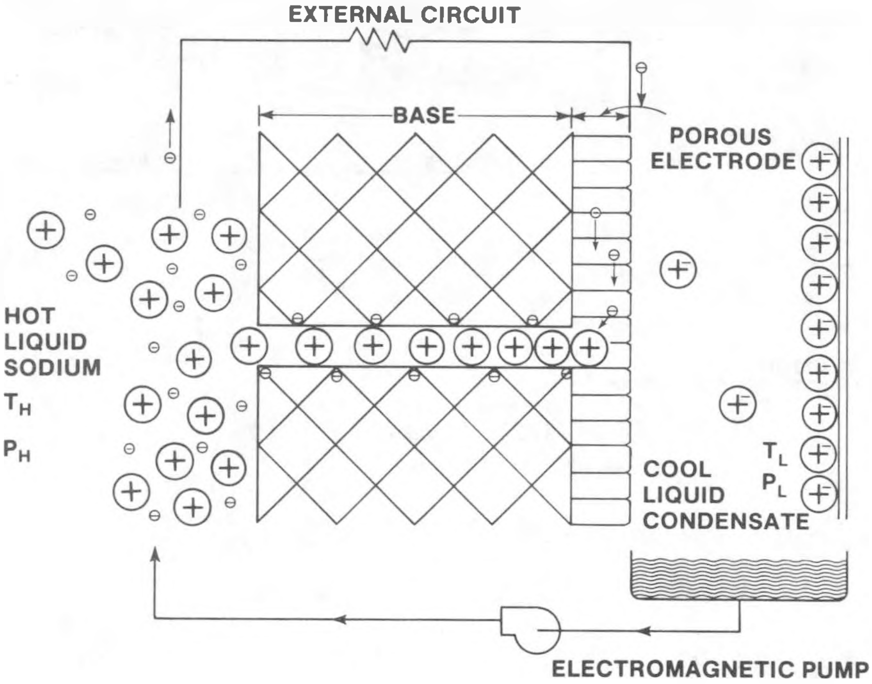

Figure 9. Atomic Level of LMTEC

Thermodynamically, the LMTEC cycle can be characterized on a temperature-entropy diagram (Figure 10). Saturated liquid metal is pumped from state a to b. From b, the metal is heated and expanded to point c producing work. The process b to c is fairly complicated and difficult to analyze because constant pressure heating and isothermal expansion take place between two state points. Point c represents the vapor pressure of the metal at the condensate temperature T_L. Process c-d-a is the heat rejection portion of the cycle. The liquid metal releases its sensible and latent heat in the condenser and returns the saturated liquid metal to the electromagnetic pump.

SNLA is developing the LMTEC concept using solar energy as the heat source with an electrical output of 25-50 kWe (Figure 11). Analysis by SNLA has shown that for the dish-electric application mercury would be the preferred working fluid [9]. The advantage of this working fluid is primarily due to mercury's better thermodynamic characteristics which are higher vapor pressure and lower freezing temperature.

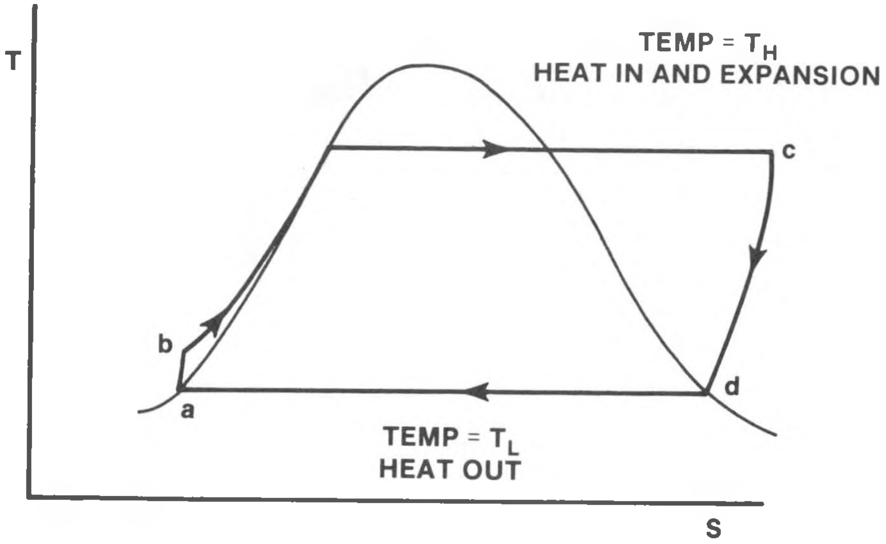

Figure 10. LMTEC T-S Diagram

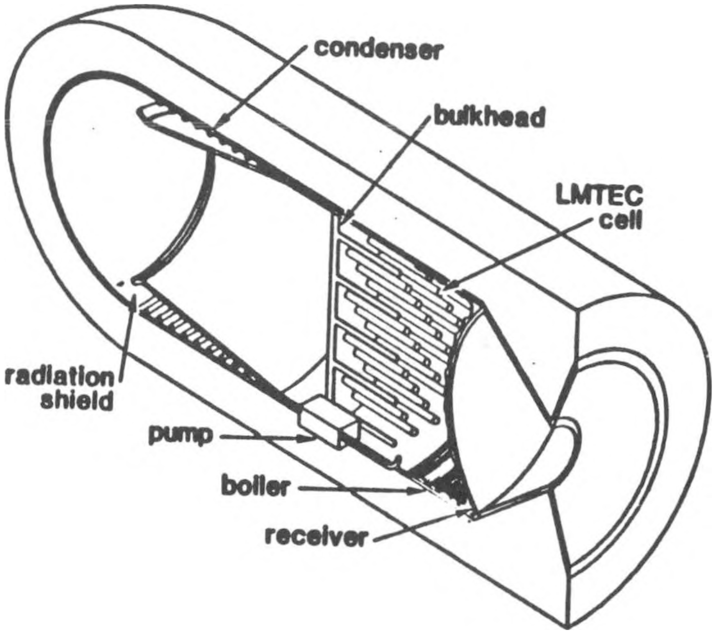

Figure 11. 25 kWe LMTEC with Solar Receiver

Prior to a full-size LMTEC, lower power (50 Watts to 1 kWe), single cell bench test modules (Figure 12) are scheduled for fabrication and evaluation during the next several years. These units will initially use sodium as the working fluid and later, as a mercury based electrolyte is developed, bench module testing will be based on the mercury LMTEC concept.

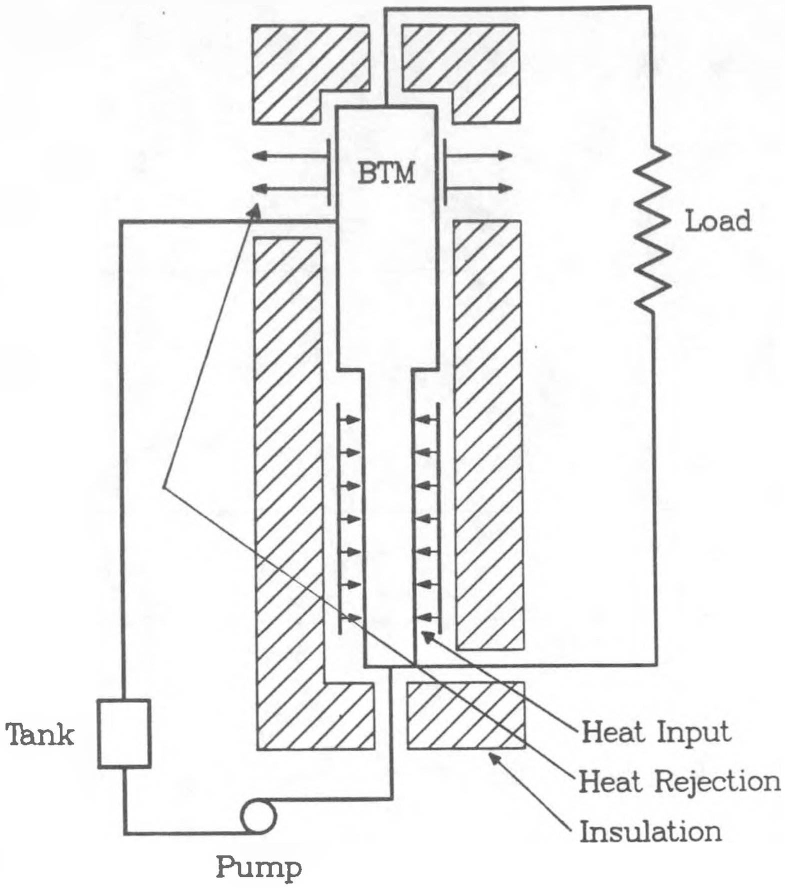

Figure 12. Bench Test Module

4. RANKINE CYCLE

The first heat engine to be developed specifically for dish-electric applications was an organic Rankine cycle (ORC). In 1979 Ford Aerospace & Communications Corporation (FACC) was awarded a contract from JPL to develop and test a Rankine cycle dish-electric system. Barber-Nichols Engineering (B-N) was subsequently chosen to design and build the ORC. This design is a single stage axial flow turbine using toluene at 750°F (400°C) as the working fluid. In a Rankine cycle the working fluid is vaporized in a boiler at high pressure, expanded through a turbine which drives an alternator and condensed in a condenser to begin the cycle again. In the B-N engine the toluene is also regeneratively heated and cooled to increase the thermal efficiency of the system (Figure 13). At the rated power point of 20 kWe, the predicted efficiency was 26% [10,11]. In February and March of 1982 the ORC was tested at JPL's Parabolic Dish Test Site (PDTS) for 33 hours. Performance of the ORC was near predicted values with an efficiency of 21.9% and a power output of 15.5 kWe [12]. After this test, it was found that improvement of an axial thrust bearing was required along with rebuilding the inverter which had caused several problems. New bearings were designed and successfully tested for 200 hours in 1984 [13].

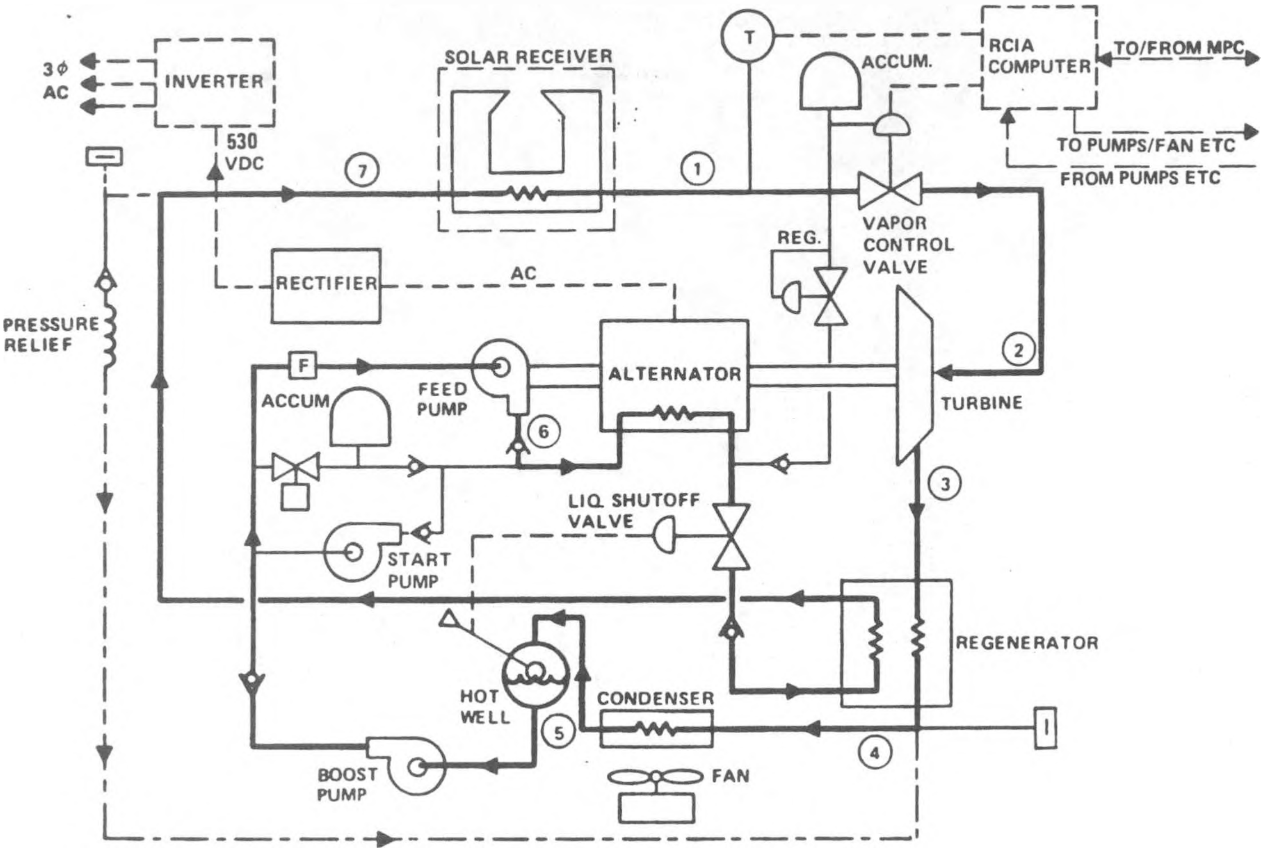

Figure 13. Schematic of ORC System

At the end of 1984, B-N began designing a new control system for the ORC under an SNLA contract. The previous control system combined engine control and data acquisition. It was felt, for ease of testing, that the controls and data acquisition should be separated. During mid-1985, the ORC and new control system were delivered to the DRTF at SNLA. This ORC has been installed on a TBC and has operated for 21 hours on-sun. In the coming months additional data for this ORC system will be gathered (Figure 14).

The next generation ORC is currently being developed by B-N under a DOE contract for Small Community Solar Experiment #1 to be installed at Osage City, Kansas. Off-the-shelf components and redesign of heat exchangers and turbine blades are being incorporated in this engine to decrease costs and improve engine performance [14] (Figure 15).

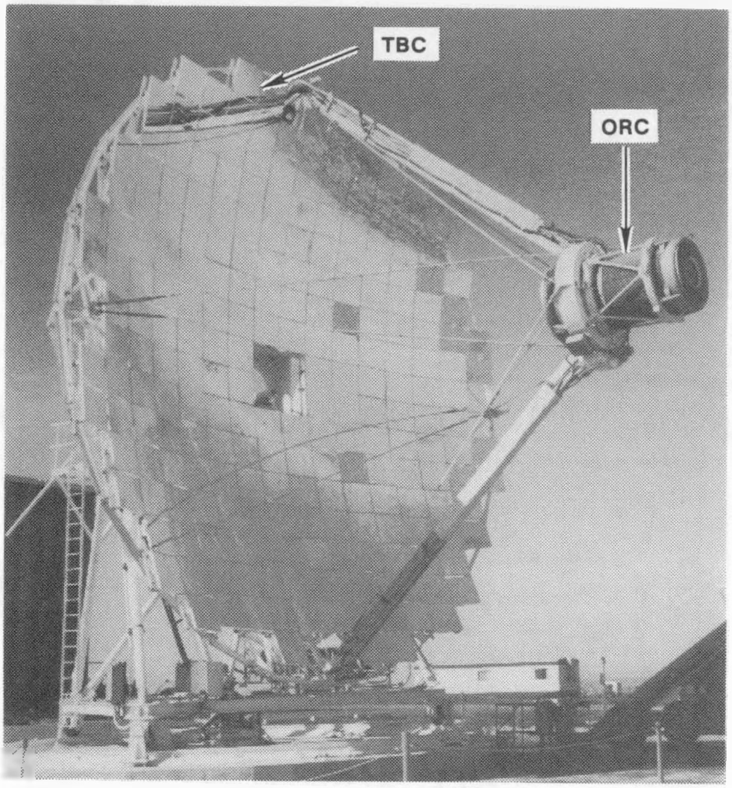

Figure 14. ORC on Test at DRTF

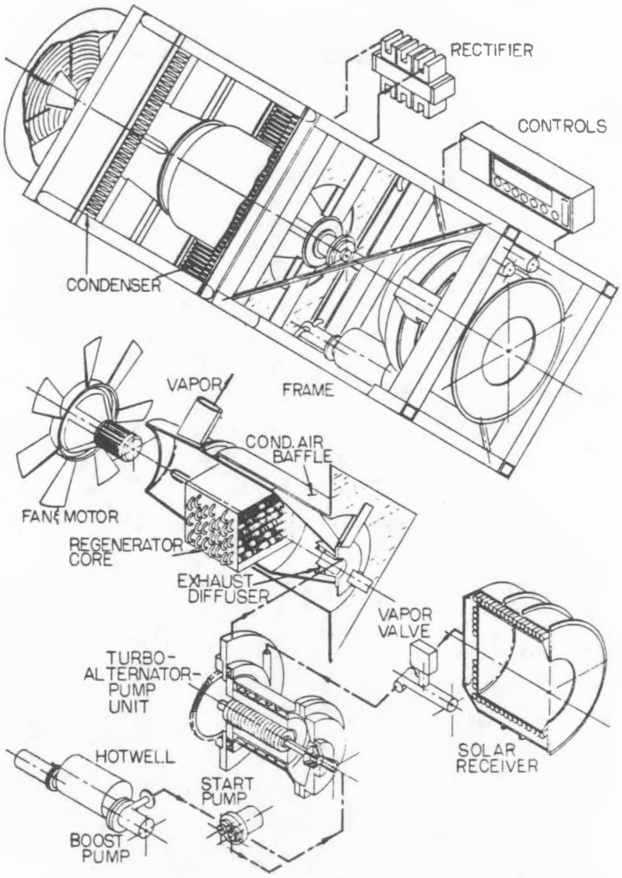

Figure 15. SCSE#1 B-N Engine

5. BRAYTON CYCLE

The use of Brayton cycle engines (gas turbines) for solar dish-electric applications has been considered for many reasons: for example, relatively simple rotating parts, existing experience base, demonstrated long life, low maintenance, and the potential for high-temperature, high-efficiency operation using ceramic parts.

The simple Brayton cycle consists of a compressor, combustor, turbine, and regenerator or recuperator. The usual working fluid air, is drawn in through the compressor, pressurized, through the combustor where energy is added to the air, and then expanded through the turbine which outputs shaft power. The regenerator or recuperator is added to increase the cycle's thermal efficiency by extracting waste heat from the exhaust and supplying it to the inlet air supply (Figure 16). In a solar application the energy input in the combustion chamber can be augmented with a solar receiver. Using a combustor and receiver, the engine would be capable of operating with various energy input modes.

JPL began an effort to solarize existing gas turbine engines that were under current development and could utilize the heat from a parabolic dish. This approach was a way for the solar program to obtain an engine with little expense for basic development. Two engines were identified as being capable of meeting the criteria. These were an Advanced Gas Turbine (AGT-101) and a Subatmospheric Brayton Cycle (SABC) being developed by Garrett Turbine Engine Company (GTEC) and Garrett AiResearch Manufacturing Company, respectively [15].

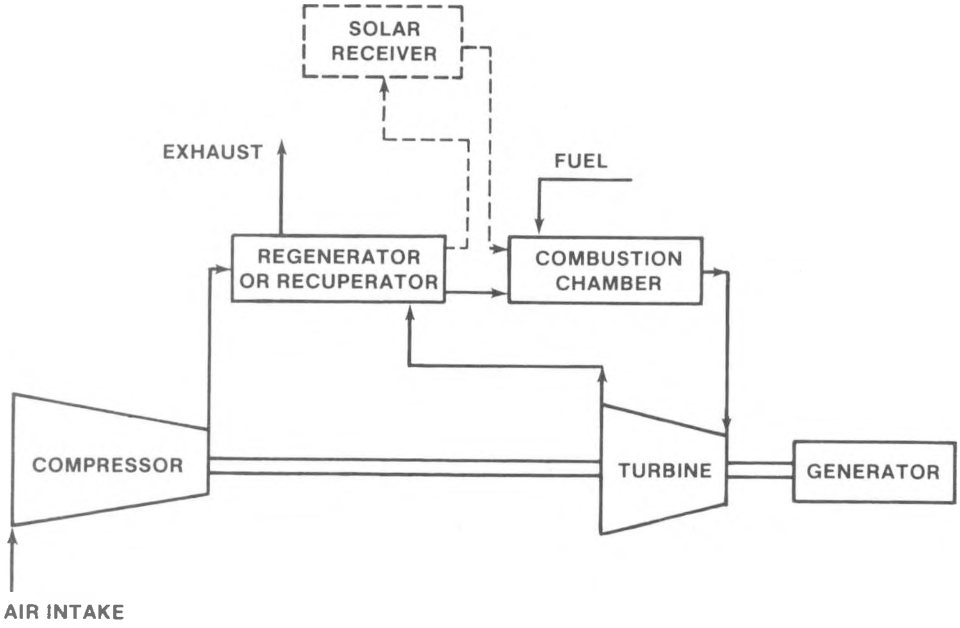

Figure 16. Open Brayton Cycle

The AGT-101 was being developed for automotive application under a DOE program. It was designed as a regenerated open cycle machine which operates at a turbine inlet temperature (TIT) of 2500°F (1370°C) and utilizes several ceramic parts. The AGT uses a single stage radial flow turbine and a single stage centrifugal compressor with a pressure ratio of 5:1 (Figure 17).

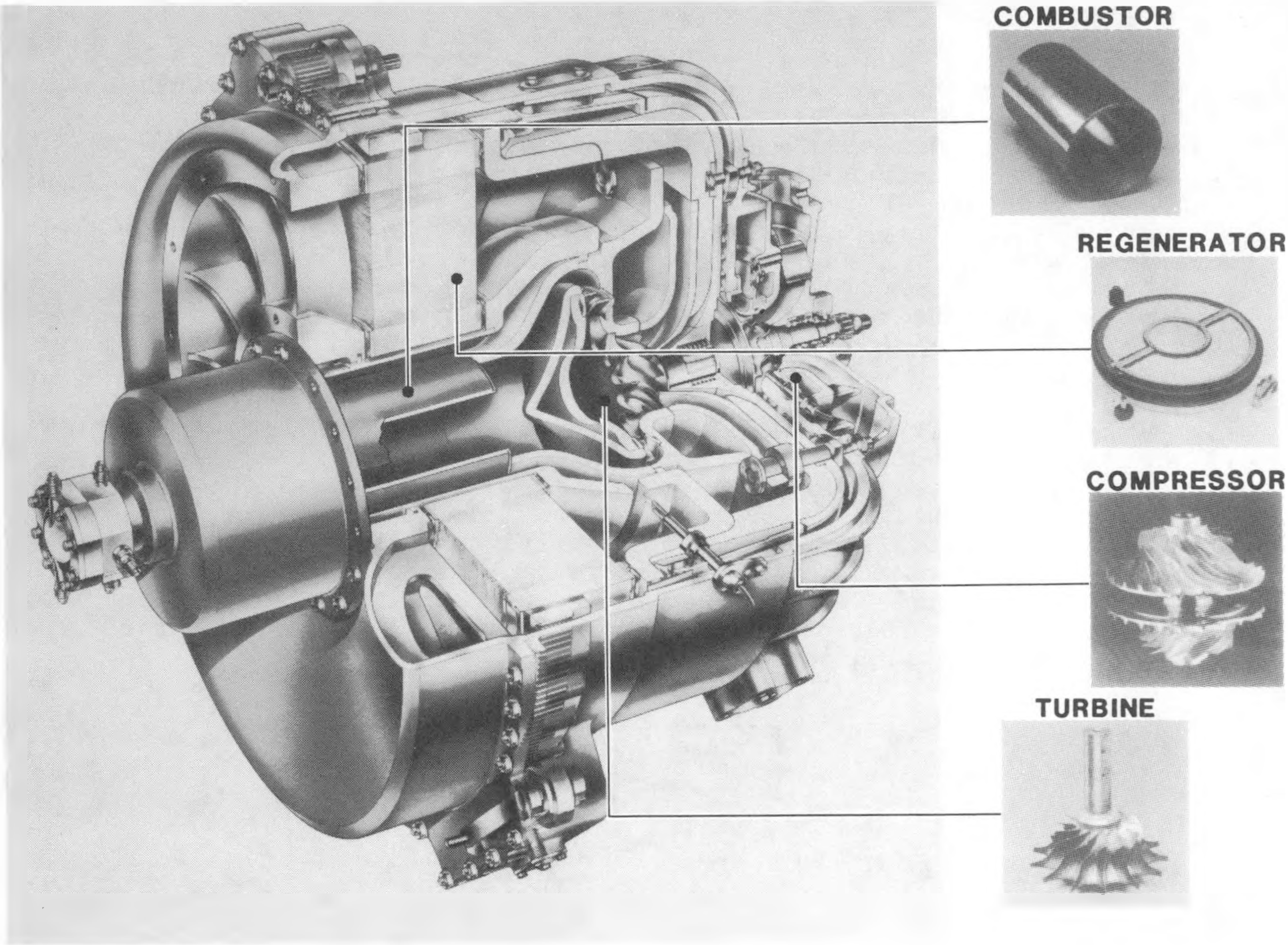

Figure 17. AGT-101 Section

Prior to the 2500°F configuration, an engine with all metal components, except for a ceramic regenerator with a TIT of 1600°F (870°C), was constructed for component testing. In 1982 JPL chose the 1600°F version for modification to operate as a PCA using a hot air solar receiver and induction generator [16]. It has been called the Solarized Automotive Gas Turbine (SAGT-1A) (Figure 18).

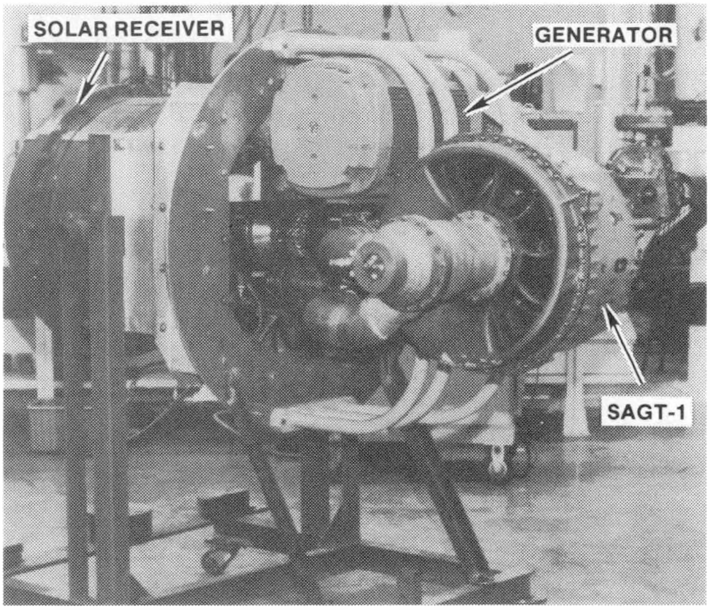

Figure 18. SAGT-1A

Its development has followed a parallel path with the development of the AGT-101. During the first quarter of 1986, GTEC completed development and bench testing of the SAGT-1A. Predicted performance for the SAGT-1A was 14 kWe at 80,000 rpm and 20% efficient at TIT of 1700°F (930°C) [17]. Measured performance has been in the range of 6-10 kWe at 9% efficient using fossil fuel input [18,19]. Reduction in performance has been mainly due to the leakage between ceramic and metal surfaces. In the 2500°F engine this problem could be eliminated because of all ceramic parts resulting in equal thermal expansion.

The SAGT-1A incorporates a 25 kWe induction generator, solar receiver, gear reduction system, and in-line combustor. With a solar receiver and combustor, the SAGT-1A is capable of operating at peak performance since both systems can supplement the heat input. The air solar receiver is a Sanders Associate design utilizing a ceramic honeycomb matrix [20].

The SAGT-1A was delivered to SNLA's Distributed Receiver Test Facility (DRTF) for evaluation on a Test Bed Concentrator (TBC). This evaluation is scheduled for late FY86 and will be the first attempt to operate the SAGT-1A in a solar-only mode. The operation of the SAGT-1A is intended only to demonstrate the AGT in a solar application.

The second Brayton cycle engine, the SABC, was adapted from a Gas Research Institute (GRI) heat pump program. The SABC is a semi-open recuperated cycle engine that utilizes a single stage radial flow turbine, centrifugal compressor, recuperator and an atmospheric combustor (Figure 19). The SABC is different from the standard Brayton open cycle in that the high pressure part of the cycle is atmospheric pressure instead of 4 or 5 times atmospheric. On the low pressure side the cycle is a partial vacuum. Because of these operating parameters the SABC must use an additional heat exchanger to pre-cool the compressor inlet air to minimize the compressor power requirements.

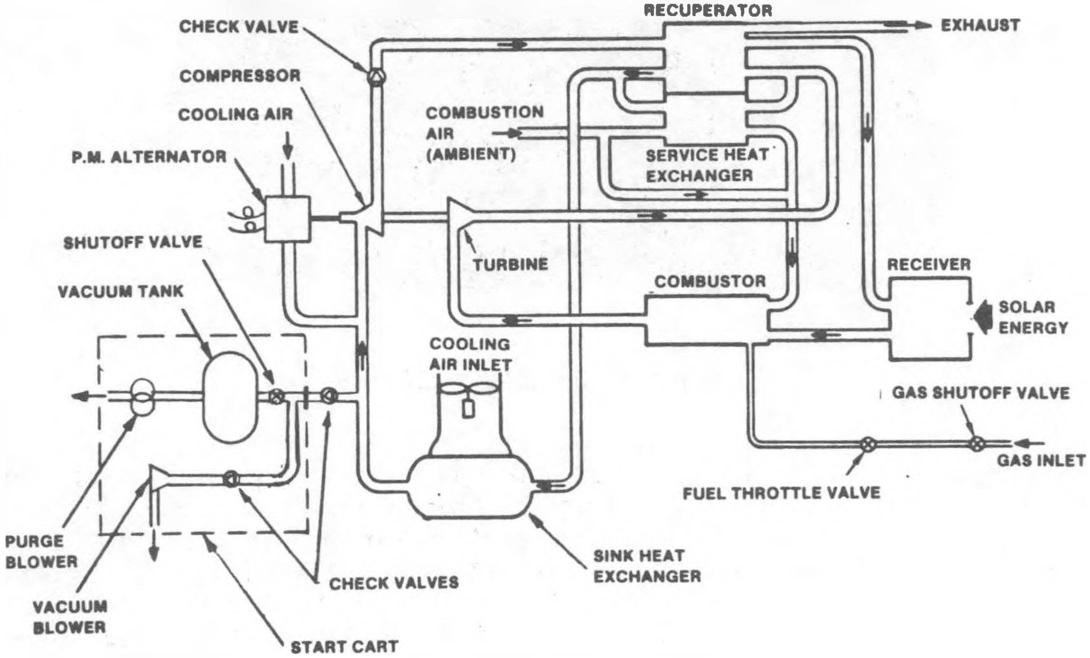

Figure 19. Schematic of SABC System

In 1981 Sanders Associates Inc. used a modified SABC for a Development Test Model (DTM). The DTM consisted of a SABC mounted to a LaJet LEC 460 concentrator with a Sanders' designed hot air receiver. The DTM was tested at Sanders' facility in Nashua, New Hampshire. The design point of the SABC was 75,000 rpm at a TIT of 1600°F with an efficiency of 25% and a power output of 5 kWe [21]. At the conclusion of the DTM testing, the actual performance of the SABC was 6.0% efficient at a 2.9 kWe output using both solar and fossil fuel input (Figure 20). Major contributors to this lower performance were infiltration leaks, high pressure drops, low heat sink effectiveness, and excess combustion make-up air [22].

As part of Sanders' contract with SNLA, they have completed a preliminary design for a 20 kWe positive pressure open cycle engine [23]. This report outlines a Brayton PCA using off-the shelf components. Sanders predicts an efficiency of 30-33% at 1600°F could be achieved with this engine.

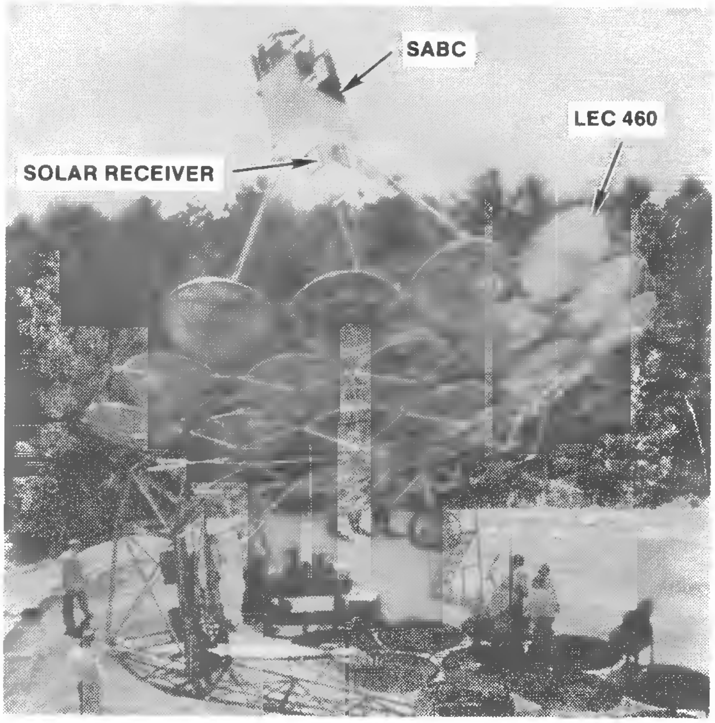

Figure 20. Development Test Model (DTM)

6. FUTURE DEVELOPMENT AND CONCLUSIONS

Because funding for heat engine development is limited in DOE's Solar Thermal Program, different heat engine technologies must be carefully evaluated before undertaking a development program. To help determine which engines fit the dish-electric application, SNLA conducted an assessment of heat engines [24]. As a result, the organic Rankine and kinematic Stirling cycles were identified as engines capable of meeting DOE's near-term goals.

The free piston and kinematic Stirling cycles had the highest probabilities of meeting DOE's long-term goals of $300 kWe (1984$) with an annual efficiency of 41% [25]. The LMTEC, although much less developed, also has high potential. Therefore, over the next few years, the DOE development program will be concentrating on these two cycles.

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