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TESTING OF THE STM4-120 KINEMATIC STIRLING ENGINE FOR SOLAR THERMAL ELECTRIC SYSTEMS*

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ABSTRACT

The Department of Energy's (DOE) Solar Thermal Program has identified the Stirling cycle heat engine as the conversion device for dish-electric systems with the most potential for meeting the program's goals for efficiency, reliability, and installed cost. In an effort to advance the technology toward commercialization, Sandia National Laboratories has recently acquired a Stirling Thermal Motors, Inc. (STM) kinematic Stirling engine, STM4-120, for evaluation. The engine is being bench tested at Sandia's Engine Test Facility (ETF) and will be combined later with a solar receiver for on-sun evaluation. This paper presents the bench-test approach including: test system layout, instrumentation, controls, testing parameters, and preliminary performance results for the STM4-120.

INTRODUCTION

The Stirling cycle heat engine has long been considered for solar thermal applications. In fact, in 1872 John Ericsson, the Swedish-American engineer, constructed a small "Stirling Cycle Sun Motor" utilizing a parabolic reflector to collect and concentrate solar energy to a Stirling engine (1). Since this time, advances in materials and the ability to theoretically analyze the Stirling cycle engine have made it a serious contender for solar applications. Stirling cycle engines have several qualities that make them excellent candidates for solar thermal systems. These characteristics include: high conversion efficiencies, 30 to 45%; completely closed cycle, which could mean a potential for extended life; high specific power, implying reduced weight at focal point of the dish; quiet and benign operation, which allows for installation in inhabited areas; and external heating, which permits for hybrid operation with fossil fuel and solar energy (2).

In the DOE-funded Vanguard project, a Stirling engine was mounted at the focus of a parabolic dish and successfully demonstrated a net solar-to-electric conversion efficiency of 29.4%. The Stirling engine in this system was a United Stirling (USAB) 4-95 automotive engine that was modified for solar applications. The design life of this engine before major overhaul is 3,500 hours. For a solar application at least 60,000 hours are required to meet levelized energy costs (LEC) goals. The major life restriction of the 4-95 was the mechanical hardware such as the drive mechanism and piston rod seals. In addition, the directly illuminated heater heads demanded an accurate and costly concentrator. With four heater heads, an equal solar flux was required on each head for high cycle efficiency and life of the engine. Finally, the power control system was very complex and required numerous pieces of hardware to change the pressure of the hydrogen working fluid. Because of these modifications, the USAB 4-95 was a compromise approach and did not lend itself to a reliable long-term system. As a result, DOE's Solar Thermal Program began the search for a near-term Stirling engine that would meet the requirements for reliability, life, and performance for a dish-electric system. The result of this search indicated that the Stirling Thermal Motors,

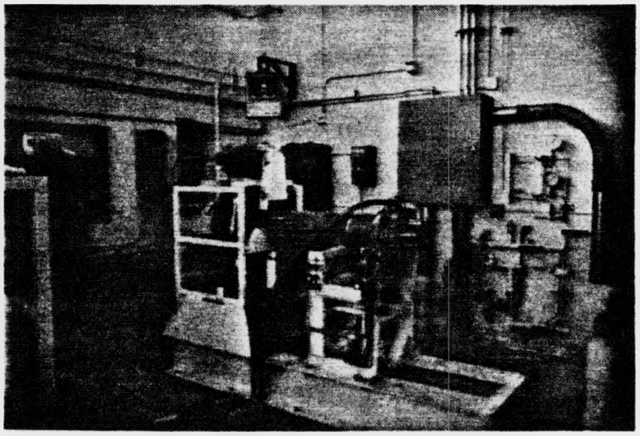

Fig. 1 STM4-120 In ETF Test Cell

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STM4-120, kinematic Stirling engine shows strong possibilities for meeting these requirements (3). Sandia National Laboratories, the lead laboratory for solar thermal electric systems, has procured an STM4-120 for bench testing at Sandia's Engine Test Facility (ETF) (Figure 1). Obtaining performance and reliability data will be the main thrust of this testing. With Sandia's reflux solar receiver development, an eventual on-sun evaluation of a STM4-120 and reflux receiver is planned during the coming year.

BACKGROUND

The STM4-120 kinematic Stirling engine is a double-acting piston design coupled to a variable swashplate drive mechanism. This drive mechanism allows for a compact, reliable and simple control system by changing the piston's stroke while maintaining a fixed volume of helium working fluid. At a heater head tube temperature of 800 °C and cooler temperature of 45 °C, the engine is designed to deliver a nominal 25 kW of shaft power when it is operating with full stroke (48.5 mm) at 1800 RPM. This corresponds to a conversion efficiency, defined as shaft power out divided by heat into the engine, of 42 to 45% without auxiliaries. In addition, the STM4-120 uses sodium heat pipe technology to provide energy input to the engine. With a sodium heat pipe design a solar receiver can be constructed that has the ability to "smooth out" the uneven flux distribution on the solar absorbing surface. Therefore, the demand for an accurate and costly parabolic concentrator is avoided. Finally, the STM4-120 was designed with a pressurized crankcase charged to the mean cycle pressure. The resulting differential pressure across the piston rod seals is relatively small as compared to the approximately 1500 psig that existed across the rod seals in the USAB 4-95. This allows the piston rod seals to act only as a means of separating the crankcase oil from the helium working fluid. All of these design features combined enable the STM4-120 to meet the objectives for a second generation of dish-electric systems.

ENGINE TEST SYSTEM LAYOUT

Figure 2 is a schematic diagram for the STM4-120 engine test system. The system consists of an engine/dynamometer skid, a dynamometer cooling system, an engine cooling skid, a combustion skid, a helium supply system, an engine control and emergency shutdown unit, and the instrumentation with the associated data acquisition system. This is all combined in a test cell at Sandia's ETF.

The engine/dynamometer skid is a teststand for the engine, the dynamometer, and the four gas-fired heat pipes. Each heat pipe has a propane-fired combustor attached to it that transfers heat to the heat pipe's sodium filled finned evaporator. Sodium is vaporized at 800 °C and travels up to the engine heater heads that contain a tube-in-shell heat exchanger. The sodium condenses on the tube bundle and transfers its latent heat to the helium. Power generated by the engine is absorbed and measured with an eddy-current dynamometer. The dynamometer maintains a constant speed by varying the shaft torque. Energy absorbed by the dynamometer is converted to heat that is then removed from the system through cooling water. The dynamometer cooling system consists of a pump, a dry-type cooling tower (located outside the test cell), and the associated pipes and valves.

The engine cooling skid provides an accurate method of controlling the cooling water inlet temperature to the engine. A 50/50 water-glycol mixture is circulated through the engine at a flowrate of 2.6 l/sec (42 gpm). The coolant is pumped through a flow control valve, a tube-in-shell heat exchanger, a filter, a turbine flowmeter, through the engine and back to a vented surge tank. The inlet temperature is maintained by controlling the flowrate of water through the shell side of the heat exchanger.

The combustion skid contains the system to control the fuel and air flows to the four combustors, and thereby, controlling the heat pipe evaporator temperatures. The evaporator temperatures are input to the PID controllers and they output to the valve controllers, which are mechanically linked to the air and fuel valves. The valves are micro-ratio valves that maintain a constant air-fuel mixture through the entire operating range of the valves. In addition, the combustion skid has the piping and electronics to safely deliver and control the propane. The propane inlet piping contains a "block and bleed" system to contain the gas. Flame sensors or UV (ultraviolet) detectors are used to monitor the ultraviolet light generated by the gas combustion. Finally, four high-temperature controllers limit the temperature on each of the evaporators. If a flame is not detected in any one of the combustors or a temperature limit is reached, the main gas valve and blocking valve are automatically closed so that unburned propane is not collected in the combustors or the exhaust system.

Helium is supplied to both the gas cycle side and crankcase side of the engine. The two sources are completely independent, eliminating the possibility of contaminating the gas cycle of the engine with crankcase oil. The helium bottles and manifolds that are located outside the test cell are connected to 1/4" stainless steel tubing run into the test cell. Each supply line has a pressure regulator, a filter, shutoff and vent valves, a safety relief valve, and a pressure gage. The lines are then routed to the engine with four individual

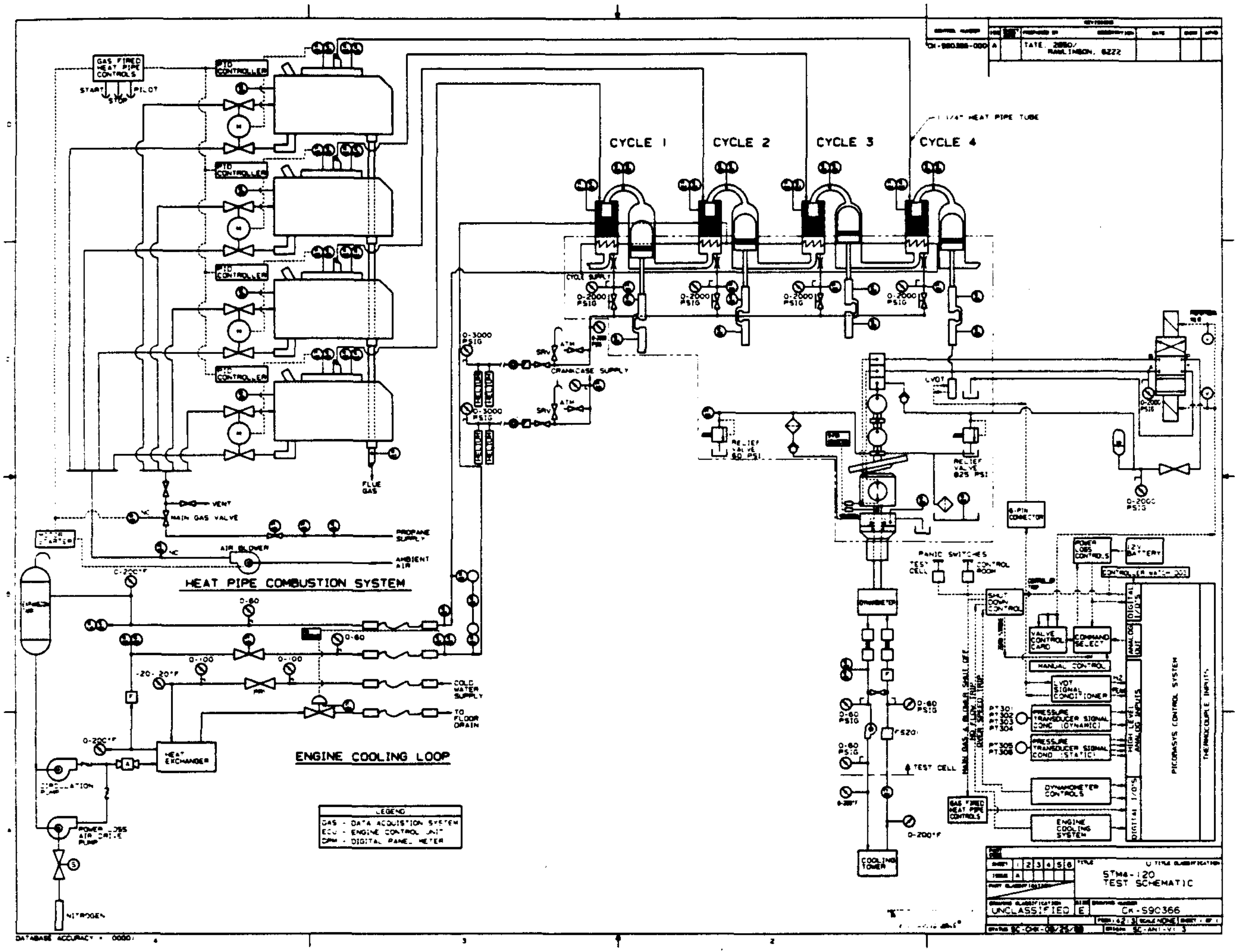

Fig. 2 Schematic Diagram STM4-120 Test

cycle lines. Each cycle line contains a shutoff valve near the engine to reduce the dead space volume. Due to the difficulty in containing helium, nearly all of the plumbing connections are silver-soldered.

Since the STM engine is being fully tested for the first time outside of STM's facilities, the engine and heat pipes are thoroughly instrumented. The engine temperatures are monitored with thermocouples (type K) at the front and rear crossheads, oil sump, and end seal. Other engine analog signals include the four cycle pressures, crankcase pressure, lube oil pressure, and piston stroke control and feedback. The heat pipes include dual thermocouples to measure the individual temperatures of the heater heads, connecting ducts, and front and rear evaporators. Dual thermocouples were used where possible for redundancy and to avoid paralleling a single thermocouple to several devices. The engine cooling system instrumentation contains mostly type T thermocouples (more accurate than type K) for cooling water inlet and outlet temperatures, as well as the cooling water flowrate and valve position. The dynamometer cooling system contains mechanical pressure and temperature gages plus thermocouples for the dynamometer water outlet temperature. Engine torque and speed signals are sent to the dynamometer controller in the control room through dedicated cables. Other miscellaneous signals include propane pressure, flowrate and temperature and the mass flowrate of air and propane supplied to each combustor.

Some of the data signals are sent to an instrumentation rack located in the test cell that contains signal conditioners. Also, some of the temperatures are run through transmitters to accommodate for multiple signal destinations and devices that cannot accept a low-level voltage signal. Current transmitters are used whenever possible to eliminate noise problems associated with long line lengths. All instrumentation wiring between these various systems is protected by conduit. All instrumentation and signal wiring is routed from the control room outside through a junction box and then to a termination box in the test cell. (Routing all wiring in this manner isolates the two rooms for safety reasons.) Signals from the test cell are then run to the various devices such as the data acquisition system, panel meters, stripchart recorders, indicating lamps and controllers.

The data acquisition system (DAS) is used to collect and store the data from every data channel in the entire system. It is composed of an HP 320 series computer coupled with an HP3852A scanner/voltmeter. The system can scan the 73 data channels in approximately 5 seconds. The HP3852A contains both a slow-speed and a high-speed voltmeter. The slow-speed voltmeter integrates the signal, eliminating any noise superimposed on the low-level signal. Future enhancements to the DAS will include a graphical display of the engine and heat pipes containing real-time data.

Many of the channels read with the DAS are also read with an emergency control unit (ECU). The ECU monitors critical parameters, interfaces with the power control system, and will shutdown the engine if any parameter is beyond its preset limit.

POWER CONTROL AND SYSTEM PROTECTION

The control system regulates the engine's operating power level and protects the system when operating limits are exceeded. The control system is independent of the DAS, but the control and data acquisition systems do share several transducers. Many control functions are carried out by software operations to add flexibility to the controls. The control system also uses hardware limits on operating parameters such as engine speed and evaporator temperatures to provide faster response times.

Developing engine power control procedures is one of the main objectives of the current program. Four variables are available for controlling the output power level of the STM4-120. These variables are 1) input thermal power, 2) engine speed, 3) length of piston stroke, and 4) engine operating pressure. Under the present testing program, only the first three variables are controlled while the engine is operating. The helium pressure is determined by precharging the engine to a given level prior to running the engine.

The power that the STM4-120 engine extracts from the heat pipes is a function of the length of piston stroke. A schematic of the system that alters the piston stroke is shown in Figure 3. As discussed earlier, the stroke is changed by tilting the rotating swashplate on which the

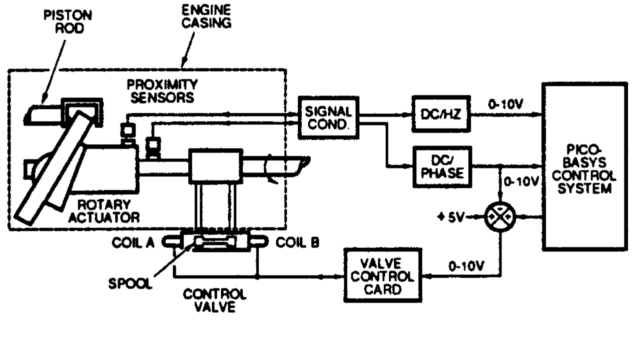

Fig. 3 Schematic of Control System

piston rods travel. A hydraulic actuator changes the swashplate's tilt relative to the drive shaft. The direction of actuator motion is determined by the position of a spool in the hydraulic control valve. Two coils, A and B, position the spool in the valve. If coil B is energized and coil A is neutral, the swashplate is driven to a maximum tilt of 22 degrees producing a 48.5-mm piston stroke. Similarly, if A is energized and B is neutral, the swashplate is driven to zero tilt angle (zero piston stroke). Coils A and B are energized with a commercial valve control card that compares a 0 to 10 VDC command signal with the feedback signal on the spool position.

The piston stroke that results from the actions of the control valve is measured using two proximity sensors. One sensor is mounted on the shaft and the other sensor is mounted on the actuator housing. The relative phase angle of signals from the two sensors determine the tilt of the swashplate. The engine speed is determined by measuring the frequency of pulses from one of the proximity sensors. The measured stroke signal is subtracted from the stroke command signal in a simple analog summing junction. This error signal is processed and fed back to the valve control card to correct the tilt of the swashplate.

The stroke command signal is either dialed-in manually using a potentiometer or the signal is provided automatically by the analog output of a PICOBASYS industrial computer. The PICOBASYS computer monitors engine and heat pipe temperatures to determine the appropriate stroke length for given operating conditions. The computer is programmed in BASICA and is relatively simple to alter control operations.

During the current phase of engine testing, the swashplate is driven to a set position, and the combustion controllers drive the gas and air valves to meet the engine's power needs. The PICOBASYS control system or ECU are used primarily to monitor engine temperatures and pressures, and check the status of subsystems (dynamometer, engine cooling system, and starter motor) to insure that they are operating within safe limits. If limits are exceeded, the computer shuts down the system by closing off the main gas valve and driving the stroke to zero. Coolant flow to the engine is continued after the engine shuts down, and air valves are driven to 20% of fully open to cool the evaporator sections of the heat pipes.

The role of the PICOBASYS control system will be expanded in the next phase of testing, when the gas combustors will be driven to given power levels and the engine stroke will be adjusted to maintain a fixed heater head temperature. The engine will be required to follow input power levels so these tests will in many ways simulate the control requirements encountered during on-sun testing. The understanding of the engine's operating characteristics that is gained during these tests will be used to develop control strategies for solar-powered Stirling engine tests.

TEST PLAN

The objective of this test is to establish the overall performance of the Stirling Thermal Motors, STM4-120 kinematic Stirling cycle engine for solar thermal applications. The power and efficiency of the STM4-120 will be critical performance parameters to be determined. These parameters will be characterized for various operating conditions such as: heater head temperature, cooling fluid temperature, piston stroke and working gas pressure. Figure 4 is a matrix of the planned operations for performance mapping. In addition, an attempt to characterize the reliability of the STM4-120 engine will be conducted. This will include documenting the cause(s) of a problem(s) along with the time and material required to correct the problem. This characterization will be helpful in establishing a data

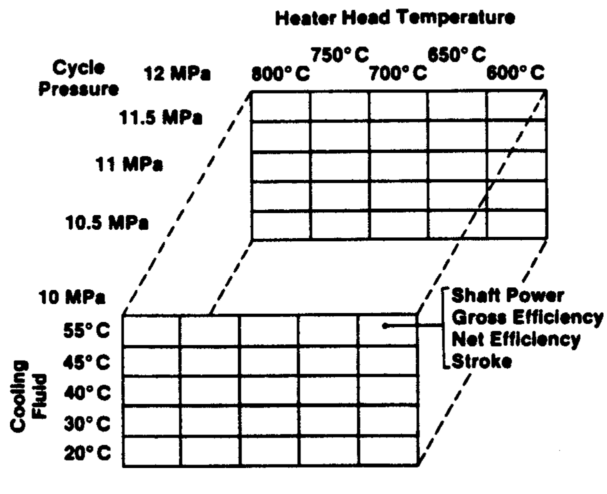

Fig. 4 Test Matrix

base for operation and maintenance of Stirling engines and in particular the STM4-120 Stirling engine.

Testing of the STM4-120 will be conducted under three phases. Each phase is a progression toward testing the STM4-120 on the Test Bed Concentrator at Sandia with a reflux solar receiver. The test plan will be broken up as follows:

Phase I - Full Power Test

During the first 200 hours the engine will be attended during operation at full power. These 200 hours will basically be an endurance test to verify that the engine is in sound working condition. Major and minor problems that occur will be documented. Power and efficiency will also be monitored.

Phase II - Performance Evaluation

For the next 200 hours the performance of the STM4-120 engine will be determined for various operating conditions. Power and efficiency will be the main concern with respect to operating temperature, cooling fluid temperature, mean cycle pressure and piston stroke.

Phase III -Engine Performance in Response to Variable Energy Input

To determine the responsiveness of the Stirling engine and controls 600 hours of simulated solar energy input will be used. This will consist of operating the combustion system up and down to follow a typical day. Cloud transients will be simulated in the daily insolation variation.

In addition to evaluating the engine under varying heat input, operating strategies for on-sun testing of the engine will be developed. These will include:

- Start-up: monitoring to determine if the sodium in the heat pipes needs to be molten before applying full heat and what ramp up of temperature is required if any.

- Starting: can the engine be motored with the induction generator or will a separate starter be required.

- Transients: determining how the engine will behave during momentary cloud cover; how long will it operate with residual heat from the receiver; whether it can be brought back on-sun immediately afterwards.

- Monitoring: determining which parameters of the engine must be monitored to control the system for operation and emergency shut-down.

RESULTS

As of this writing, Sandia has demonstrated 10 hours of operation on the STM4-120 at the ETF. These first several hours were primarily intended for checkout of Sandia's test facility. The test facility had the normal problems associated with initial operation. Two areas of note were the dynamometer drive shaft and the combustion system. These both are part of the testing apparatus, not the engine. First, at the 1800 rpm operating speed, a resonance was observed in the drive line between the engine and dynamometer. It was later discovered that the incorrect drive shaft had been delivered to Sandia. A new shaft was installed and the resonance disappeared. Second, the combustion system built by Sandia had to be rebalanced to correct the excessively rich fuel combustion. Excess hydrogen was being formed and migrating into the heat pipes where it was swept to the heater heads and reducing the heat transfer to the helium. Since this rebalancing took place the reduced heat transfer symptom has not been observed.

During the limited operation of the engine, its performance has been very good. With a mean cycle pressure of 5 MPa, a heater head temperature of 760 •C, 1650 RPM, and full stroke (48.5 mm) the engine produced 7.4 kW of shaft power. Figure 5 is a plot showing several operational parameters measured

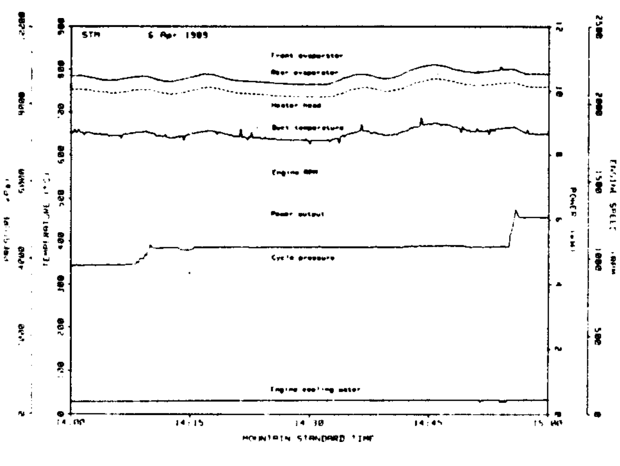

Fig. 5 Measured Operating Parameters

during a single day of operation. With the lower rpm, reduced heater head and cooling water temperatures, the measured performance was slightly lower than Stirling Thermal Motors' predictions (Figure 6). The discrepancy between the actual and predicted data probably is due to the reduced heater head temperatures caused by the excess hydrogen.

Sandia has partially dismantled the STM4-120 heater heads and pistons, in preparation for the delivery of a second set of up-graded heater heads that will allow operation of the engine at full cycle pressure of 12 MPa. After removing the pistons, the rod seals or scrapers were found to be completely dry. This suggests that leaking piston rod seals which have been a problem with earlier Stirling engines in the past do not appear to be a difficulty here. This area will continue to be monitored during testing.

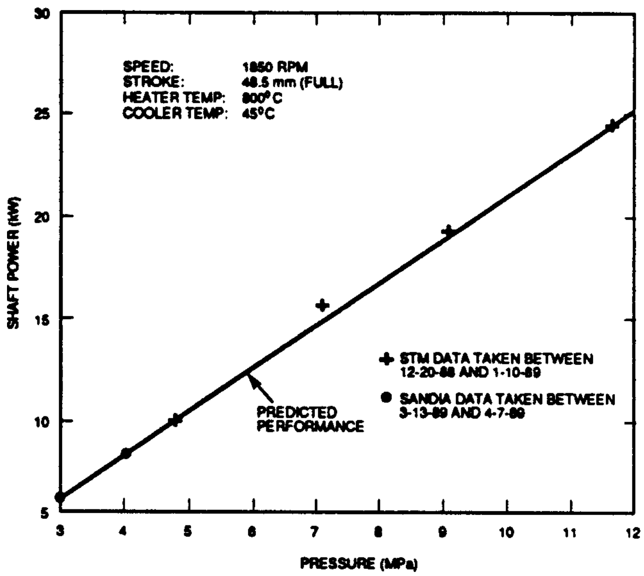

Fig. 6 Predicted versus Measured Performance

CONCLUSIONS

Preliminary results indicate that the STM4-120 is performing to expectations. Check out of the engine testing system is completed and is now in operational condition. During the coming year, Sandia will be gathering more data regarding performance characteristic of the STM4-120 kinematic Stirling engine.

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