DOE/NASA/0333-1
NASA CR-174771

Free-Piston Stirling Engine/ Linear Alternator 1000-Hour Endurance Test

Jeffrey Rauch and George Dochat
Mechanical Technology Incorporated

March 1985

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-333

for
U.S. DEPARTMENT OF ENERGY
Office of Building and Community Systems
Building Equipment Division

DOE/NASA/0333-1
NASA CR-174771

Free-Piston Stirling Engine/ Linear Alternator 1000-Hour Endurance Test

Jeffrey Rauch and George Dochat
Mechanical Technology Incorporated
Latham, New York 12110

March 1985

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-333

for
U.S. DEPARTMENT OF ENERGY
Office of Building and Community Systems
Building Equipment Division
Washington, D.C. 20545
Under Interagency Agreement DE-AI05-82OR1005

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

1.0 SUMMARY

1.1 Scope of Work

The Free-Piston Stirling Engine (FPSE) has been under development at Mechanical Technology Incorporated (MTI) since 1976. As the design has matured and performance improved during the development/testing process, it has become important to demonstrate the potential of the FPSE for long life and high reliability. The first part of this demonstration, a 1000-hour endurance test, was defined and testing has been successfully accomplished. This report presents the information concerning this first test.

1.2 Objectives

The goal of this endurance test was to accumulate 1000 hours of engine operation, which has been successfully completed with several typical loading conditions. Further, the test was structured to accumulate data on the wear and life of engine components. Therefore, this program consisted of four phases:

1. Phase I - Low-Power Test - Accumulate 100 test hours at 0.5 kWe power, 600°C mean heater head temperature to evaluate the stability of gross engine parameters.

2. Phase II - Full-Stroke Test - Accumulate 300 test hours at full piston stroke, 700°C mean heater head temperature to evaluate endurance at this load.

3. Phase III - Duty-Cycle Test - Accumulate 300 test hours at loads between 0.5 and 2.5 kWe, 700°C mean heater head temperature.

4. Phase IV - Stop/Start Test - Accumulate 300 test hours while performing 1000 start/stop tests of the engine system. The engine was to be cycled on and off approximately every 15 minutes, with load between zero power and the power point defined in Phase II.

The goals of Phase III and IV were modified in that the duty-cycle test was extended to nearly 700 hours, thus completing over 1100 hours of engine testing by the end of Phase III. Phase IV was modified to accumulate $\sim$12 start/stop cycles per running hour. The test was terminated after 262 start/stop cycles had been accumulated.

1.3 Results

The test was begun on 7 April 1983 with the low-power testing; 1000 hours of engine testing were completed on 3 October 1983; and the test program was completed on 22 February 1984.

The engine used for this test was one of three engineering models (EM) EM No. 2 (Figure 1-1), which were built by MTI in 1981 and have been undergoing continuous development since that time. The engine was tested in cell No. 6 of MTI's free-piston Stirling lab. This cell has been prepared specifically for endurance testing and is capable of automatic unattended engine operation.

1.4 Conclusions

Over 1100 FPSE test hours were successfully completed during the course of the endurance program. The major conclusion is that there was no appreciable wear of the critical bearing and sealing surfaces of the EM as documented by inspection. This test program confirms the potential of FPSE's to provide long life and high reliability. Other conclusions that resulted from the test program are:

- Test conditions and/or load did not affect wear or durability. Differences between the various test/load conditions did not appear to have any effect on the condition of the hardware and/or performance. Start-stop testing did show a number of fine scratches on bearing surfaces that did not seem to affect performance.

- Engine system was very mechanically reliable over the duration of the test. Except for a displacer magnet segment coming loose during operation, the engine hardware remained very reliable, with the last 400 test hours of duty-cycle testing accomplished in 432 available hours. Unintentional shutdowns were primarily a result of facility type

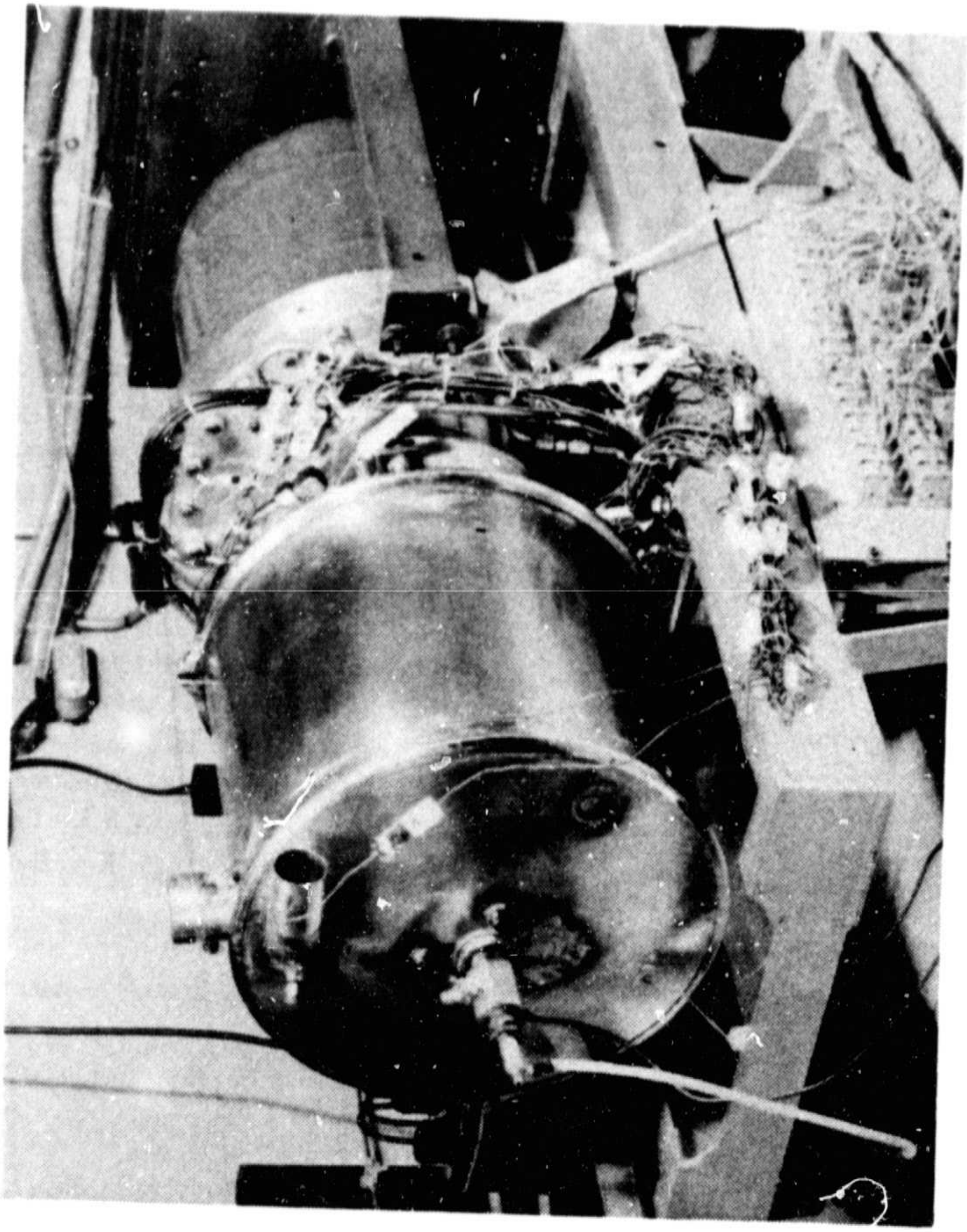


Figure 1-1 MTI FPSE EM #2 Installed for 1000-Hour Endurance Testing

failures (i.e., pressure out of tolerance, loss of electrical power, loss of shop air).

- A successful build of the EM requires time and care during assembly. With regard to future FPSE designs, it was seen that the design of the EM engine, with its many displacer drive hardware stack-up fits, requires significant attention to detail to achieve a successful build (one with no rubs during bench checkout of the hardware). Improvements in design to permit quicker and more reliable assemblies should be considered.

1.5 Recommendations

The most important recommendation resulting from the test results and conclusions to date is the need to continue endurance testing of this engine. The critical 1000-hour test confirms the potential for long life and durability, but many additional hours ($\sim$10,000) are needed to fully demonstrate these FPSE features. Continued testing will also identify long-term potential problems that may require a redesign to achieve the goal of long life and high reliability.

At present, the chromium oxide (Cr_2O_3) material used to provide a durable coating of the critical surfaces has worked extremely well. It has been a tough and forgiving surface. Cr_2O_3 has not been put on our small inner diameter (I.D.) because of plasma spraying limitation. It is recommended that evaluation of other Cr_2O_3 processes and/or simpler alternatives to Cr_2O_3 be investigated.

Both the complexity and energy requirements of the displacer drive system are concerns. A lighter displacer would reduce input energy requirements, the material chosen must be compatible with existing materials to assure maintenance of the proper clearances during operation. Information concerning light weight materials and their dimensional stability as a function of time and temperature should be sought.

In summary, the recommendations that result from the Endurance Test Program are:

- Continue endurance testing with a goal of demonstrating 10,000 hours
- Eventually improve design for assembly consideration

* Evaluate alternative protective surface coatings
* Investigate material dimensional stability as a function of time and temperature.

The engine, instrumentation, and data acquisition system (DAS) are described in Section 2.0. A history and discussion of the overall endurance test is given in Section 3.0. Sections 4.0 through 7.0 present results of each phase of the endurance test.

2.0 ENGINE AND INSTRUMENTATION DESCRIPTION

2.1 Engineering Model Description

The major components of the EM power module are schematically depicted in Figure 2-1. The following subsections describe the design of the EM.

2.1.1 Engine Thermodynamics

Thermodynamically, the FPSE is similar to more conventional (i.e., kinematic) Stirling engines except that the piston/displacer motions are controlled by a resonant spring/mass system rather than a mechanical linkage.

The thermodynamic elements of the engine consist of an expansion and compression space connected by three heat exchangers, 1) heater; 2) regenerator; and, 3) cooler, which convert thermal energy into mechanical energy at high efficiency. The expansion space is the volume enclosed by the displacer hot end and cylinder head, including the "shuttle gap" in the annular space between the displacer and cylinder walls. The compression space is actually two displaced volumes that are connected: one due to motion of the displacer cold end, and the other due to piston motion. A clearance seal at the cold end of the displacer isolates the compression space from the expansion space. The compression space is also isolated from the "bounce" chamber and gas springs by clearance seals around the power piston and displacer rod. Since pressure in the bounce chamber is essentially constant, the pressure difference across the rod and piston seals is the compression-space cycle pressure amplitude. Ducts through the displacer post and flange assembly connect the two compression spaces. The displacer and piston elements are contained within the same cylinder. The purpose of the displacer is to reciprocate the working gas through the heat exchangers. The engine derives power from the changing pressure amplitude of the cycle acting on the power piston face area (see Figure 2-2).

2.1.2 Displacer Drive

The posted design is an MTI design feature that improved dynamics and relaxed tolerances between the displacer and power piston. With the separation of the

PAGE 6 INTENTIONALLY BLANK

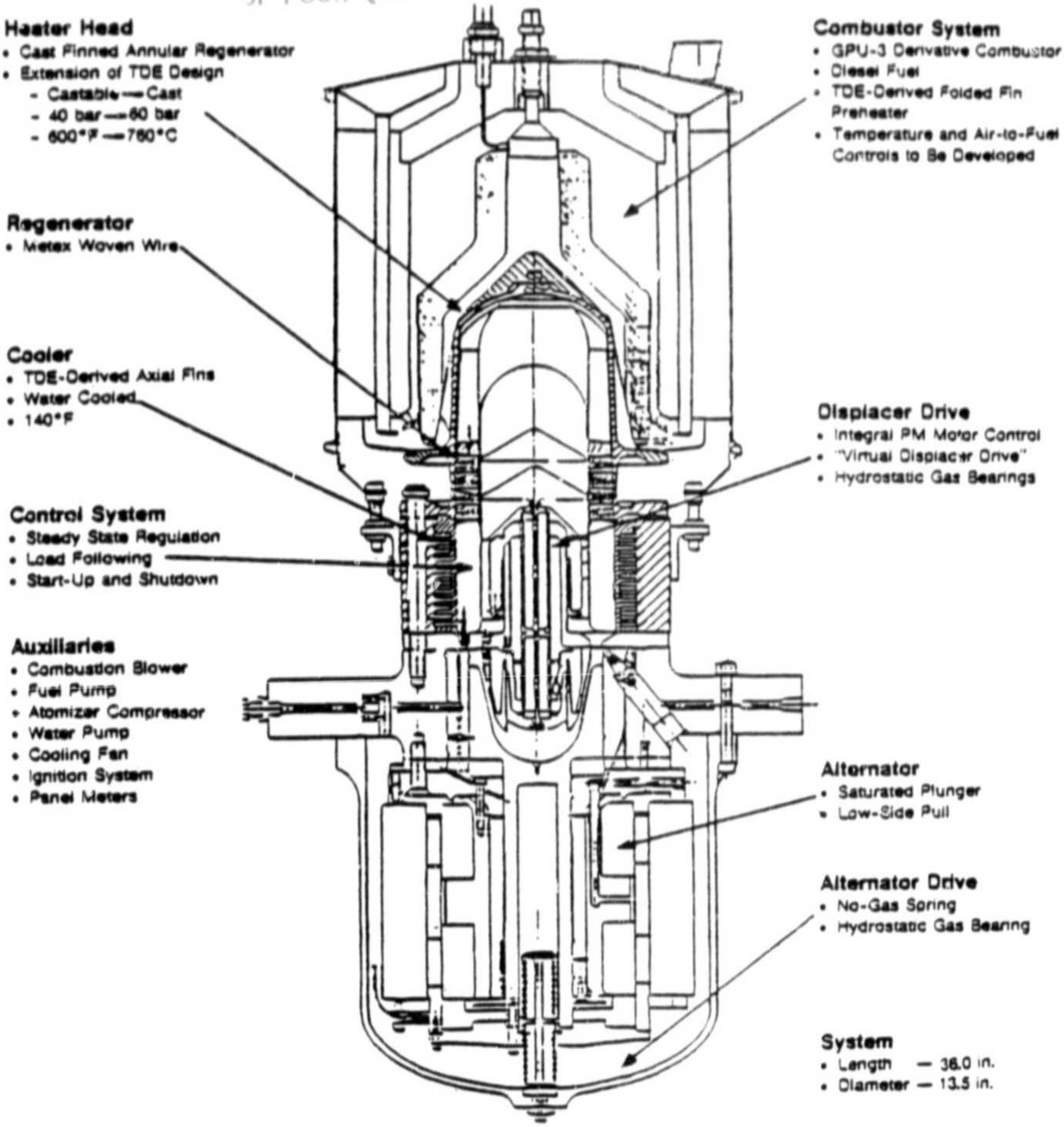


Figure 2-1 Engineering Model - Major Components

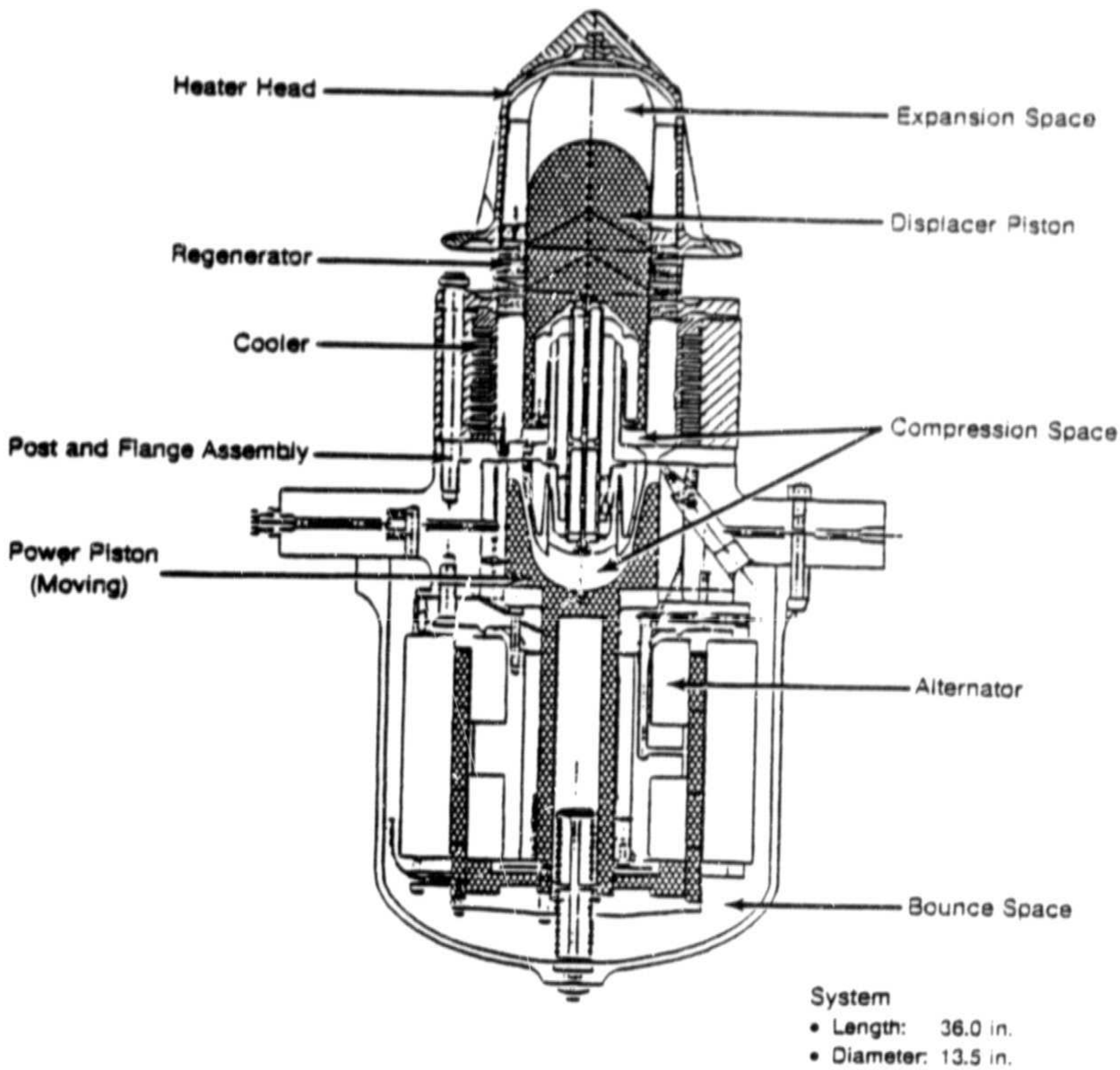


Figure 2-2 Schematic of Engine Components

power piston and displacer via the posted displacer design, the dynamics of the FPSE system can be tuned to obtain the desired thermodynamics. The engine incorporates a variable-volume displacer gas spring, therefore allowing dynamics/thermodynamics of the engine to be altered by changing the spring rate.

2.1.3 Engine Control

Typically, a FPSE is a low-stored energy, multidegree-of-freedom engine made to oscillate freely by designing the system parameters so that the dominant system eigenvalue is neutrally damped. Such a system is simple to operate in a laboratory environment at constant load; however, it is difficult to operate in a transient environment due to its low-stored energy capability and neutrally damped dominant eigenvalue. Any significant change in a working parameter requires a rapid change in another system dynamic parameter to maintain unit stability, which is not practical without providing a hydraulic, pneumatic, or electric buffer between the load and the engine. By driving the displacer with a linear motor at all times, the controllability of the EM is the single most important and proprietary feature that makes it suitable for various applications and loads.

The combined EM posted displacer concept and linear motor drive consists of the displacer body and dome, hydrostatic gas bearing displacer rod, linear motor drive, and displacer gas springs. The displacer body contains the displacer cylinder clearance seal, and an integrally fabricated, linear electric motor armature, which is a basic part of the engine power-control system. The displacer rod and body are supported on gas bearings within the post and flange assembly (Figure 2-3). The rod area, which is the difference between the effective expansion-space face area of the displacer and the effective compression-space face area, determines the thermodynamic input power to the displacer.

2.1.4 Heat Exchanger System

2.1.4.1 Heater Head. The EM heater head (Figure 2-4) was designed as a monolithic pressure vessel that is integral with the annular regenerator pressure wall (see Figure 2-5). This design, which requires no high-temperature structural weld or brazed joints, can be cast with integral internal and external fins.

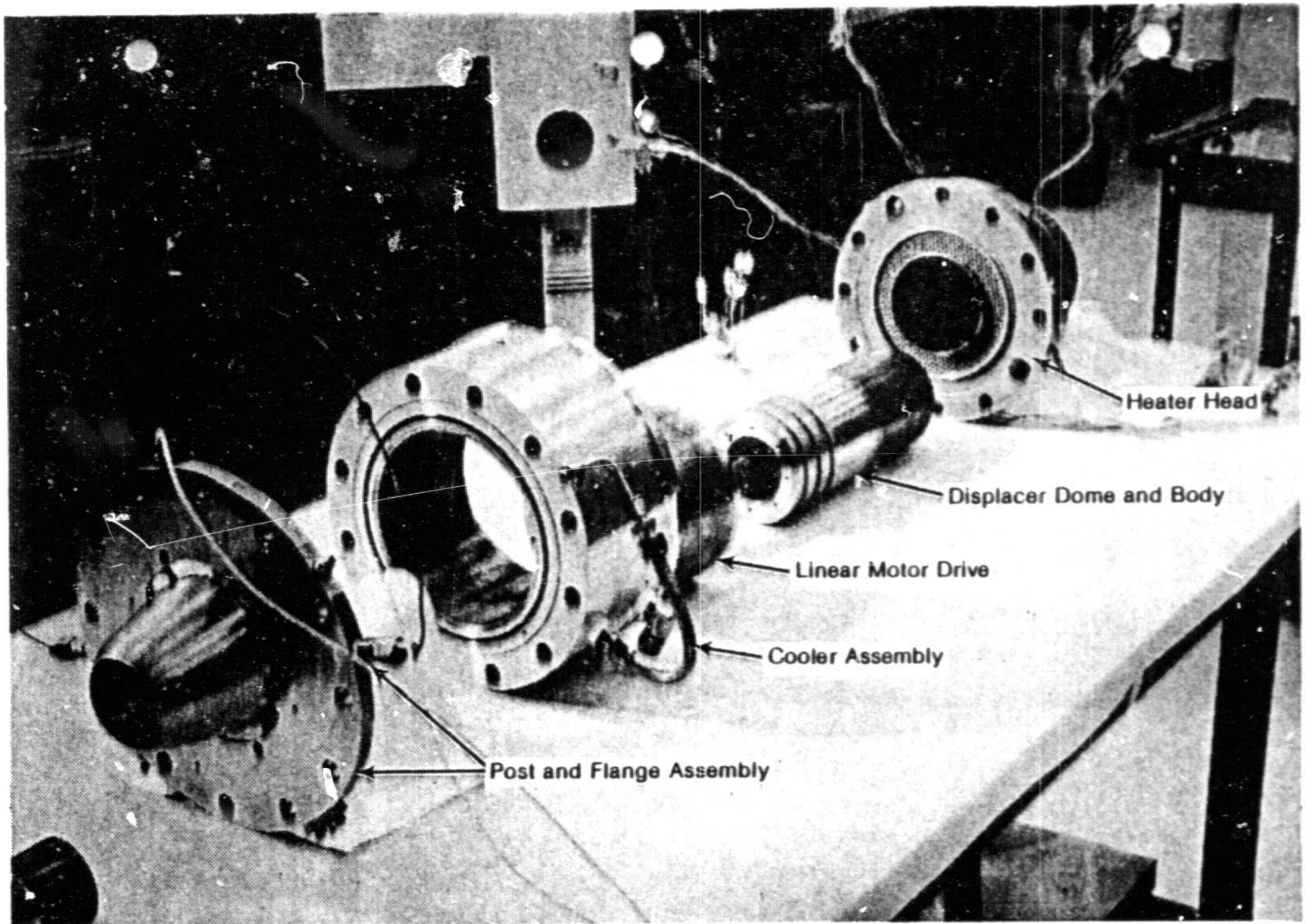
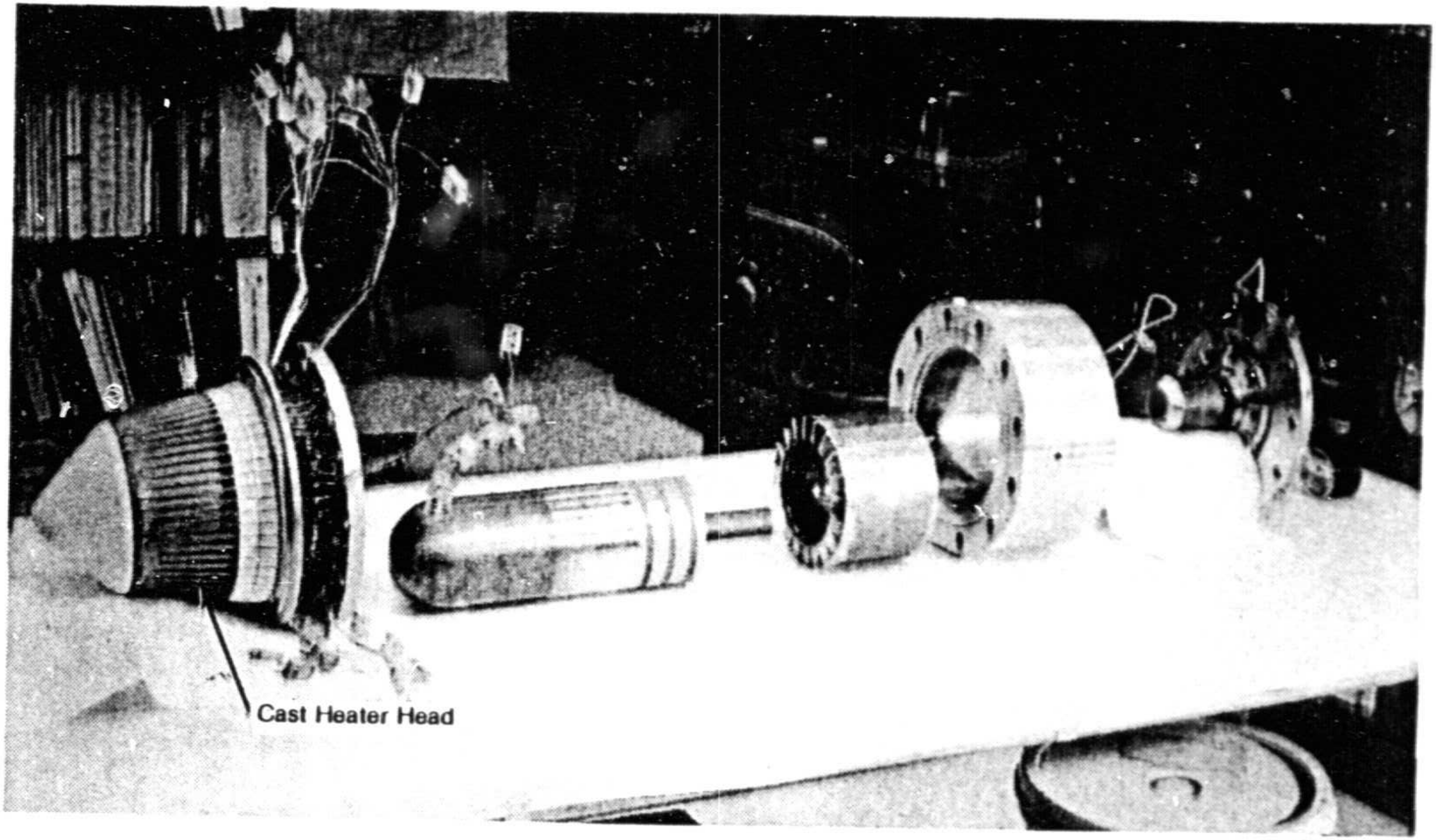


Figure 2-3 MTI EM Linear Motor Driven Displacer Hardware



CT-82622A-20

Figure 2-4 The EM Heater Head and Displacer Components

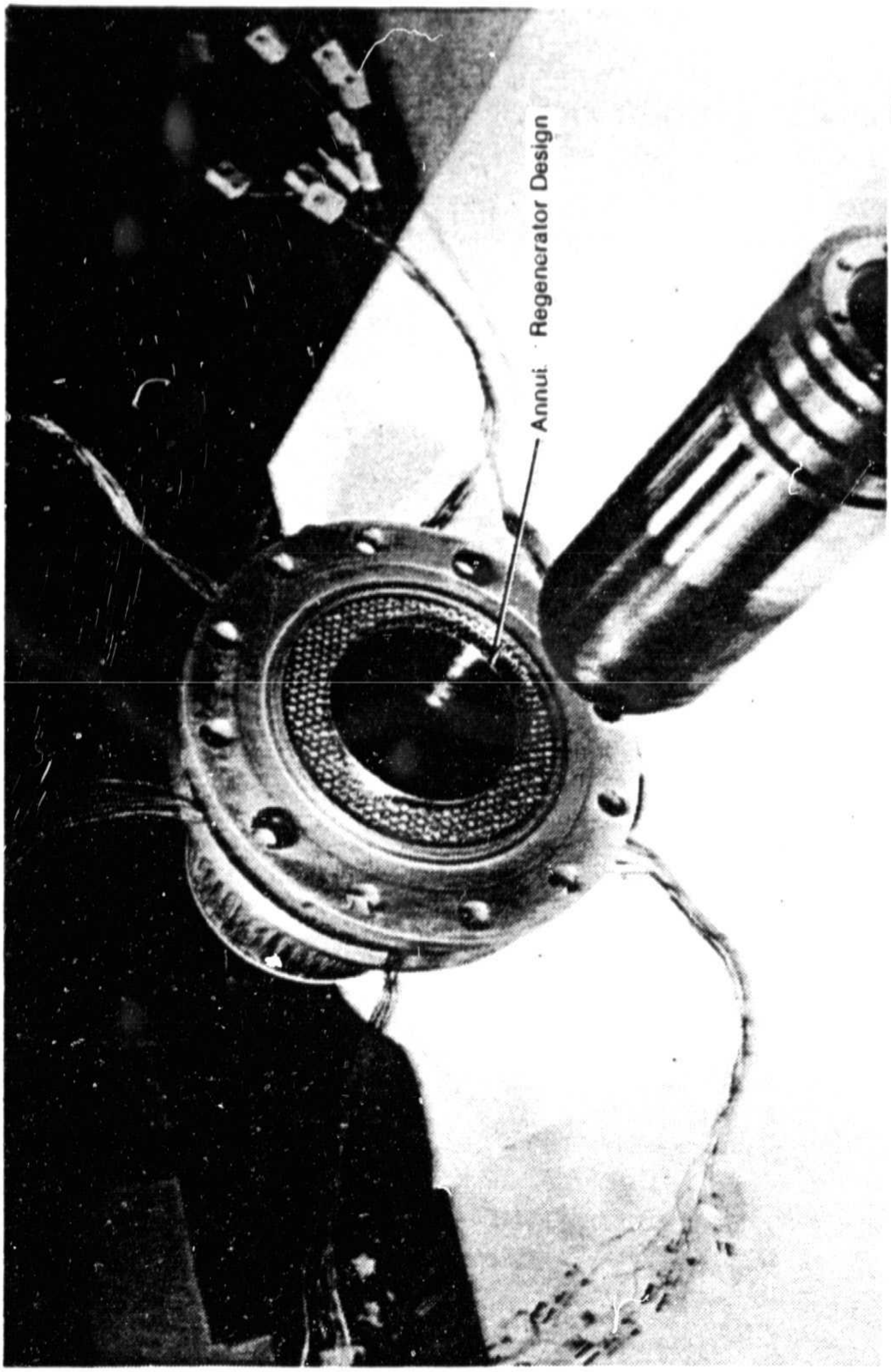


Figure 2-5 Heater Head and Regenerator Housing

2.1.5 Combustion System

The EM combustor is a spin-off developed from the technology demonstrator engine (TDE) with major improvements in the preheater. Fuel and air are supplied to the combustor from an external air/fuel (A/F) control system. Inlet air is preheated by the combustion exhaust in a folded fin preheater. The preheater air enters the combustion chamber through a swirler cup to create a turbulent mixing zone, and fuel is injected through the center of the swirler cup into the combustion zone. The current combustor system (shown in Figure 2-6) is designed to burn natural gas at a peak firing rate of 16 kW. The combustor control senses heater head temperature and adjusts fuel and airflow to maintain the heater head temperature at the fixed operating temperature.

2.1.6 Regenerator

The regenerator is an annular, porous ring located between the heater and cooler. The regenerator matrix (Figure 2-7) is metex, a .0035-in. diameter knitted wire, formed and pressed in a disk to the specified porosity.

2.1.7 Cooler

The engine cooler (Figure 2-8) is located in an annulus between the regenerator and compression spaces. The helium-side flow passages are rectangular slots milled axially onto the inside of a thin, aluminum pressure wall, whereas the water-side assages are circumferential grooves machined onto the outside of the pressure wall. The cooler is connected to the compression-space volume through the compression-space connecting duct.

2.1.8 Gas Bearings

Both the displacer and power piston are radially supported by hydrostatic gas journal bearings. The displacer bearing feed holes, located in the engine post and flange assembly, consist of a single-plane series of holes at one end and a double-plane series of holes at the other end, while the power piston bearings consist of two sets of double-plane feed holes located at each end of the alternator cylinder.

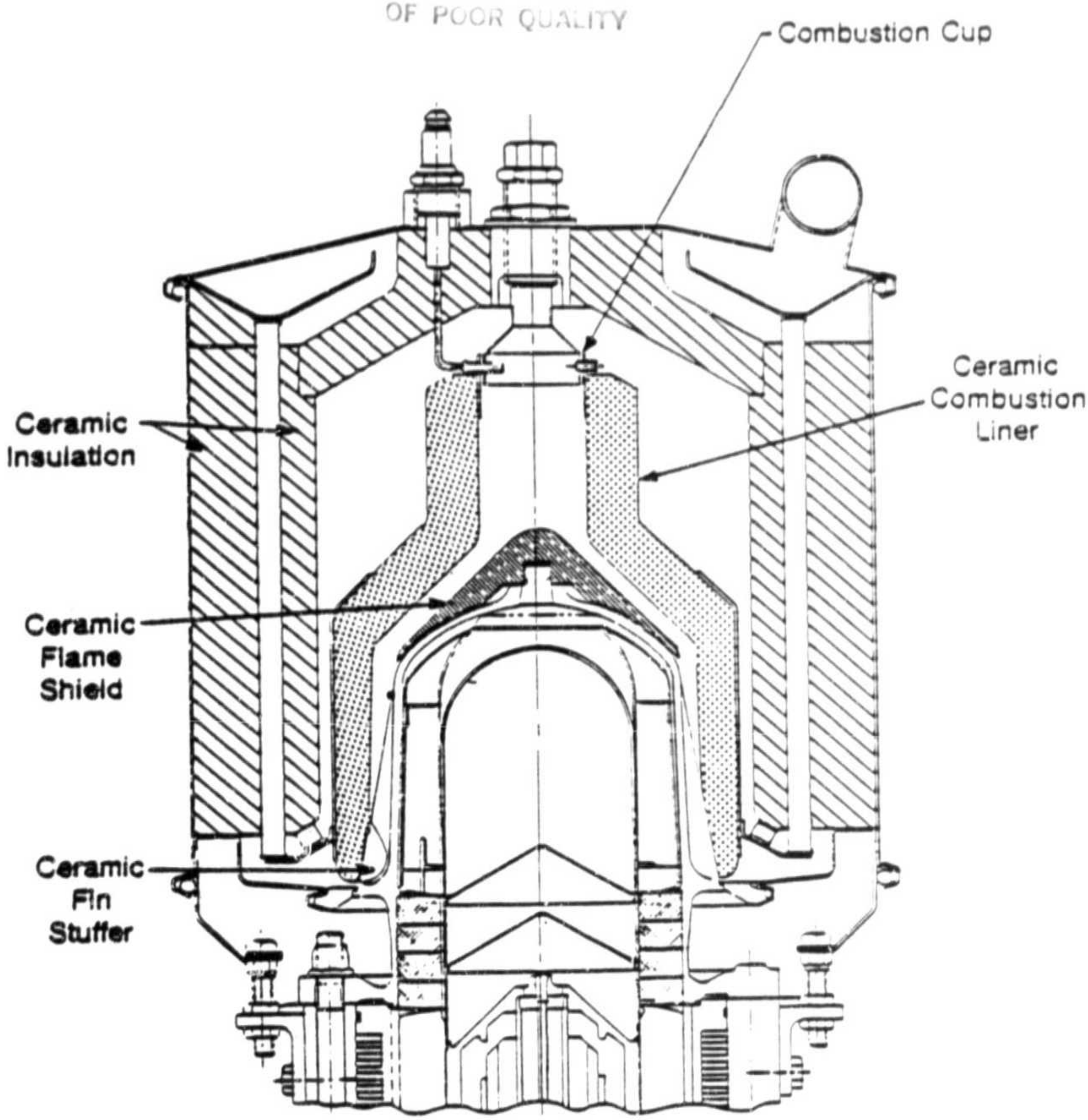
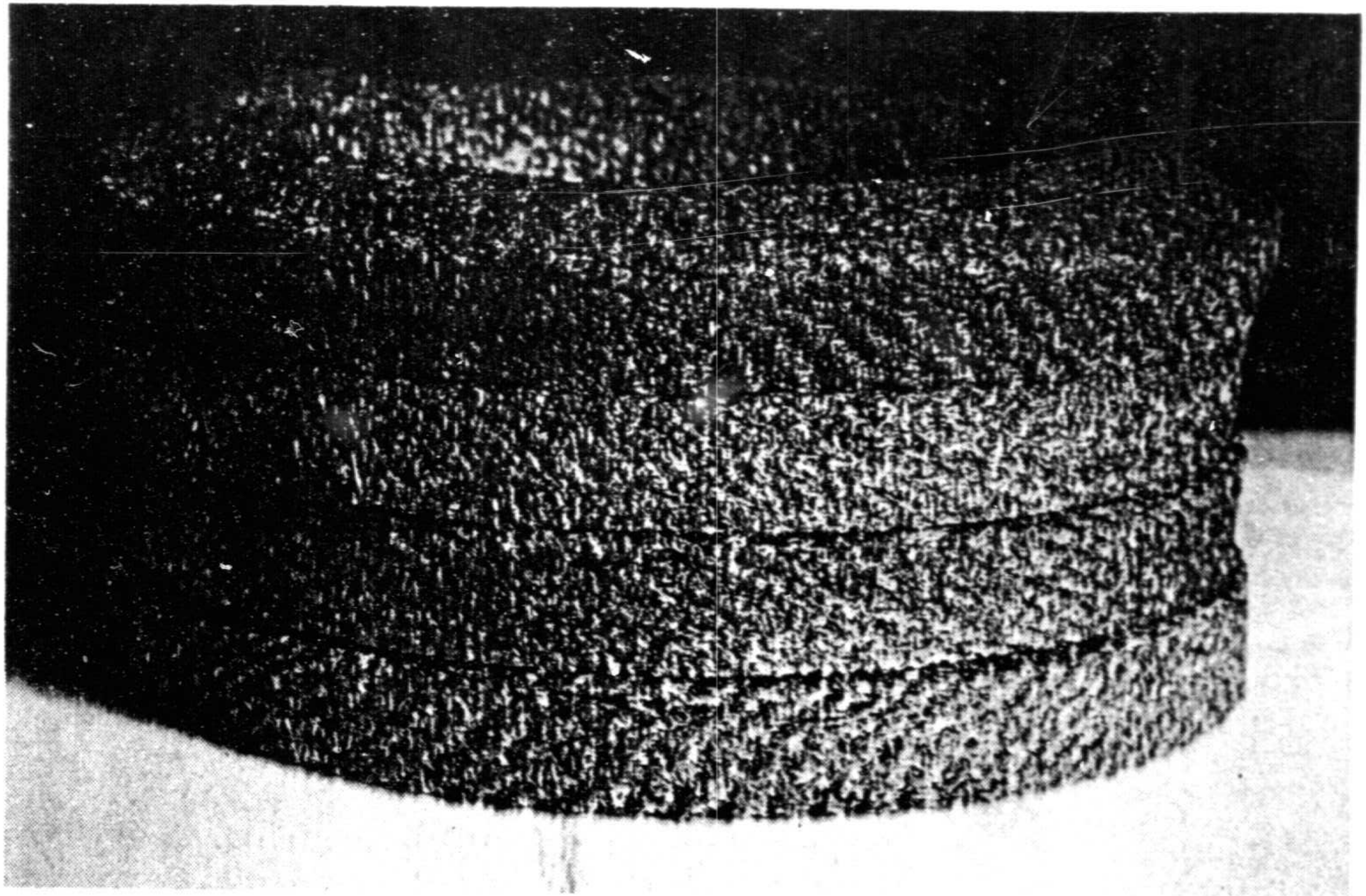


Figure 2-6 Engineering Model External Heat System



CT-82387E-2A

Figure 2-7 Metex Regenerator Stacks

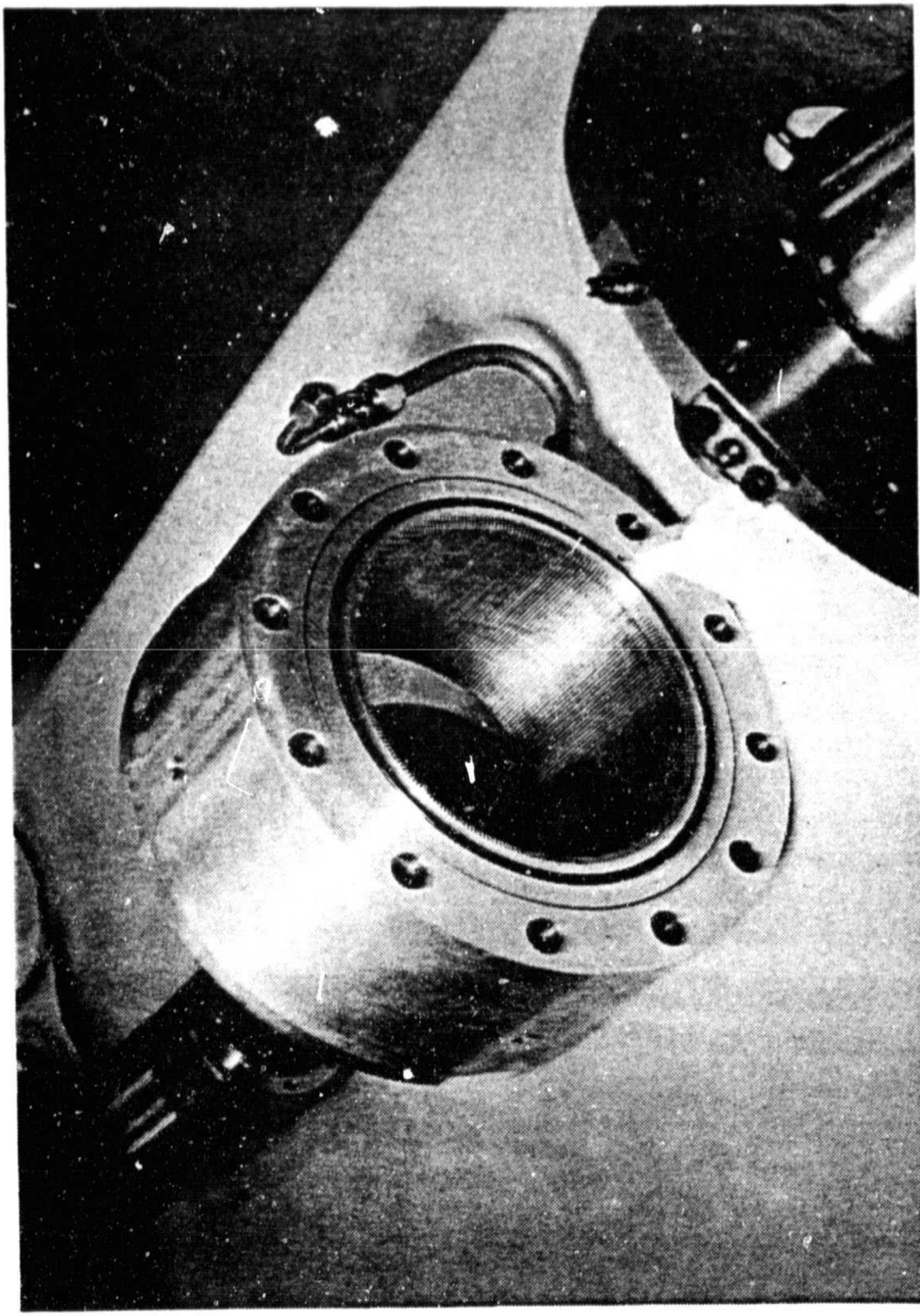


Figure 2-8 Engine Cooler

2.1.9 Close-Tolerance Seals

The EM utilizes close-tolerance, noncontacting seals to isolate the various gas volumes in the power module. The engine seals (Figure 2-9) consist of the:

- Forward Gas Spring Seal - Isolates gas spring volume from compression-space volume
- Aft Gas Spring Seal - Isolates gas spring volume from compression-space volume
- Forward and Aft Bearing Seals - Isolate the bearing drain pressure (bounce pressure) from gas spring pressure
- Shuttle Gap Seal - Isolates expansion-space volume from compression-space volume
- Power Piston Seal - Isolates compression-space volume from bounce-space volume.

2.1.10 Alternators

The "partially-saturated plunger" alternator evolved from earlier flux-switching alternator configurations. This concept (shown in Figure 2-10) is based on the principle of minimizing the weight of the driven mass (plunger) at the sacrifice of the stationary mass (stator). The result is that only the pole pieces (required for "flux-switching") are needed to form the moving member. Furthermore, both inside and outside stator coils have been devised to optimize overall packageability and to enhance the alternator conversion efficiency. The latter can be achieved by virtue of the smaller mean diameter of the coil windings on the inner stator relative to the outer coils, thereby reducing the overall I^2R losses for the alternator system.

The linear alternator consists of a 0.5-in. thick cylindrical plunger that reciprocates between the inner and outer cylindrical stators. A DC field coil generates a toroidal flux path linking the inner and outer stators which passes through the two magnetically active rings on the plunger and passes in and out of the two

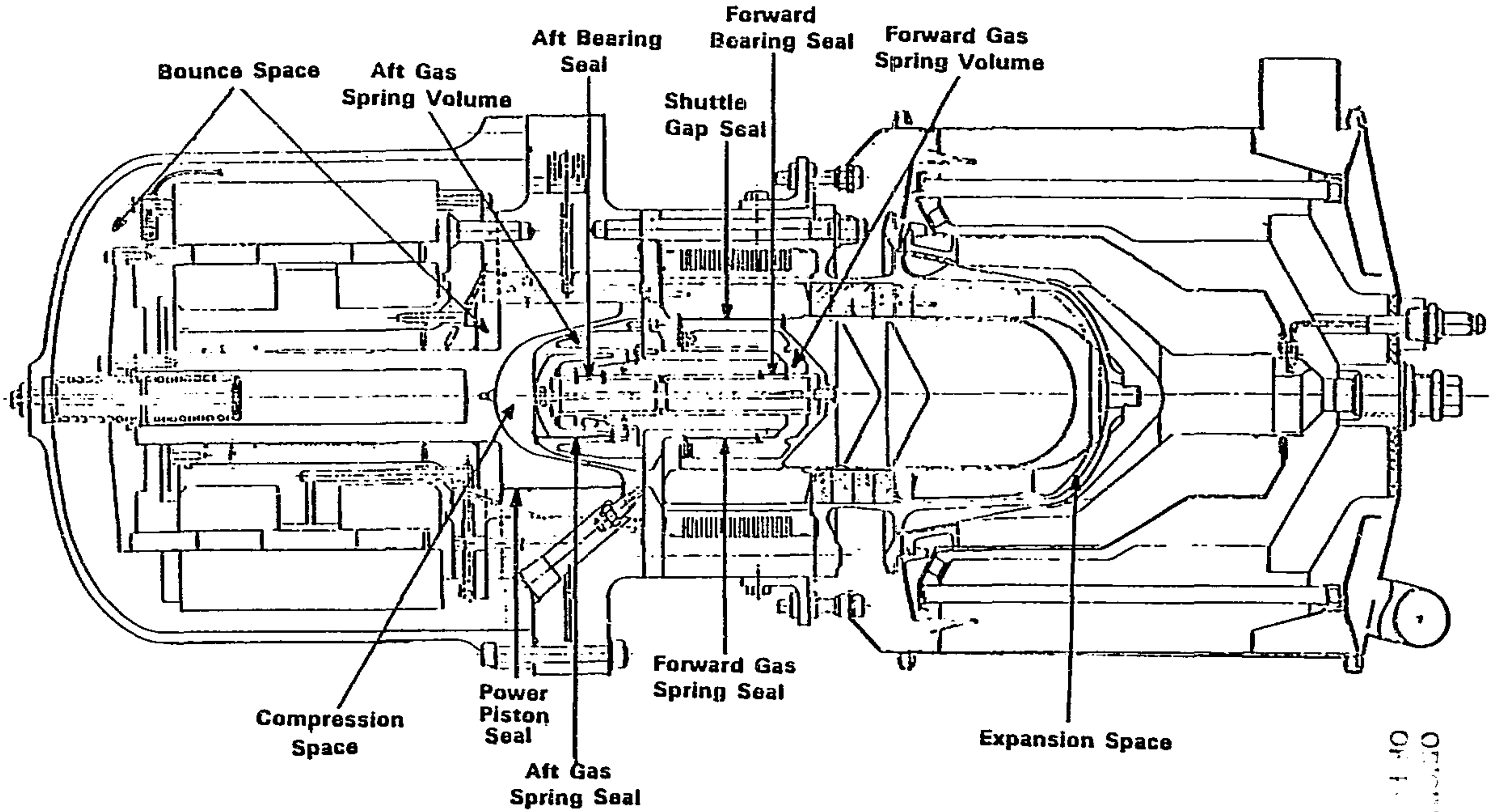


Figure 2-9 Close Tolerance Seals

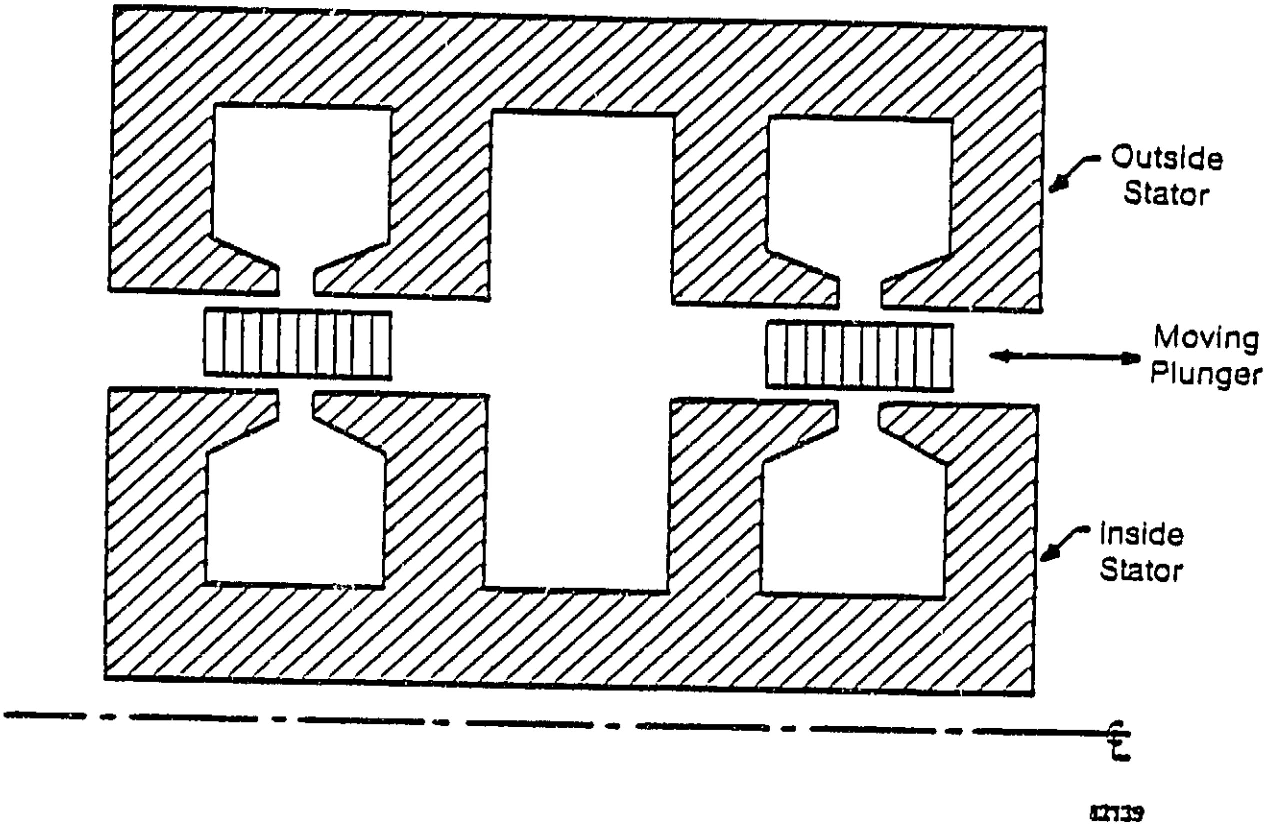


Figure 2-10 Partially Saturated Plunger
with Inner and Outer Stator

stators. Consequently, reciprocation of the plunger causes the flux toroid to move axially along the stator, sinusoidally linking and unlinking four physically separate AC output coils. These electrically connected coils act as a single output coil, providing alternating AC voltage and power.

The EM alternator is relatively rugged and has a low plunger weight. The lightweight plunger allows the EM to operate at 60 Hz without the use of an auxiliary piston gas spring. A layout of the alternator and plunger configuration is shown in Figure 2-11, and a photograph of this configuration is shown in Figure 2-12.

2.1.11 Skid and Support

The EM, presently mounted in a horizontal orientation on a structural aluminum stand, makes use of five soft rubber mounts, four of which are located on the mounting flange between the engine and alternator, and one on the alternator pressure vessel (see Figure 2-13). The machine is allowed to vibrate freely in this configuration. A structural integrity problem with the combustor was encountered during initial testing. Work is being performed on a new combustor design to solve the problem. In the interim, the EM is linked to a large mass, reducing the casing vibration, located at the rear of the machine and attached by means of two steel stringers fastened to the mounting flange of the EM (Figure 2-14).

2.2 Engine Instrumentation

The purpose of the test was to accumulate durability hours. In instrumenting the EM No. 2, the primary consideration in selecting the parameters to be measured was to be able to use the measurements to monitor the operation of the machine and be able to use the measured values to observe changes in operating conditions that would be indicative of component wear. Therefore, the measurements could be used to trouble-shoot problem areas and be able to adjust, to some degree, for minor wear or to shutdown should major problems occur. The entire instrumentation package was streamlined to exclude what was considered nonessential parameters. The instrumentation chosen measures parameters of pressure (P), flow (V), position (X_p and X_D), case acceleration which indicates case position, and temperature (T); along with appropriate voltages (V) and currents (I). Table 2-1 is a listing of those measurements along with a description of the measuring equipment used.

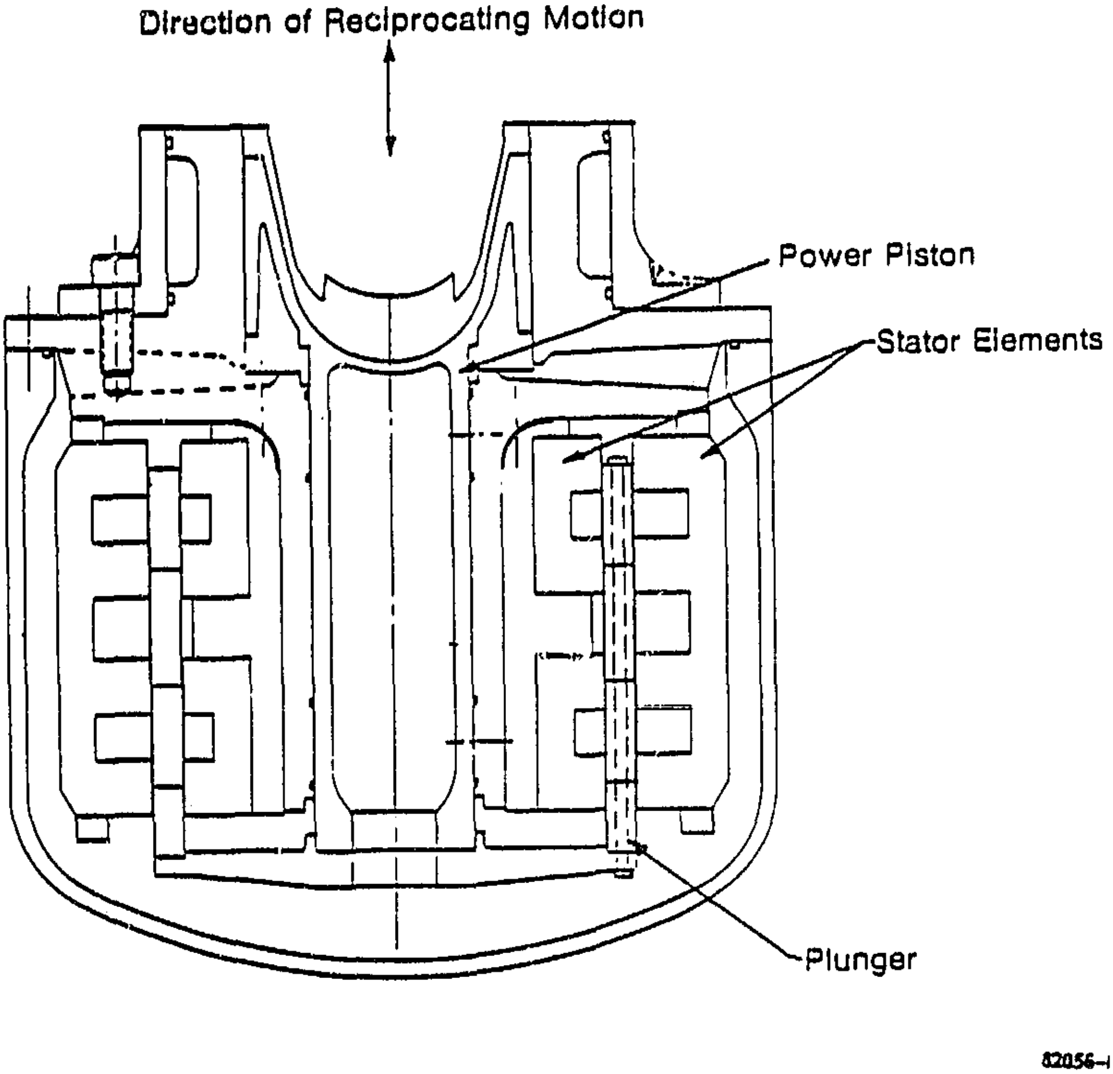


Figure 2-11 Partially Saturated Plunger Alternator Subsystem

ORIGINAL PAGE IS
OF POOR QUALITY

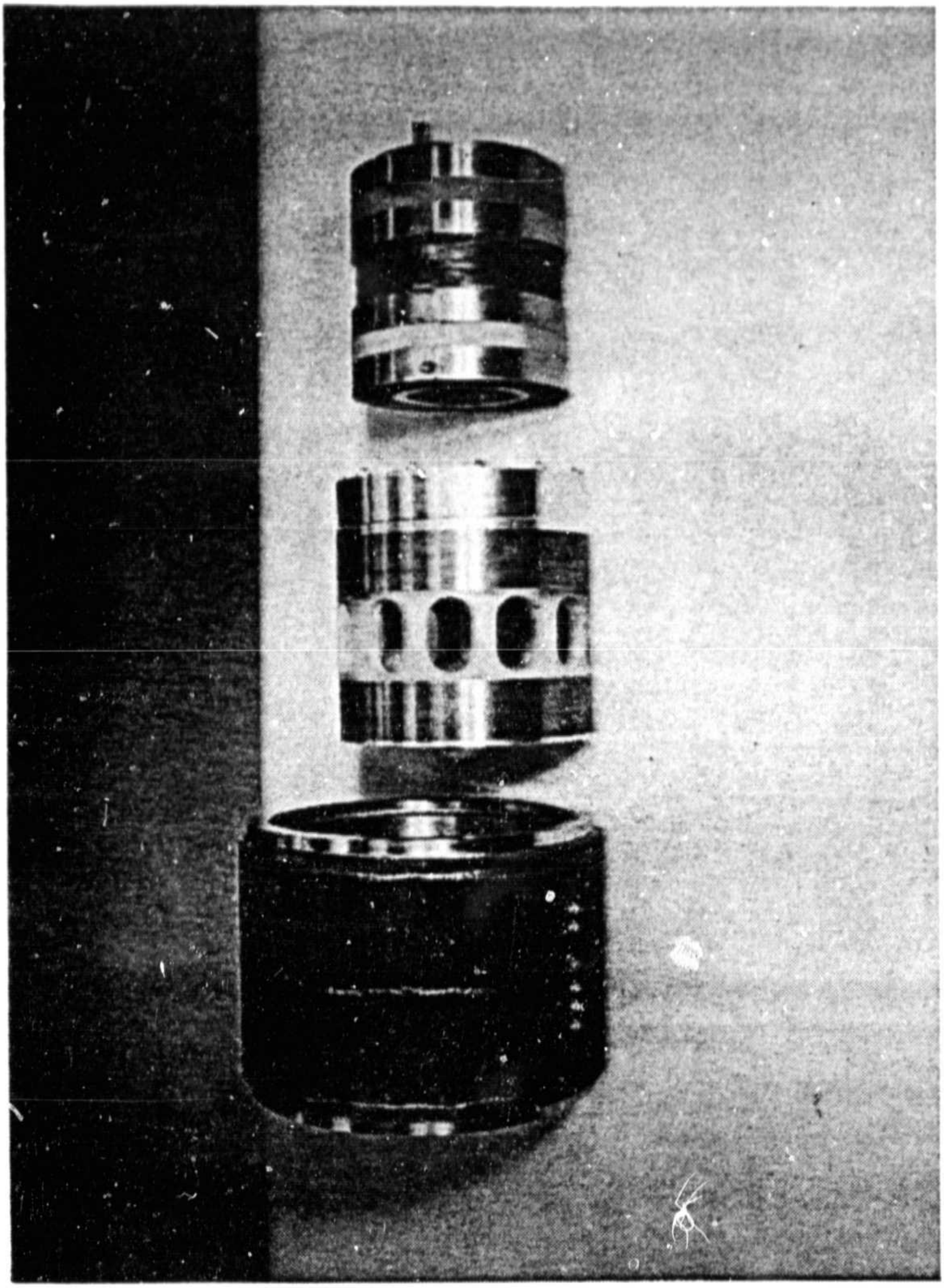


Figure 2-12 Partially Saturated Alternator Components

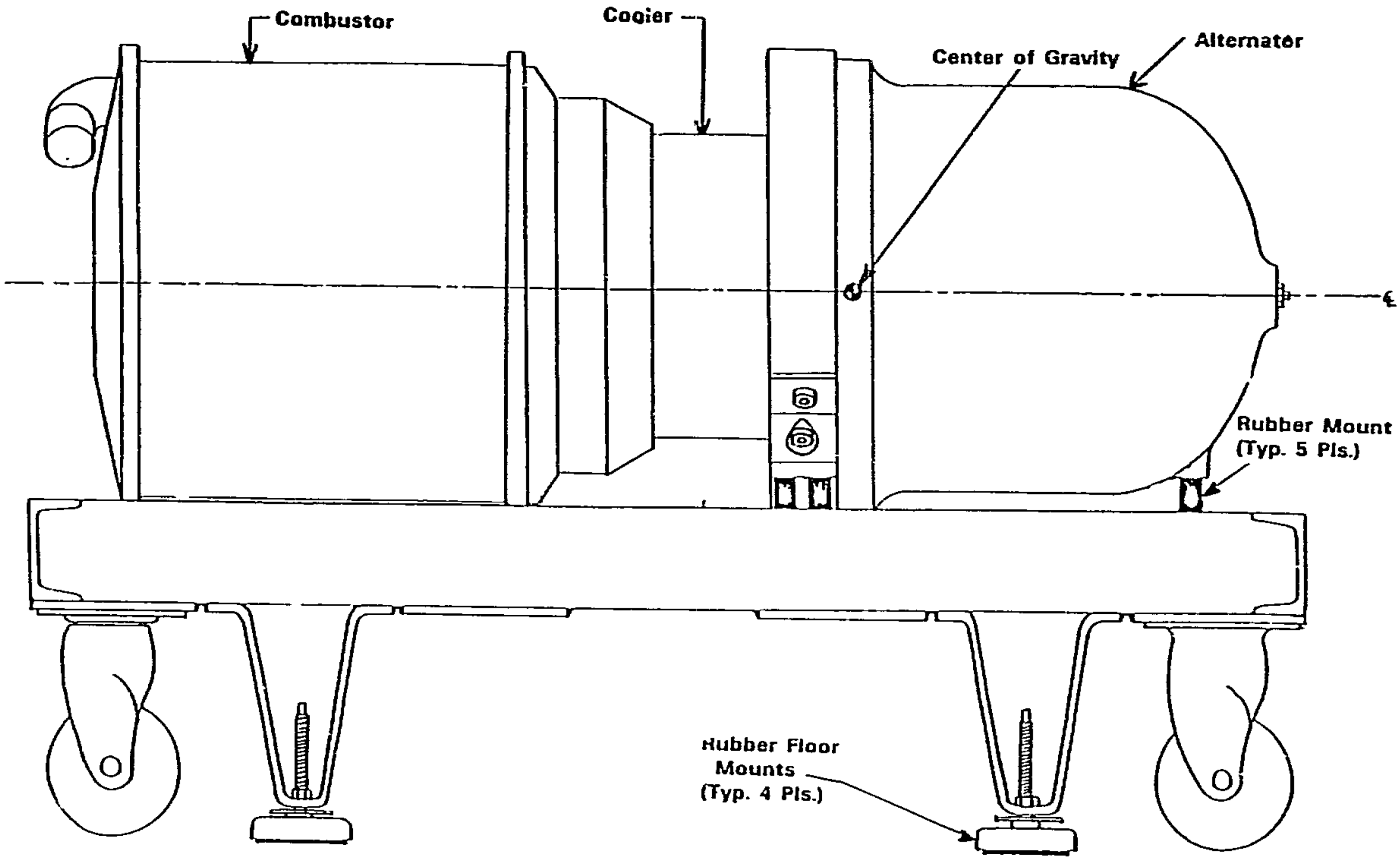


Figure 2-13 EM Skid Mounting Diagram

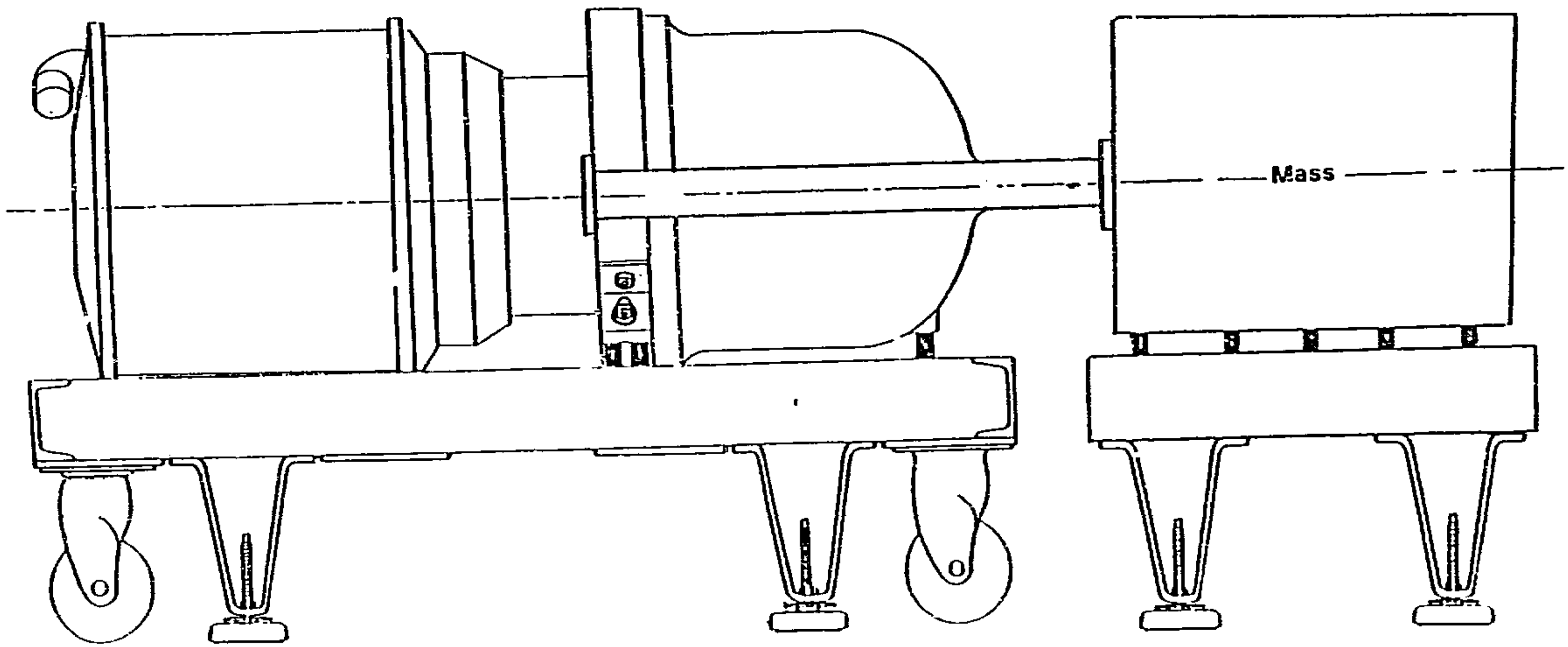


Figure 2-14 EM Skid Mount with Vibration Dampening Mass

TABLE 2-1

ENDURANCE ENGINE INSTRUMENTATION

Pressures

P_{mean}	Kistler 4045A100 with 4601 amplifier
$P_{bearing}$	Kistler 4045A100 with 4601 amplifier
PDGS2'	Kistler Piezoelectric 601A with 5002 charge amplifier
PDGS2	Kulite XF-1-190-2000 with analog device with 2B31J conditioner
PC	Druck PDCR/200 with analog device 2B31J conditioner
PDGS1'	Kistler piezoelectric 601A with 5002 charge amplifier
PDGS1	Kulite XF-1-190-2000 with analog device 2B31J conditioner
Pair	Dynisco APT-320J-25
P_{fuel}	Dynisco APT-320J-25

Flows

Air	Meriam LFE laminar flow element with Validyne DP-45-16/CD-15 differential pressure transducer and carrier demodulator
Fuel	Meriam LFE laminar flow element with Validyne DP-45-16/CD-15 differential pressure transducer and carrier demodulator
Coolant	Bearingless flow meter model E-100 with analog devices AD 451J frequency-DC converter. Coolant temperatures are monitored by thermistors (2252 Ω @ 25°C)

Displacements

XD_1, XD_2	Kaman KD-2350-2UB Eddy current displacement measurement systems
XP_1, XP_2	Kaman KD-2350-1U Eddy current displacement measurement systems
Voltage, Current	Vmotor, Imotor, Vload, Iload, Valt, Ialt are sensed by resisture voltage dweden, step-down potential transformers, current transformers

The measurements taken can be classed in two categories, static and dynamic measurements.

Static Measurements. The static measurements consist of DC readings, along with some mechanical visual readings. Measurements of heater head temperatures, air temperature, fuel temperature, coolant temperature, air pressure, fuel pressure, mean charge pressure, combustor pressures, and air, coolant, and fuel flows are all static measurements.

Dynamic Measurements. The dynamic measurements consist of AC readings and are parameters which change at the engine frequency, which is 60 Hz. Examples of these measurements are piston and displacer position, compression space pressure, and electrical input and output measurements (such as motor current and alternator output current). The AC measurements were made with an RMS voltmeter; the result was used to calculate amplitudes. The disadvantage of this approach is that phase angles are lost; therefore, parameters such as engine PV power and spring losses can not be routinely calculated.

2.3 Data Acquisition System

The DAS used for FPSE testing has been in use since January 1981. This overall system is configured around two processing units; HP1000XL microcomputer and an HP9825 calculator. The HP1000XL computer and its peripheral instruments is the primary system. This system is used where detailed performance evaluation is required, since it is capable of acquiring and analyzing dynamic signals generated by position and pressure signals. This system is also used to acquire steady-state data from several "performance" test cells. The real-time operating system of the HP1000 can coordinate and schedule several concurrent tasks, and is thus capable of performing data acquisition tasks for several simultaneously operating cells as well as background program development and data reduction tasks. The use of the HP1000 for this endurance testing was limited to analysis of up to four dynamic signals during the duty-cycle test and post test storage and analysis of data collected by the HP9825 calculator based system.

The 9825 calculator controls a satellite DAS, which was the primary system used for monitoring and controlling the endurance test. This system includes the calculator, a frequency counter, a precision DVM, scanners, and a six-channel relay actuator, which are used to acquire data and provide limited engine control. The primary limitations of this system are that it can not quickly acquire and analyze high-speed dynamic signals, and it must be dedicated to, basically, a single task (limited multi-tasking has been implemented via user software). To support the endurance test, this system has been programmed to perform:

- Basic data acquisition and limited real time data analysis

- Continuous monitoring of critical engine operating parameters and detection of out-of-tolerance conditions

- Automatic shutdown of the engine should one or more out-of-tolerance conditions be detected

In spite of its limitations, this system provides all essential functions for monitoring of the endurance test, including measurement of dynamic signal amplitudes. This is accomplished by measuring these parameters with the true RMS function of the DVM and scaling the result, assuming that they are sinusoidal.

The measurement of PV power and internal losses was limited during the test by insufficient high-speed channel capability and the lack of necessary software to easily and efficiently measure these parameters. These limitations were substantially eliminated near the end of the test; therefore, future endurance testing will have DAS support which is very similar to that of the performance test cells.

2.4 Engine Control

There are three major control systems associated with the engine test cell:

1. Combustor control system
2. Power control system
3. Unattended operation interlock system

The combustor control is a digital electronic unit [1] which monitors and controls heater head temperature and combustor A/F ratio. The primary inputs to the controller include 10 type K heater thermocouples (T/C), fuel flow and

1 Automatic combustor Controller Development and Liquid-Fuel Combustor Design Program, Aerospace Laboratory, Wright-Patterson AFB, January, 1983.

airflow. The required air and fuel flow rates are set points to PID algorithms which control the position of the actual air and fuel control valves. This unit also monitors the status of several contactors which are part of the unattended operation function described below.

The power-control system is an analog electronic control which monitors and controls the alternator output voltage. For most of the first, second, and fourth phases of the endurance test, this control was used in a manual mode (i.e., the motor input voltage and frequency were set manually). However, during the duty-cycle test, the operating frequency and required output voltage were set, and the proportional/differential algorithm of the control unit determined the motor voltage required to maintain a constant output voltage for various load resistance values.

The unattended cell control is provided by a variety of hardware, including:

- Combustor control system
- HP9825 DAS
- Hardwired relay and switch logic

The faults which this system protects against and the action taken for each is summarized in Table 2-2. The basic control approach was to turn off the combustor and engine motoring when any faults were detected. The more critical faults are handled by hardwired relay logic. Several faults associated with the combustion system are handled by the combustion control system. The least critical faults are detected by the DAS. Due to the time required to complete a scan by the DAS ($\sim$30 s), these faults are related to slowly varying or less critical to engine parameters.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 2-2

CELL NO. 6 - UNATTENDED OPERATION

Fault	System Affected	Indication(s)
1. Fire in cell	"Halon" relay contact will open to de-energize cell exhaust fan. Loss of airflow will D.E. (open) natural gas solenoid and notify combustion controller to shutdown (loss of 110 volts AC)	1. Visual in cell 2. "Purge/fire alarm" light on combustion controller illuminutes
2. Loss of primary coolant flow	Solon flow/DP switch will open, D-EN relay/CR. Contacts/CR-A will close to notify combustion controller, which illuminates light; will open 1CR-B to extinguish green OVHD light; will open/CR-C in displacer motor power circuit to shutdown control relay CRM and disconnect motor power; will close latching contact/CR-D (manual reset)	1. Overhead green light extinguishes 2. Combustion controller "LoCool Flow" light illuminates 3. Displacer MTR green running light will extinguish
3. Loss of secondary coolant flow	Solon flow/DP switch will open, D-EN relay 3CR. Contacts 3CR-A will close to initiate combustion controller shutdown; will open 3CR-B to extinguish yellow OVHD light; will open 3CR-C in displacer MTR power circuit to D-EN CRM and disconnect motor power; will close latching contact 3CR-D (manual reset)	1. Overhead yellow light extinguishe 2. Audible alarm via relay actuator 3. Displacer MTR green running light will extinguish 4. Combustion controller "LoCool Flow" light illuminates
4. High secondary coolant temperature	Scanchan 1-65 monitors "T " thermistor value; DAQ compares RDG with software setpoint of 50 C; DAQ initiates shutdown of combustion controller	1. Audible alarm via relay actuator
5. Loss of room exhaust blower flow (fan)	Natural gas supply de-energized; combustion controller shutdown	1. Audible alarm via DAQ and relay actuator 2. "Exhaust air off" light on combustion controller illuminates
6. High test cell ambient air temperature	Scanchan 1-71 monitors thermistor located 5' above engine; DAQ compares RDG with software setpoint of 45 C; DAQ initiates engine shutdown and combustion controller shutdown	1. Audible alarm via DAQ relay actuator
7. Loss of combustion air blower flow	Midwest flow/DP switch closes to signal combustion controller to shutdown; DAQ initiates combustion controller shutdown fuel solenoid (close) and engine	1. Audible alarm via DAQ and relay actuator 2. "LoBlower Pressure: light on combustion controller illuminate
8. High heater head exhaust temperature	Software interlock - engine shutdown initiated; fuel solenoid closed via combustion controller	1. Audible alarm via DAQ and relay actuator
9. Low fuel pressure	Mercoid pressure switch closes to initiate combustion controller shutdown; shutdown fuel solenoid (closed) and engine	1. Audible alarm via DAQ and relay actuator 2. "LoFuel Pressure" light on combustion controller illuminates

TABLE 2-2 (Continued)

Fault	System Affected	Indication(s)
10. Loss of shop air	Whitman-General pressure switch opens on fail to DE-EN relay 2CR; contact 2CR-A will close to initiate combination controller shutdown; contact 2CR-B will open to extinguish red OVHD light; contact 2CR-C open to initiate displacer MTR CRM shutdown; contact 2CR-D will latch to maintain red light failure indication (manual reset); close fuel solenoid	1. Red OVHD light will extinguish 2. Audible alarm via DAQ and relay actuator 3. Displacer MTR green running light will extinguish
11. Excessive axial vibration	Accelerometer signal X is monitored by DAQ scanchan 1-50; software setpoint; DAQ will initiate shutdown; fuel solenoid closed	1. Audible alarm via DAQ and relay actuator
12. Emergency stop	Depressing the emergency stop (red) pushbutton on the combustion controller will D-EN 7CR relay; contact 7CR-A will open to D-EN CRM relay and shutdown motor	1. Green displacer MTR running light will extinguish
13. Combustion controller failure	Contact closure in the combustion controller is sensed by the DAQ via scanchan 1-70; initiates engine shutdown and fuel solenoid closure	1. Audible alarm via DAQ and relay actuator 2. "Fault" light on combustion controller illuminates

3.0 GENERAL DISCUSSION AND HISTORY

The 1000-hour endurance test was divided into four phases as described in Section 1.0. A discussion of aspects common to all phases of the test, history of the test, and a chronology of significant events are described in this section.

3.1 Test History

A complete chronological history of the endurance test, indicating significant events during the test program is given in Table 3-1. This information is also presented versus engine operating hours in Figure 3-1. In general, testing proceeded smoothly, with few interruptions. However, there were three major unplanned shutdowns during the program:

1. The heater head instrumentation necessary to monitor and control the heater temperature failed. This was caused by a combination of rough handling and vibration which broke the sheathed thermocouples (T/C's) that were brazed to the heater head. Since the T/C's were brazed to the head, their repair was involved and caused a substantial delay in the program. A subsequent redesign of the head instrumentation has substantially reduced the possibility of failure and, at the same time, will permit easy replacement of the T/C's if they should fail.

2. After the completion of the full-stroke test, the engine was being run to repeat selected test point performance. Due to an operator error, the engine was run for approximately three minutes (∿10000 cycles) without the hydrostatic gas bearings operating before the error was noticed and the engine shutdown. The subsequent inspection showed a number of local scratches, attributed to the dry-bearing operation, on the power piston (Figure 3-2) and mating bearing. The depth of the local scratches were not measurable by conventional instruments (micrometers); the surface profile (Figure 3-3) was measured in the areas shown in Figure 3-4 with a surface analyzer. Further, the bearing flow rate increased less than 10%

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3-1

ENDURANCE TEST CHRONOLOGICAL HISTORY
Apirl 8, 1983 through February 21, 1984

Date	Event	Comments
4/8	Initiated 100-hr low-power test	
4/15	Completed 100-hr low-power test	Total 100 hr
4/15-4/25	Planned inspection	No measurable hardware changes
4/25-5/20	Limited full-stroke test	Heater head instrumentation problems
5/20-7/11	Heater head refurbishment	Heater head thermocouples completely replaced
7/13	Initiated 300-hr full-stroke test	Minor problems with unattended operation mode. corrected during testing.
8/3	Completed 300-hr full-stroke test	Total 400 h
8/4	Engine run without bearings pressure	
8/5-8/15	Planned inspection	No measurable hardware changes
8/17	Initiated 600-hr duty-cycle test	
8/29	Unscheduled shutdown at hour 210 of 60-hr test	Small section of magnet separated and jammed displacer; damaged liner
8/29-9/14	Teardown	Engine rebuilt with new motor liner, reparied dispalcer
9/14	Restarted duty-cycle test	
10/2	Completed 600-hr duty-cycle test	Total 1000 hr
10/2-10/9	Continuted duty-cycle test additional 100-hr	Total 1100 hr
10/9-10/15	Planned inspection	No measurable hardware changes
10/15-2/13/84	Internal bearing development and demonstration	
2/13/84-2/21	Start-stop test	No measurable hardware changes; 262 start-stop cycles

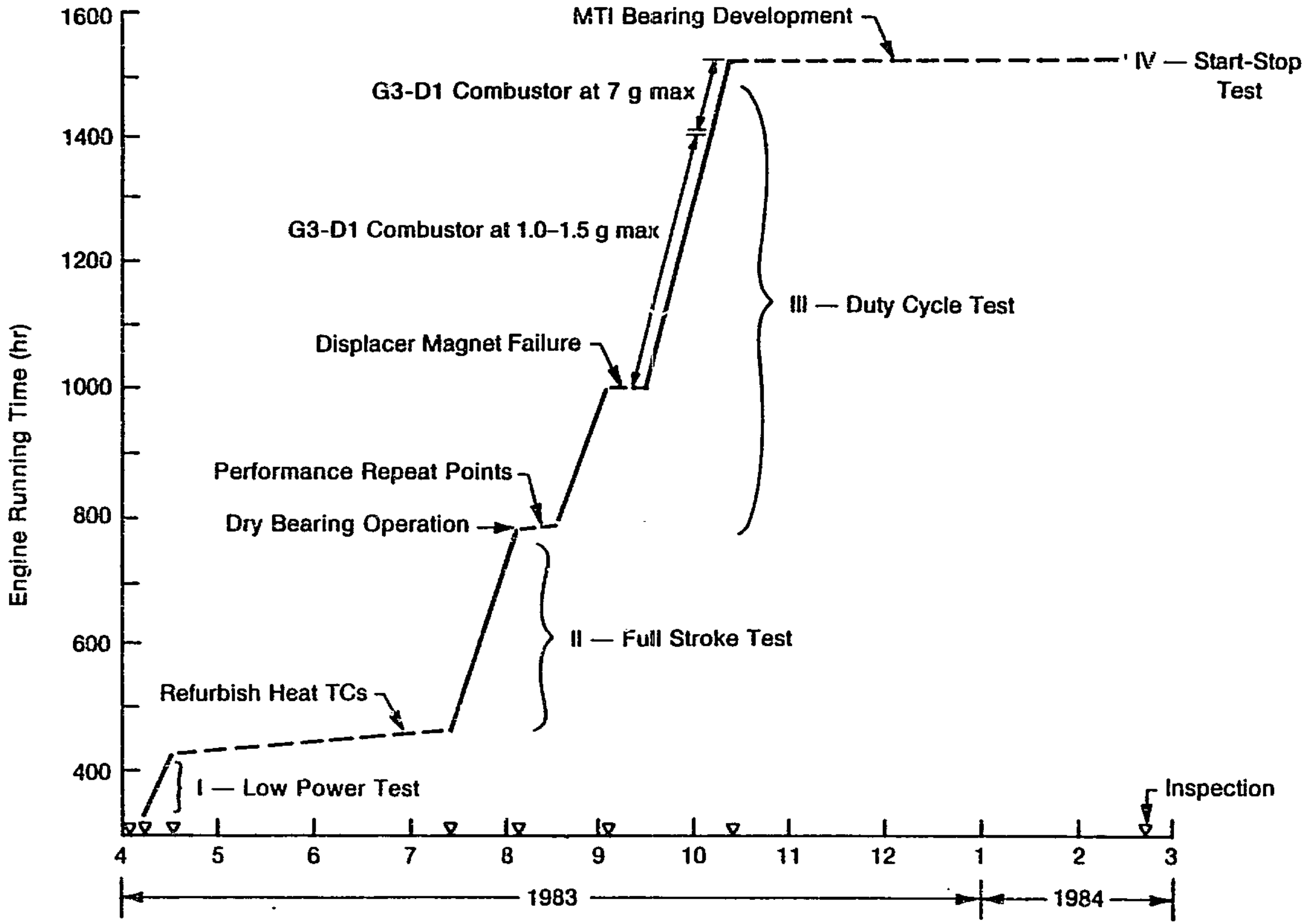


Figure 3-1 Chronological Engine History Chart

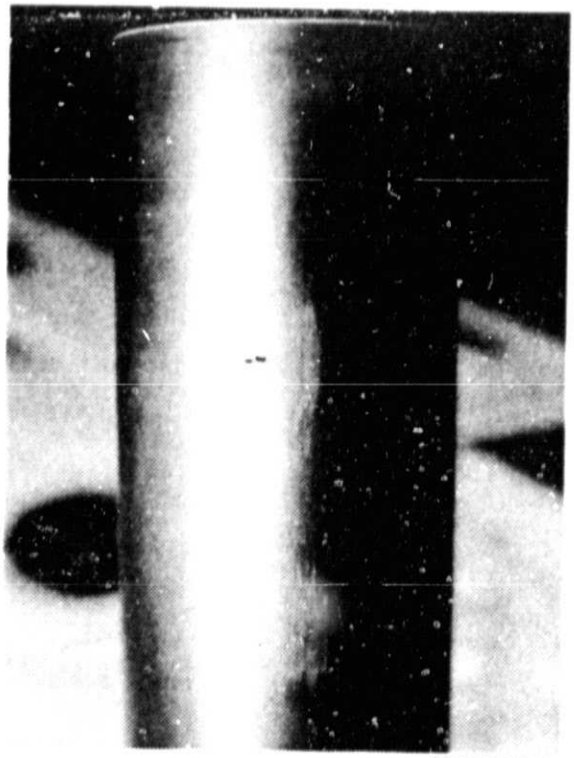


Figure 3-2 Piston Rub Due to Dry Bearing Operation

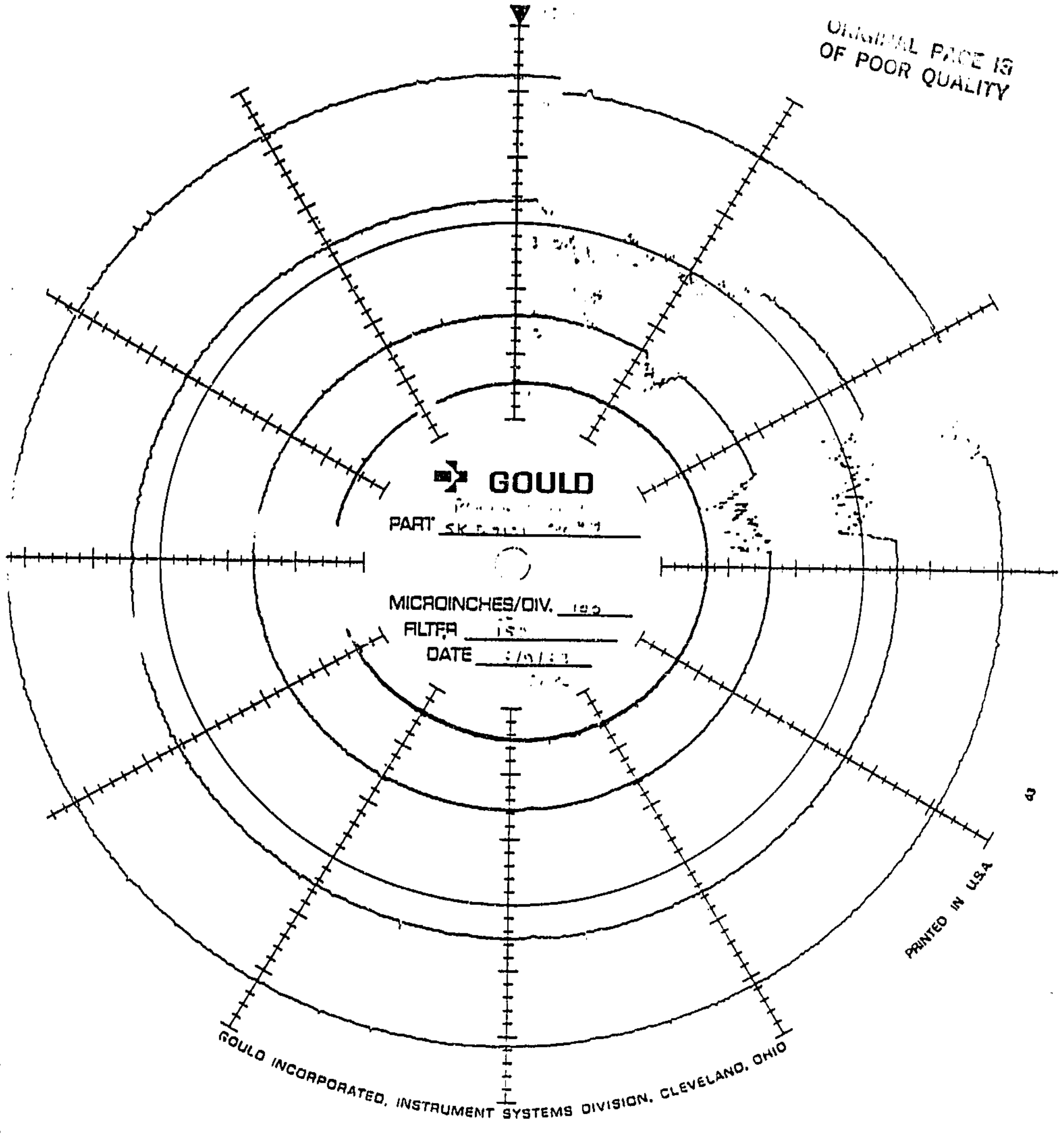


Figure 3-3 Surface Profile After Dry Bearing Operation

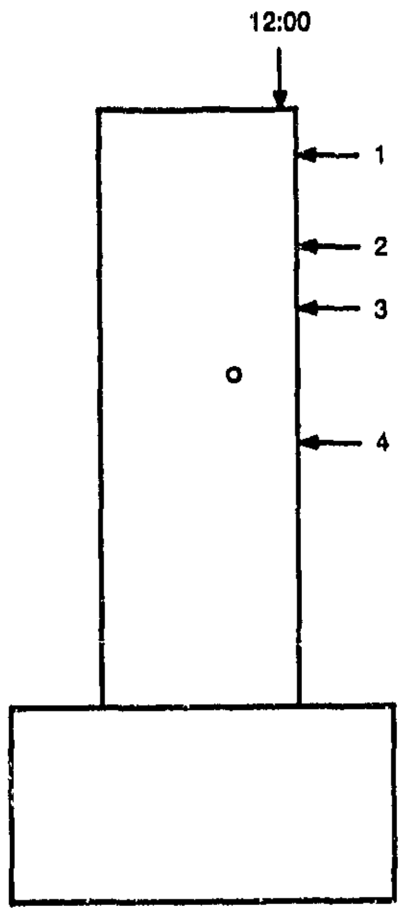


Figure 3-4 Location of Profile Measurement on Power Piston

from pre-test measurements. The scratches were polished and cleaned to remove high spots and debris before continuing the test.

3. A small (1/4" X 1/4") segment of the displacer drive magnet became dislodged and jammed the displacer. The magnet material is very brittle, although it is securely bonded to the displacer and protected from chipping, it is subject to damage during manufacture and assembly. The failed segment had broken during assembly prior to the start of the endurance program and had been cemented back in place with an anaerobic adhesive. This repair, however, proved to be temporary and the segment dislodged 220 hours into the duty-cycle testing. The magnet became lodged between the displacer magnet and motor stator causing significant damage to the phenolic motor liner. The dislodged magnet was pulverized before the failure became evident and the engine stopped. The engine was repaired by filling the void in the magnet with the same epoxy used to bond the magnets to the displacer. The phenolic liner was also replaced. No noticeable loss of motor performance has resulted from the resulting reduction of magnet volume.

Other causes of engine shutdown were related to the external combustor, engine support stand, and support facilities.

3.2 Combustor

The combustor used to supply heat to the engine proved to be less reliable than desired early in the test program and was modified several times to correct various problems. As the engine power module endurance (excluding the combustor) was the objective of this test, its durability and life potential will be only briefly discussed.

The poor durability of the early combustors can be attributed to the relatively high vibration levels ($\sim$7 g's at full stroke) to which the combustor was subjected. Substantial improvements were made to the combustor design during the endurance test. The latest combustor design (C3-D1) was run for $\sim$380 hours with the engine tied to an inertial mass ($\sim$1-1.5 g) followed by $\sim$90 hours of operation at 7 g operation where the engine case was free to vibrate (see Figure 3-1). The durability of the combustor in the high g environment was found to be limited by the relatively soft rigid insulation materials used in its construction. While substantial improvements in the combustor proper were made, the most successful solution was to substantially reduce or eliminate the engine vibration.

3.3 Engine Support Stand and Facilities

There were several failures of the struts which connected the engine to the inertial mass. This had no effect on power module; however, if not caught quickly, operation after strut failure could cause rapid degradation of the combustor. The facility and interlock system designed to protect the engine from facility related failures caused numerous engine stoppages early in the test program. These problems were corrected and the test continued. By the duty-cycle test phase, the number of facility related stoppages were substantially reduced. The last 400 hours of duty-cycle testing were completed in 432 clock hours (18 days) or only 8% down time.

3.4 Critical Clearance Inspection

Prior to each test phase, the critical wear surfaces were thoroughly inspected and photographed. The engine was also inspected when a failure involving the power module occurred and following each test phase. Critical measurements and inspection locations are shown in Figure 3-5. These areas and the clearances are outlined as follows:

- <u>Displacer Bearings/Seals</u> - Clearance between displacer rod (rod that attaches to the displacer body) and post manifold. This clearance is important for proper operation of displacer gas bearings and to seal the forward and aft displacer gas springs from the bearing drains.

- <u>Displacer Motor Seal</u> - Clearance between outer diameter (O.D.) of the displacer body in the area of the permanent magnets and displacer motor liner which seals between the hot-expansion and cold-compression spaces.

- <u>Displacer Gas Spring Seals</u> - Clearance between the forward gas spring and outside diameter of the post, or between aft gas spring and gas

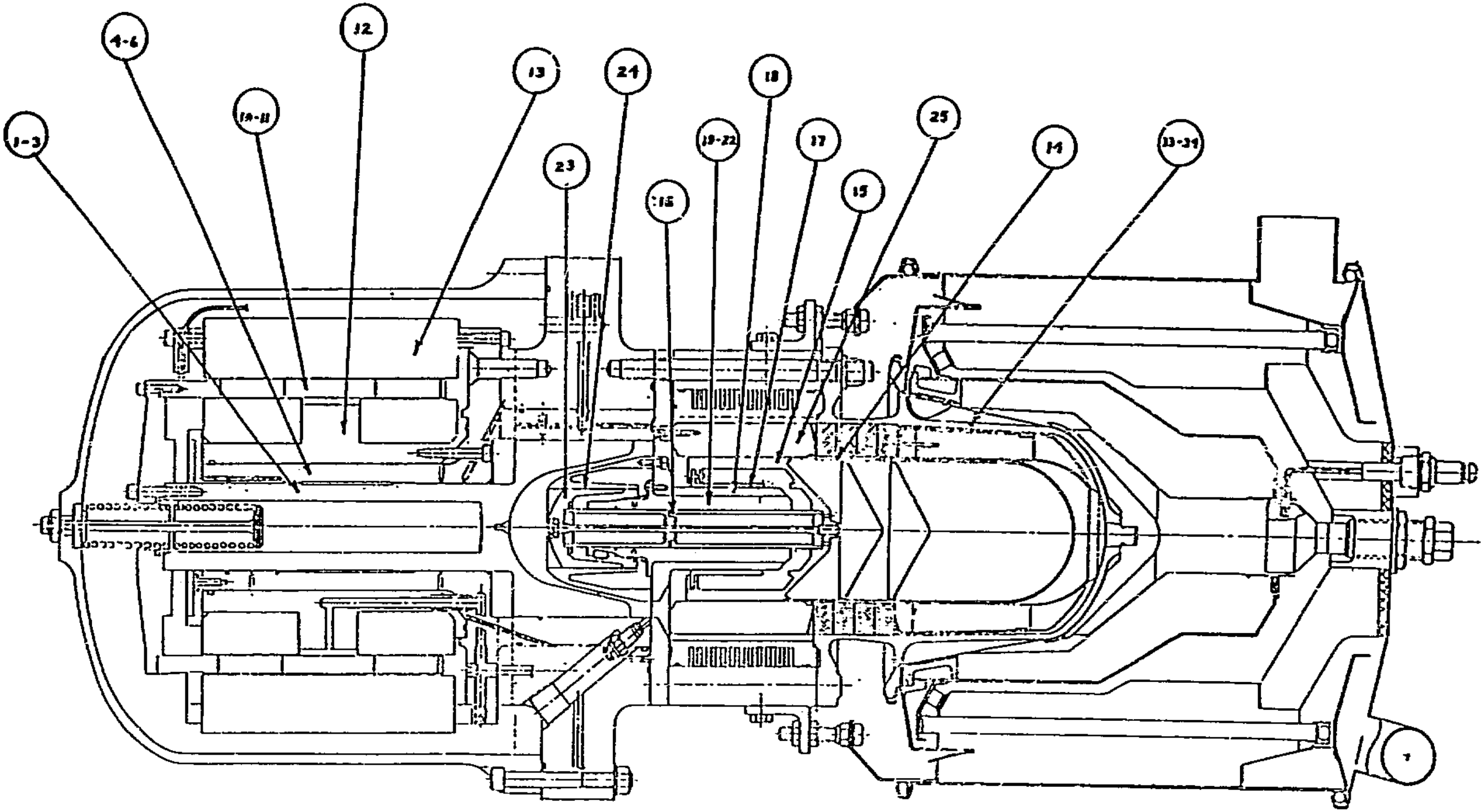


Figure 3-5 Critical Wear Surfaces Measured (numbers reference items on Inspection Summary Sheet, Table 3-2)

spring cylinder. The purpose of this clearance is to prevent leakage between the gas springs and engine pressure wave.

- Power Piston Seal - Clearance between forward power piston and power piston cylinder which provides sealing between the engine pressure wave acting on the face of the power piston and engine mean or bounce pressure.

The inspection data for the initial test was tabulated on the form shown in Table 3-2. As shown in Table 3-2, all critical surfaces have been given an item number (Column 1), Figures 3-5 to 3-7 locates each item on an overall assembly. The detail drawing number for the part is given in Column 2 and the serial number in Column 3. The item is described in Column 4. The nominal print dimension for each item is given in Column 5, and Column 6 gives the average as measured dimension. Column 7 lists the results of a flow check for several bearings or seals; these flow paths are shown in Figures 3-6 and 3-7. The flow measurement rig used for these checks is shown in Figure 3-8. Columns 8 and 9 list the design and as measured surface finish. These are done with a surface comparitor; the initial surfaces are in new condition. A detailed surface profile (Column 10) will be completed where appropriate, for subsequent inspections. The part weights are listed in Column 11; these are measured with a balance which has a resolution of 1 gm. Column 12 lists the picture numbers of the critical surfaces. For each surface a picture is taken with the part in each of four orientations (12, 3, 6 and 9 o'clock). The final column is provided for miscellaneous remarks.

The clearance was determined by measuring the bore (I.D.) of the cylinder and subtracting the measurement of the outside diameter of the mating part. This procedure resulted in a measurement of two relatively large diameters; the subtraction of one from the other resulting in extremely small clearance dimensions. Since the inspection itself was a difficult task, care was taken to have the same inspector conduct each inspection in an attempt to maintain consistency. Because of the instruments used and the number of measurements taken, the uncertainty of the resulting measurement was 70-millionths of an inch (.00178 mm).

The results for the critical clearances as a function of test hours are graphically presented in Figures 3-9 through 3-14 and include measured clearances relative to the design value of the displacer bearings, displacer seals, displacer

TABLE 3-2

INSPECTION SUMMARY SHEET

MTI

INSPECTION SUMMARY SHEET

INSPECTION #: DESCRIPTION: DATE:

TOTAL HRS:

ITEM #	PART #	SERIAL #	DESCRIPTION	PRINT DIMENTIONS	ACTUAL DIMENTIONS	BEARING FLOW TEST	PRINT SURFACE FINISH (✓)	ACTUAL SURFACE FINISH (✓)	SURFACE PROFILE	WEIGHT (kg)	PHOTOGRAPH #	REMARKS
			POWER PISTON -									Dynamic Mass - Kg
1			SEAL O.D.									
2			FWD. BEARING O.D.									
3			AFT. BEARING O.D.									
			ALT. CYL./BEARING -									
4			SEAL I.D.									
5			FWD. BEARING I.D.									
6			AFT. BEARING I.D.									
			POWER PISTON -									
7			ALT. SEAL CLEARANCE (4-1)									
			POWER PISTON -									
8			FWD. BEARING CLEARANCE (5-2)									
9			AFT. BEARING CLEARANCE (6-3)									
			ALT. PLUNGER -									Without Hardware
10			OUTSIDE DIAMETER									
11			INSIDE DIAMETER									
			ALT. STATORS -									
12			INSIDE STATOR O.D.									
13			OUTSIDE STATOR I.D.									
			ENGINE DISPLACER -									Dynamic Mass - Kg
14			SHELL (DOME) O.D.									
15			MOTOR PLUNGER (MAGNETS) O.D.									
16			ROD O.D.									
17			END COVER I.D.									
			POST AND FLANGE ASSEMBLY -									
18			POST O.D.									
			MANIFOLD -									
19			FWD. SEAL I.D.									
20			AFT. SEAL I.D.									
21			FWD. BEARING I.D.									
22			AFT. BEARING I.D.									
23			GAS SPRING PISTON O.D.									
24			GAS SPRING CYLINDER I.D.									
25			MOTOR STATOR I.D.									
26			DISPLACER MOTOR SEAL CLRNCE. (25-15)									
27			DISPLACER FWD. BRNG. CLRNCE. (21-16)									
28			DISPLACER AFT. BRNG. CLRNCE. (22-16)									
29			FWD. GAS SPRING SEAL CLRNCE. (17-18)									
30			DISPLACER BRNG. SEAL CLRNCE. (19-16)									
31			AFT. GAS SPRING SEAL CLRNCE. (24-23)									
32			DISPLACER BRNG. SEAL CLRNCE. (20-16)									
			HEATER HEAD -									
33			DIAMETER AT HALF WAY POINT OF O.S. FINS									
34			OVERALL HIGHT UNDER CAP THREADS									

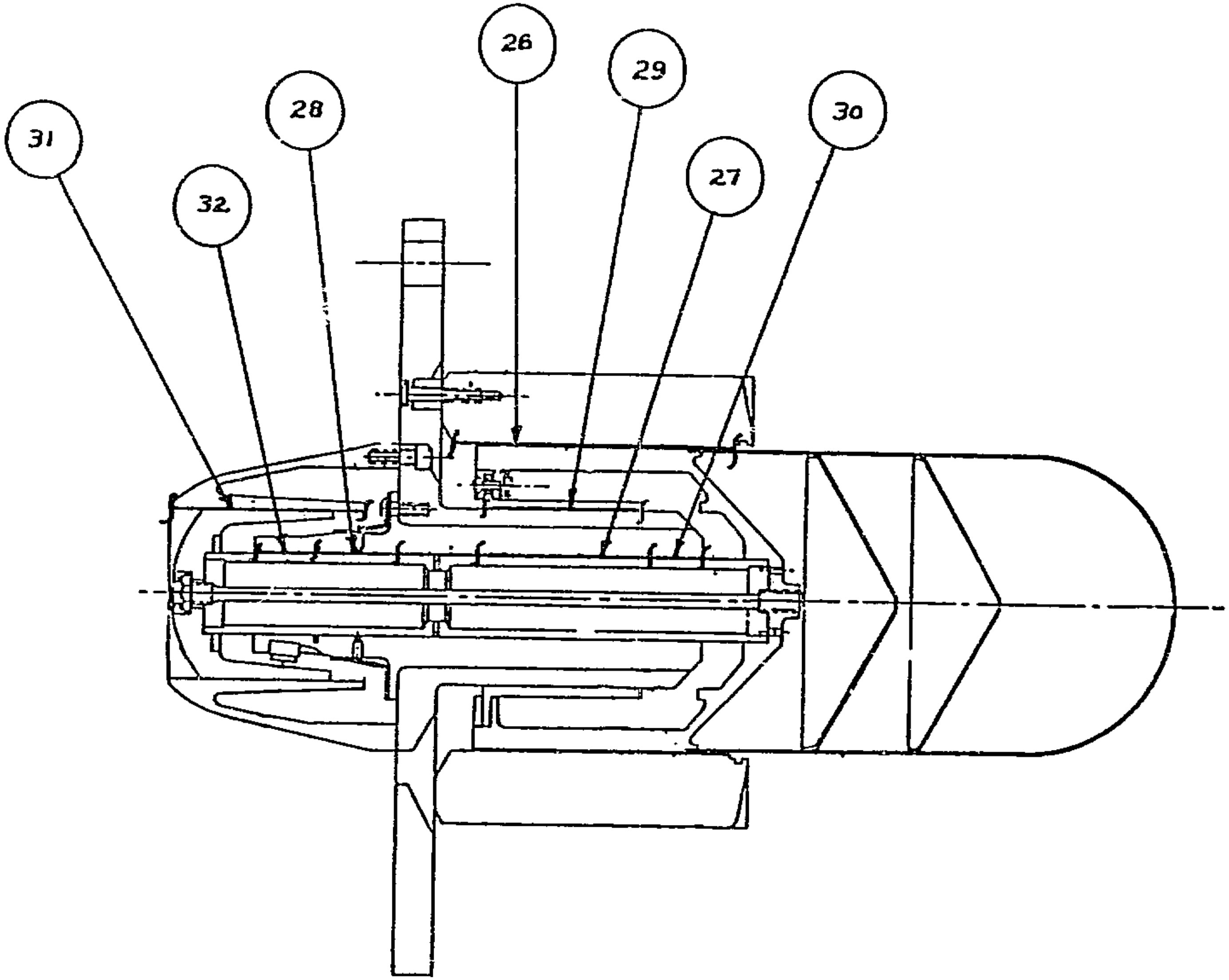


Figure 3-6 Critical Engine Clearances (numbers reference items on Inspection Summary Sheet, Table 3-2)

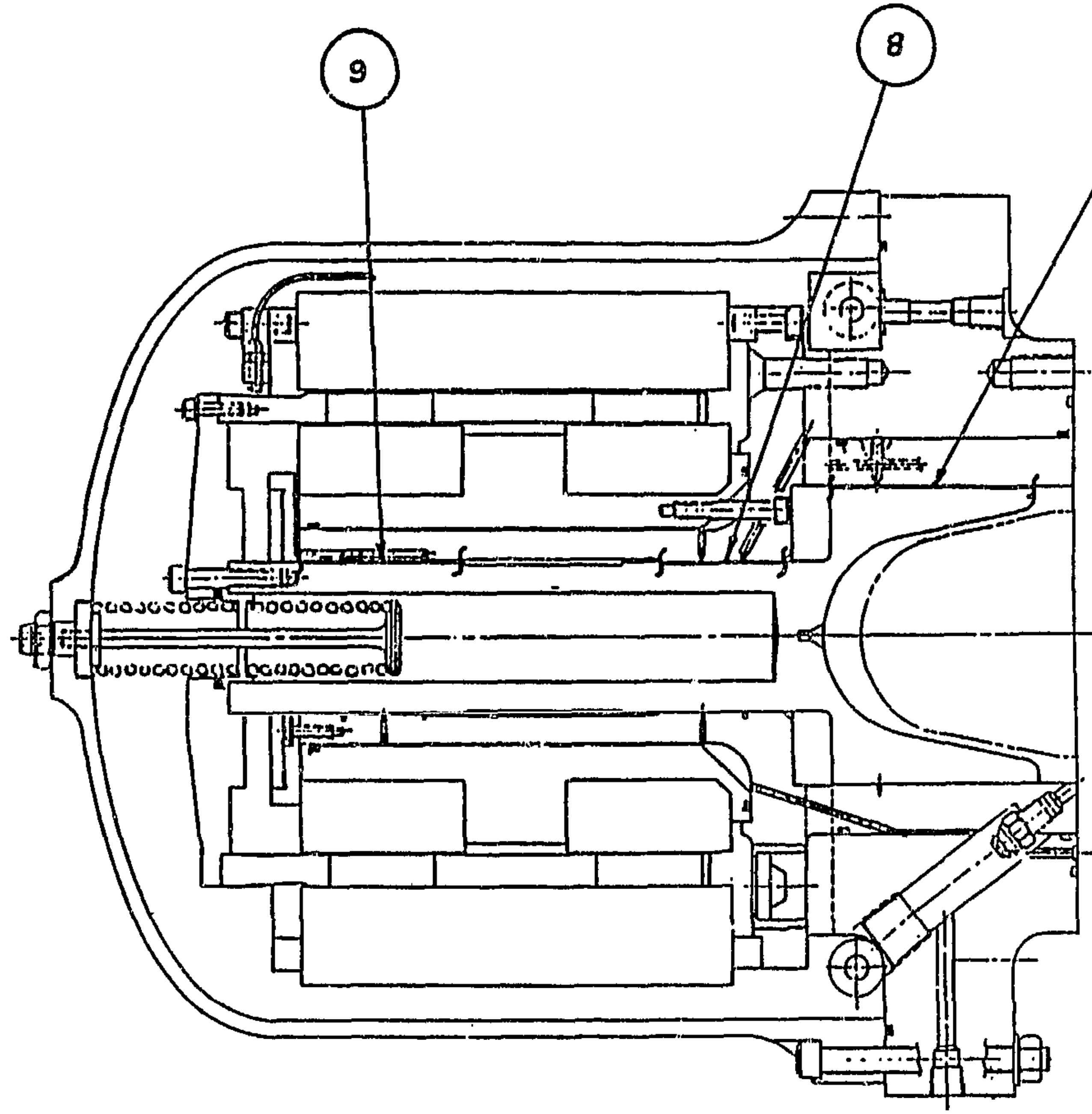


Figure 3-7 Critical Alterantor Clearances (numbers reference items on Inspection Summary Sheet, Table 3-2)

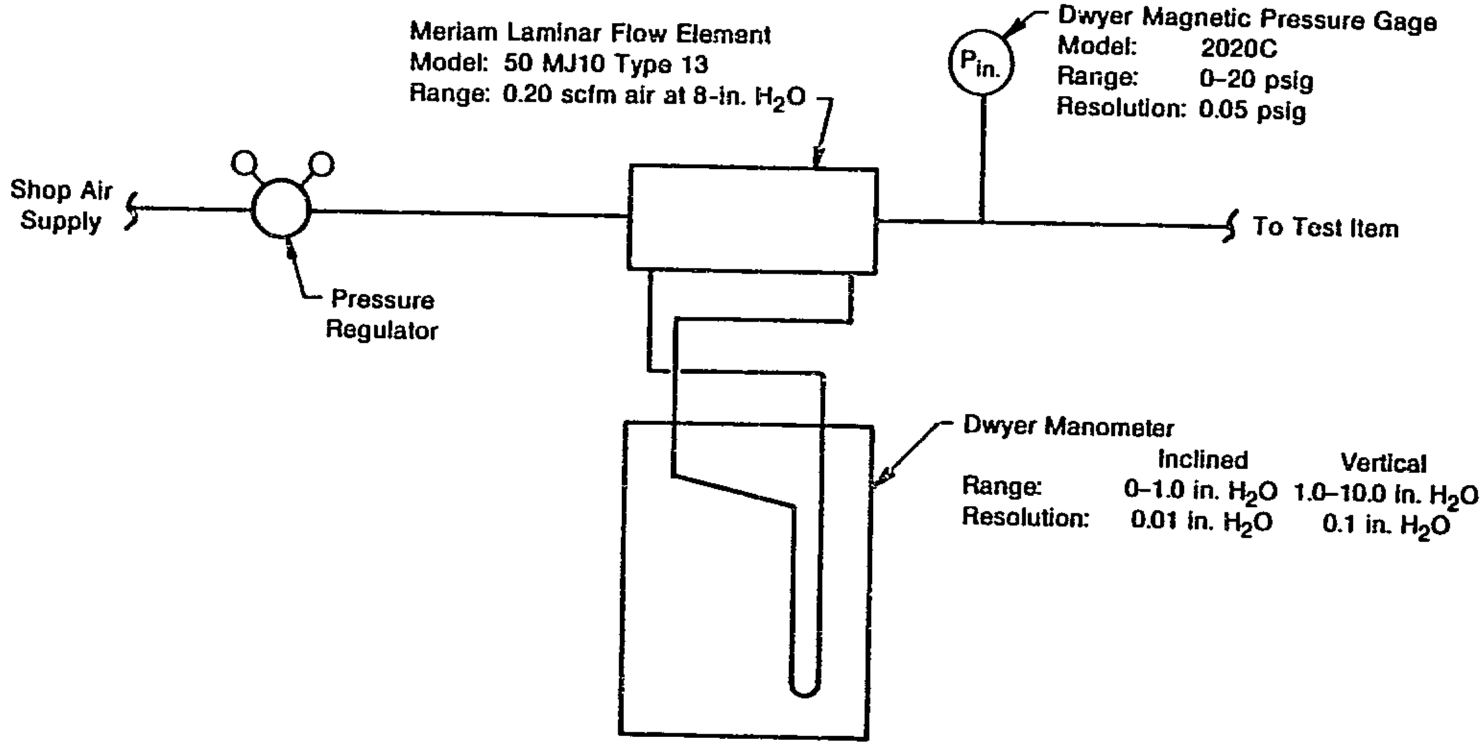


Figure 3-8 Bearing/Seal Flow Check Rig

Measurements Taken after 1220 hr

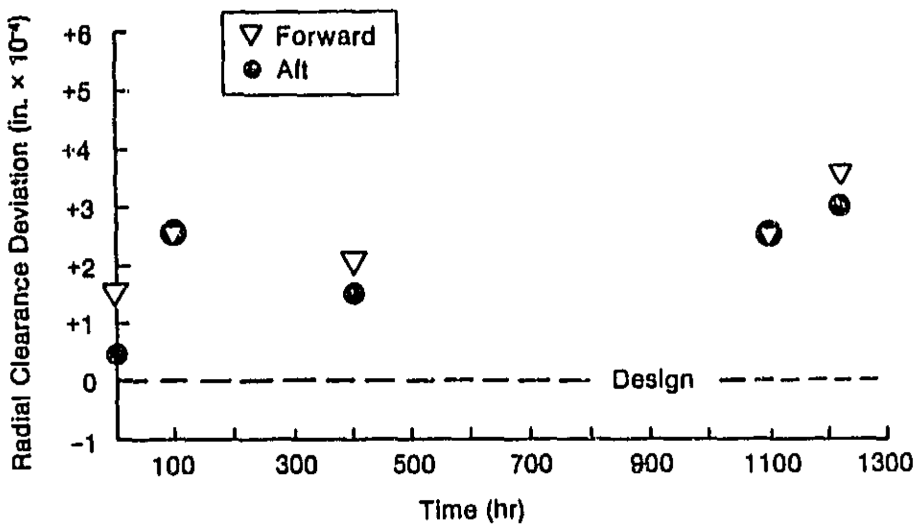


Figure 3-9 Measured Clearances - Displacer Bearings

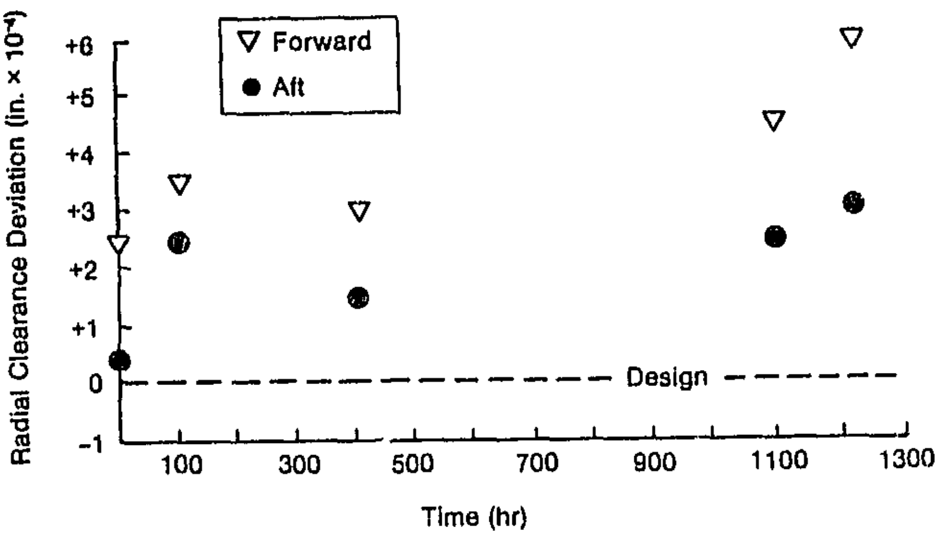


Figure 3-10 Measured Clearances - Displacer Rod Seals

Measurements Taken after 1220 hr

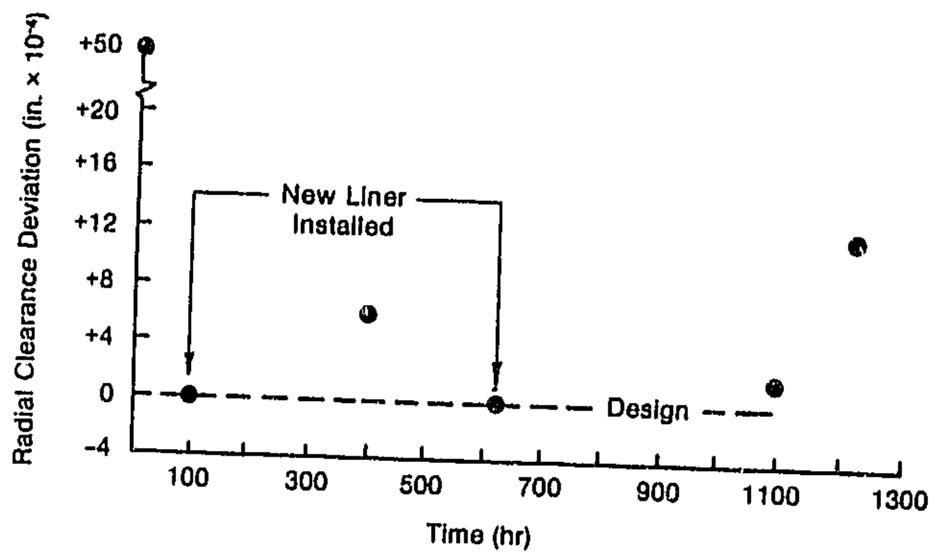


Figure 3-11 Measured Clearances - Displacer Motor Seal

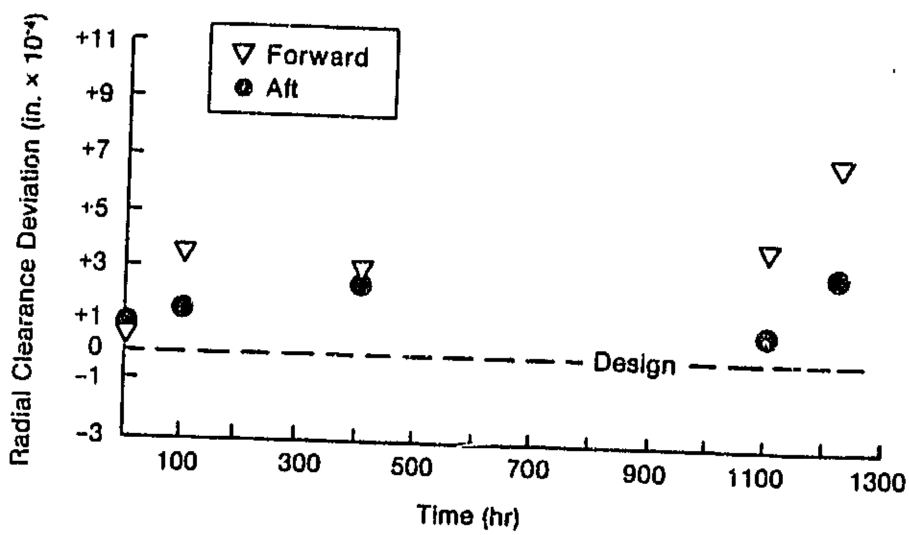


Figure 3-12 Measured Clearances - Gas Spring Seals

Measurements Taken after 1220 hr

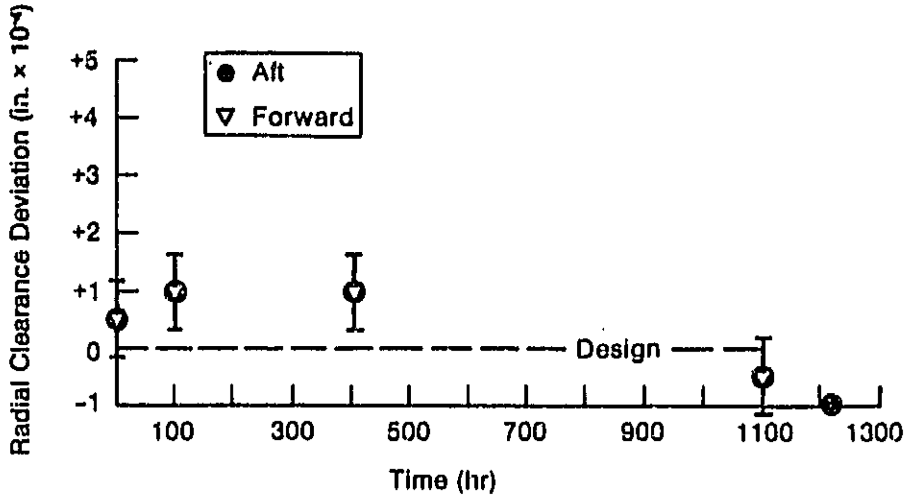


Figure 3-13 Measured Clearances - Power Piston Bearings

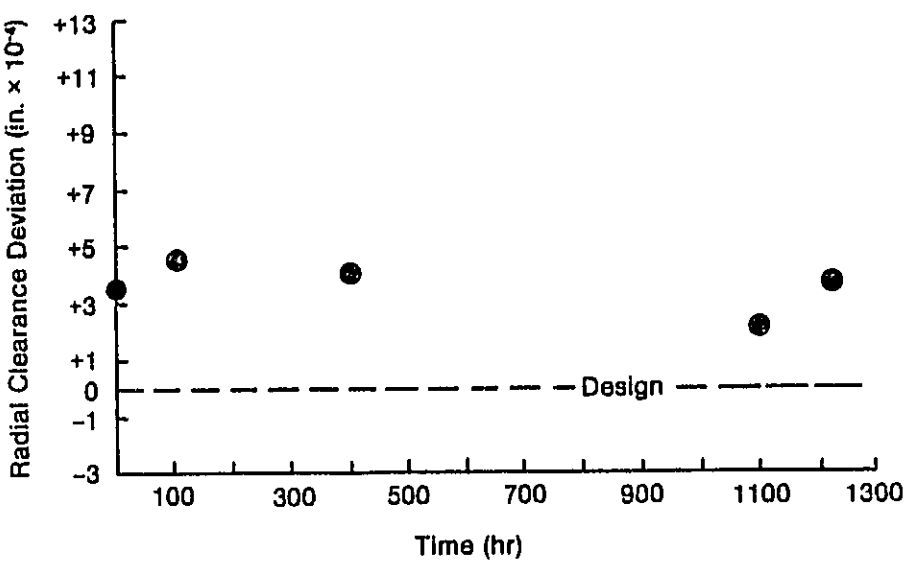


Figure 3-14 Measured Clearances - Power Piston Seal

motor seal, gas spring seal, power piston bearings, and power piston seal, respectively.

As can be seen, no trend is exhibited in the critical clearance measurements, even though variations between clearances exist at the various inspection points. Since the variations over time are within the measurement uncertainty band, they are not statistically significant and do not represent a change in clearance.

3.5 Bearing Flow Measurement

As another check on bearing clearances within the displacer and power piston, bearing flow measurements were made on the assembled engine at the beginning of the test and prior to teardown for each inspection. Flow versus back pressure is a very sensitive indicator of changes in the bearing surface clearances.

The change in bearing flow as a function of time, which is an indication of the change in bearing clearance, shown in Figure 3-15. The flow is seen to slightly increase during the first 400 hours of the test, but is nearly constant throughout the remaining 700+ hours. These flow measurements confirm these inspections of the critical clearances that showed no significant increase in bearing clearances during the test.

3.6 Internal Bearing Supply Development

Phases I, II, and III were all conducted with externally supplied gas bearing pressure.

The demonstration of internal bearing operation was carried out on MTI funds between the end of the duty-cycle test and prior to beginning the start/stop task of the 1000-hour endurance program.

The engine hardware was modified to add a check valve that would pump working fluid from the engine compression space to the bearing supply plenum. The check valves are based on a commercially available o-ring check valve in which an o-ring expands radially when the valve opens, then springs back into a groove to close. The power piston and cylinder were also modified to increase the mid-stroke port area and to enlarge the passages between the ports and bounce space. The initial

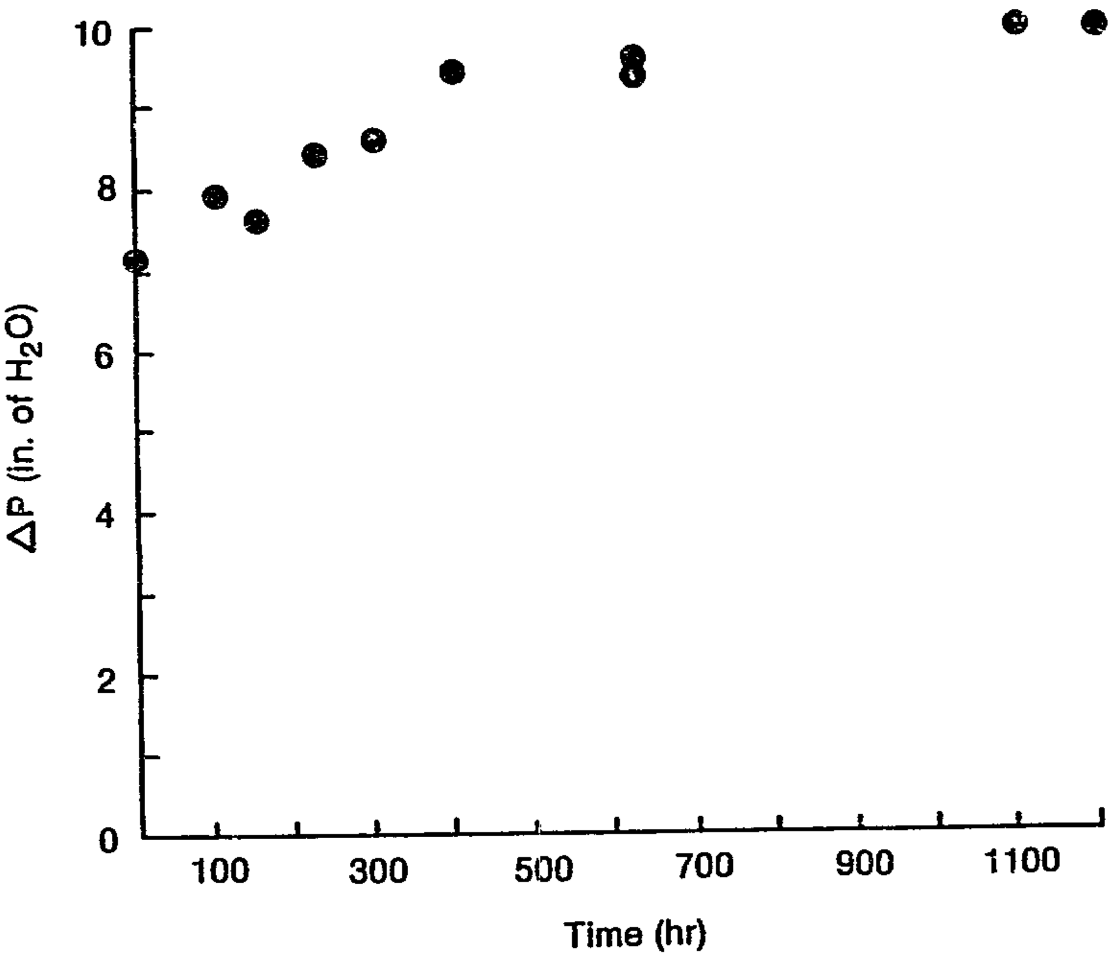


Figure 3-15 System Bearing Flow

tests of this hardware showed the relatively small ports originally in the piston would have been adequate to maintain the piston mid-stroke position. During the testing, several improvements were made to the check valve assemblies to reduce the pressure drop in the valve and connecting tubing. Two check valves were found to be too restrictive for the desired bearing flow. Furthermore, the check valve plenum was found to be too small, causing high pressure pulsation in the discharge when the valve opened. Therefore, a plenum assembly was fabricated which provided for four check valves and substantially increased the plenum size.

When this assembly was tested, the discharge plenum was found to have a relatively large pressure amplitude at a frequency corresponding to the resonant frequency of the plenum and discharge tube system. Several tests were carried out to characterize the internal compressor flow and pressure for various discharge tube lengths and frequencies. From these results, the bearing compressor was tuned to give the maximum bearing pressure. Approximately 10-20 hours of exclusive internal bearing testing was accomplished.

4.0 PHASE I - LOW-POWER TESTING

4.1 Objective

The objective of the low-power test was to accumulate 100 operational test hours at ~5 kW power and 600°C mean heater head temperature. The purpose of the test was to provide check-out of the operating power module and test cell interaction, and to evaluate engine performance to determine if changes occurred to engine performance parameters. It was expected that engine performance parametrics would be more sensitive to small changes at low power, since parasitic losses represent a higher percentage of power output.

4.2 Conclusions

The low-power test was successfully completed. Although there were indications that some critical clearances did increase, they could not be confirmed by other measurements. Most all clearance changes were in the level of inspection resolution. Gross engine parameters remained constant throughout the test. Therefore, the engine was readied for 300 hours of full-stroke testing.

4.3 Discussion

4.3.1 Test Description

The engine seal and bearing clearances were inspected prior to starting this phase of engine testing.

This test was conducted with the engine load and motor input set to constant values such that the piston stroke was ~50% of design. The heater temperature was set to a constant 600°C and the engine pressure was 60 Bar.

Supplementing the inspection of critical clearances, photographs of all critical parts and surfaces were taken prior to the start of the test. In addition, a flow check was also made on the power piston bearings and displacer bearings. All measurements and inspections are performed at the beginning and end of each test phase. The pre-test inspection performed prior to the 100-hour test is the nominal inspection from which magnitude of changes are evaluated.

4.3.2 Test History and Results

The 100 hours of low-power testing was uneventful. Testing was initiated on 8 April 1983 and concluded on 15 April 1983. The engine performance did not change from the start to finish of the test. The displacer motor power increased slightly (20-30 watts), which may be due to even smaller changes in other operating parameters. Power variation, which would indicate gross changes in the engine, remained steady throughout the test (Figure 4-1). Table 4-1 presents a summary of engine parameters X_D, X_p, P_{mean}, and T_{HD} as a function of test hours.

4.3.3 Post-Test Inspection

Post-test inspection of the hardware, which is also the pre-test inspection for the 300 full-stroke test, was completed on 20 April 1983. Visual inspection of the hardware indicated a small scratch $\sim$0.2 in. (5.08 mm) wide in the area of a feed hole of the forward power piston bearing. This may be due to debris from the feed hole, since the damage was very localized. This damage also appeared in piston bearing flow check which increased 26.9%.

The pre- and post-test inspections showed some clearance changes. Figures 3-10 through 3-15 indicate the clearance change between the initial inspection (No. 1) and the inspection at the end of 100 hours (No. 3). Table 4-2 summarizes these particular measurements. Most of the clearance changes were on the order of the measurement resolution. The displacer forward and aft bearing clearance, forward displacer gas spring clearance, and displacer bearing seal, however, appear to be significant. The motor clearance seal actually decreased during the test, which may be due to shrinkage of the phenolic liner. There was some heat discoloration of the liner. The increase in the displacer bearing clearance is not substantiated by the bearing flow check, which indicated a slight decrease in clearance. The other clearances, while significant, could not be checked against independent measurements. These would tend to increase the respective gas spring losses and, consequently, displacer motor power. However, displacer motor power and respective gas spring measured losses only increased slightly during the 100-hour test.

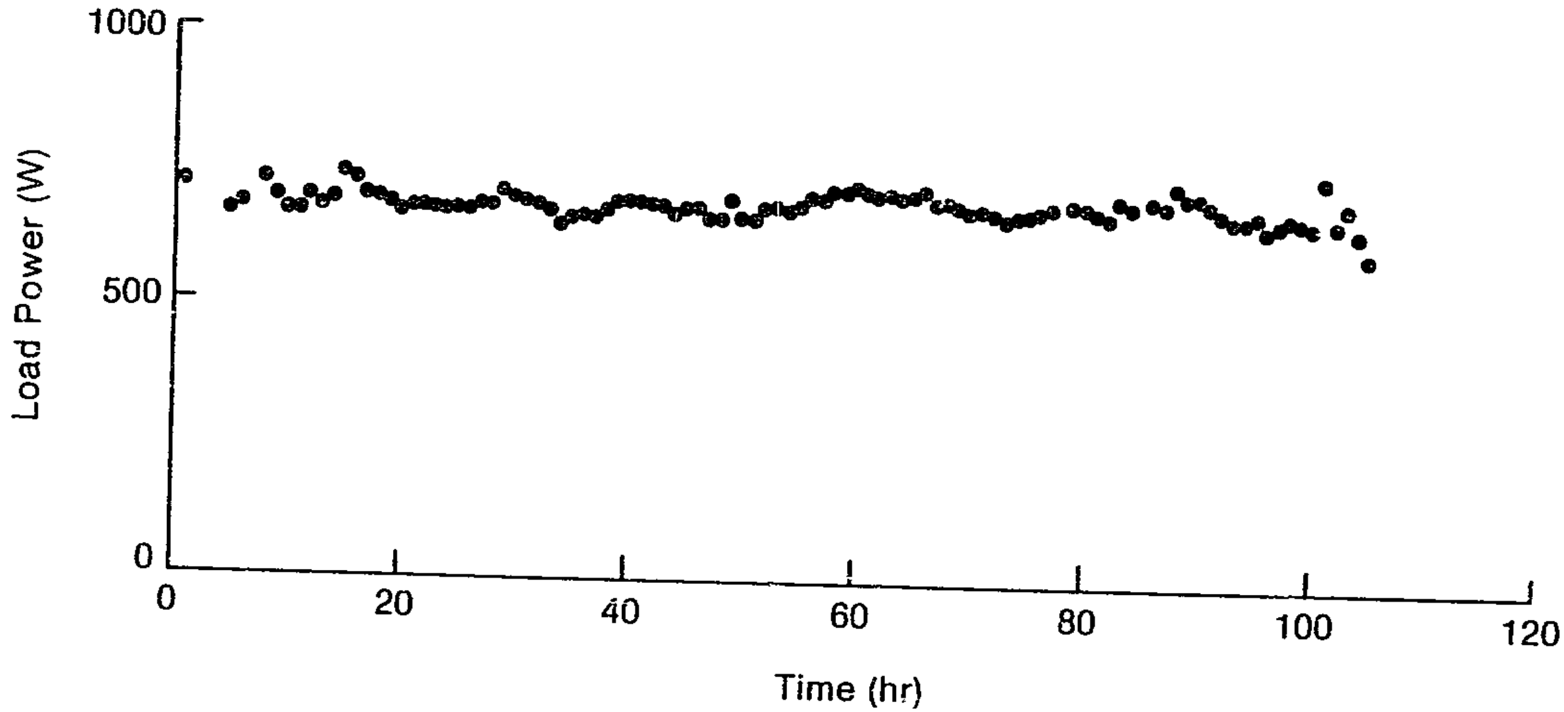


Figure 4-1 Power Output During Phase I (Low Power) Testing

TABLE 4-1

HOURLY AVERAGE OF SELECTED LOW-POWER DATA

NO	DATE	TIME FIRST	TIME LAST	PMEAN	XD AMP	XP AMP	IMTR	IFIELD	OAD PWR	THD MEAN	A/F RAT	FIRERATE	LOAD RES
1	408	1008	1059	6.1123E+01	3.7283E-03	4.9192E-03	4.0818E+00	2.0215E+00	7.1000E+02	6.1008E+02	2.4498E+01	7.3478E+03	2.7569E+00
2	408	1106	1157	6.0577E+01	4.6980E-03	6.5614E-03	6.8000E+00	2.0045E+00	1.1155E+03	6.2729E+02	2.4815E+01	1.0658E+04	2.7456E+00
3	408	1202	1258	5.9830E+01	4.8440E-03	7.4336E-03	6.4867E+00	1.9938E+00	1.3433E+03	7.0584E+02	2.2305E+01	1.3162E+04	2.7403E+00
4	408	1303	1358	5.9719E+01	4.7140E-03	7.2037E-03	6.2808E+00	2.0050E+00	1.2923E+03	6.9050E+02	2.2581E+01	1.2161E+04	2.7377E+00
5	408	1403	1459	5.9817E+01	3.5306E-03	4.9569E-03	3.7767E+00	2.0328E+00	6.6017E+02	6.0064E+02	2.7113E+01	7.3902E+03	2.7520E+00
6	408	1504	1559	5.9723E+01	3.5224E-03	4.9476E-03	3.8125E+00	2.0543E+00	6.6783E+02	6.0102E+02	2.6748E+01	7.4451E+03	2.7530E+00
7	408	1604	1655	5.9717E+01	3.8249E-03	5.3533E-03	4.5418E+00	2.0561E+00	7.8555E+02	6.0197E+02	2.6654E+01	8.3982E+03	2.7588E+00
8	408	1700	1755	5.9833E+01	3.6251E-03	5.1247E-03	3.9675E+00	2.0493E+00	7.1658E+02	6.1557E+02	2.6587E+01	7.8570E+03	2.7496E+00
9	408	1800	1855	5.9824E+01	3.5178E-03	4.9812E-03	3.7783E+00	2.0581[illegible]+00	6.8542E+02	6.1373E+02	2.6066E+01	7.5722E+03	2.7500E+00
10	408	1901	1956	5.9820E+01	3.4621E-03	4.9463E-03	3.8267E+00	2.0448E+00	6.6458E+02	6.1713E+02	2.6548E+01	7.6944E+03	2.7483E+00
11	408	2001	2056	5.9749E+01	3.4609E-03	4.9650E-03	3.8433E+00	2.0386E+00	6.6333E+02	6.1728E+02	2.6600E+01	7.2011E+03	2.7506E+00
12	408	2101	2157	5.9887E+01	3.5004E-03	5.0039E-03	3.8933E+00	2.0469E+00	6.8575E+02	6.1394E+02	2.6694E+01	7.6160E+03	2.7475E+00
13	408	2202	2257	5.9890E+01	3.4611E-03	4.9411E-03	3.8367E+00	2.0533E+00	6.7342E+02	6.1571E+02	2.6866E+01	7.6867E+03	2.7479E+00
14	408	2302	2302	5.9957E+01	3.4563E-03	4.9469E-03	3.8700E+00	2.0530E+00	6.8100E+02	6.1817E+02	2.7925E+01	6.9540E+03	2.7412E+00
15	411	1053	1058	6.0089E+01	5.2700E-03	4.8557E-03	3.4450E+00	1.9935E+00	7.2850E+02	6.0896E+02	2.6929E+01	8.4790E+03	2.7635E+00
16	411	1103	1153	5.9961E+01	3.6955E-03	4.9440E-03	3.4975E+00	2.0175E+00	7.1975E+02	6.1537E+02	2.6142E+01	8.1301E+03	2.7572E+00
17	411	1207	1258	5.9901E+01	3.5643E-03	4.9634E-03	3.4467E+00	2.0270E+00	6.9250E+02	6.1333E+02	2.5700E+01	7.8232E+03	2.7630E+00
18	411	1308	1351	5.9840E+01	3.5347E-03	4.9681E-03	3.4760E+00	2.0158E+00	6.8760E+02	6.1165E+02	2.5551E+01	7.4812E+03	2.7483E+00
19	411	1402	1452	5.9880E+01	3.4984E-03	4.9409E-03	3.4260E+00	2.0102E+00	6.7600E+02	6.0711E+02	2.5624E+01	7.1580E+03	2.7545E+00
20	411	1506	1559	5.9825E+01	3.5107E-03	4.9293E-03	3.4757E+00	2.0033E+00	6.6643E+02	6.1349E+02	2.5821E+01	7.4812E+03	2.7571E+00
21	411	1609	1659	5.9927E+01	3.5822E-03	4.9485E-03	3.5100E+00	1.9952E+00	6.7317E+02	6.0823E+02	2.5454E+01	7.7928E+03	2.7619E+00
22	411	1710	1750	5.9931E+01	3.5960E-03	4.9353E-03	3.5540E+00	1.9894E+00	6.7220E+02	6.1324E+02	2.5817E+01	7.7496E+03	2.7640E+00
23	411	1800	1851	5.9872E+01	3.6050E-03	4.9294E-03	3.6233E+00	1.9858E+00	6.6850E+02	6.1161E+02	2.5874E+01	7.8485E+03	2.7627E+00
24	411	1901	1952	5.9828E+01	3.6060E-03	4.9327E-03	3.6483E+00	1.9830E+00	6.6817E+02	6.1383E+02	2.5802E+01	7.7023E+03	2.7557E+00
25	411	2002	2053	5.9835E+01	3.6057E-03	4.9452E-03	3.6533E+00	1.9805E+00	6.6617E+02	6.1444E+02	2.5943E+01	7.6377E+03	2.7543E+00
26	411	2103	2154	5.9882E+01	3.6168E-03	4.9476E-03	3.6283E+00	1.9822E+00	6.6983E+02	6.1430E+02	2.5447E+01	7.6332E+03	2.7520E+00
27	411	2204	2255	5.9904E+01	3.6260E-03	4.9587E-03	3.6033E+00	1.9920E+00	6.7967E+02	6.1576E+02	2.5801E+01	7.6732E+03	2.7525E+00
28	411	2305	2325	6.0089E+01	3.6128E-03	4.9290E-03	3.5000E+00	1.9900E+00	6.7367E+02	6.1932E+02	2.5858E+01	7.7464E+03	2.7591E+00
29	412	935	955	6.1178E+01	3.9006E-03	4.8804E-03	4.2260E+00	2.0278E+00	7.0140E+02	5.8913E+02	2.6233E+01	7.9595E+03	2.7563E+00
30	412	1000	1051	6.0655E+01	3.7830E-03	4.9401E-03	3.8155E+00	1.9959E+00	6.8764E+02	5.8652E+02	2.5634E+01	7.6793E+03	2.7615E+00
31	412	1104	1155	5.9897E+01	3.6677E-03	4.9141E-03	3.6967E+00	1.9998E+00	6.8383E+02	5.9692E+02	2.5583E+01	7.7403E+03	2.7544E+00
32	412	1205	1257	5.9910E+01	3.6406E-03	4.9219E-03	3.6933E+00	1.9827E+00	6.7800E+02	6.0240E+02	2.5773E+01	7.3716E+03	2.7571E+00
33	412	1307	1358	5.9917E+01	3.6319E-03	4.9509E-03	3.6750E+00	1.9747E+00	6.6633E+02	6.0253E+02	2.5710E+01	7.2011E+03	2.7588E+00
34	412	1408	1459	5.9830E+01	3.5723E-03	4.8703E-03	3.6950E+00	1.9953E+00	6.4200E+02	6.0051E+02	2.5762E+01	7.5688E+03	2.7610E+00
35	412	1509	1550	5.9835E+01	3.5791E-03	4.8999E-03	3.7720E+00	1.9968E+00	6.5480E+02	5.9767E+02	2.5527E+01	7.5385E+03	2.7550E+00
36	412	1600	1651	5.9837E+01	3.5800E-03	4.8905E-03	3.7983E+00	2.0263E+00	6.5933E+02	5.9782E+02	2.5688E+01	7.6044E+03	2.7600E+00
37	412	1701	1701	5.9879E+01	3.5808E-03	4.9228E-03	3.7800E+00	2.0260E+00	6.5600E+02	5.9657E+02	2.6378E+01	7.1058E+03	2.7577E+00
38	412	1715	1755	5.9920E+01	3.5825E-03	4.9209E-03	3.6380E+00	2.0336E+00	6.6760E+02	6.0694E+02	2.4879E+01	7.8503E+03	2.7569E+00
39	412	1806	1856	5.9866E+01	3.6064E-03	4.9462E-03	3.7233E+00	2.0418E+00	6.8167E+02	6.0952E+02	2.5390E+01	7.8400E+03	2.7573E+00
40	412	1907	1957	5.9822E+01	3.6017E-03	4.9589E-03	3.7967E+00	2.0378E+00	6.8517E+02	6.0616E+02	2.5662E+01	7.5800E+03	2.7550E+00
41	412	2008	2058	5.9776E+01	3.6072E-03	4.9537E-03	3.8150E+00	2.0353E+00	6.8167E+02	6.0934E+02	2.5568E+01	7.6993E+03	2.7515E+00
42	412	2109	2159	5.9813E+01	3.5937E-03	4.9438E-03	3.8050E+00	2.0455E+00	6.7917E+02	6.0495E+02	2.5739E+01	7.6867E+03	2.7485E+00
43	412	2210	2250	5.9811E+01	3.5870E-03	4.9469E-03	3.7920E+00	2.0454E+00	6.7640E+02	6.0773E+02	2.5987E+01	7.7479E+03	2.7503E+00
44	412	2300	2300	5.9775E+01	3.5666E-03	4.9129E-03	3.8000E+00	2.0410E+00	6.6200E+02	6.0368E+02	2.5537E+01	6.7374E+03	2.7523E+00
45	413	915	953	6.0913E+01	3.7032E-03	4.8680E-03	3.6180E+00	2.0120E+00	6.7120E+02	5.9027E+02	2.5748E+01	7.6534E+03	2.7567E+00
46	413	1003	1054	6.0824E+01	3.7205E-03	4.9186E-03	3.7433E+00	1.9977E+00	6.7300E+02	5.8459E+02	2.5289E+01	7.5524E+03	2.7538E+00
47	413	1104	1155	6.0855E+01	3.7168E-03	4.9435E-03	3.8140E+00	1.9904E+00	6.5720E+02	5.8372E+02	2.6025E+01	7.6185E+03	2.7636E+00
48	413	1205	1255	6.0838E+01	3.6786E-03	4.9242E-03	3.7517E+00	1.9865E+00	6.5600E+02	5.8178E+02	2.5455E+01	7.6550E+03	2.7546E+00
49	413	1305	1356	6.0733E+01	3.6884E-03	5.0281E-03	3.6457E+00	2.0076E+00	6.8771E+02	6.0758E+02	2.5443E+01	7.7540E+03	2.7578E+00
50	413	1529	1549	6.0849E+01	3.6887E-03	4.8380E-03	3.7067E+00	2.0283E+00	6.5733E+02	5.7285E+02	2.5901E+01	6.5695E+03	2.7766E+00
51	413	1600	1650	6.0772E+01	3.6776E-03	4.9158E-03	3.7000E+00	1.9942E+00	6.5367E+02	5.9684E+02	2.5229E+01	7.3405E+03	2.7678E+00
52	413	1700	1750	6.0418E+01	3.6776E-03	4.9490E-03	3.7267E+00	2.0152E+00	6.7267E+02	5.9567E+02	2.5518E+01	7.5540E+03	2.7658E+00
53	413	1800	1851	6.0454E+01	3.6783E-03	4.9372E-03	3.7583E+00	2.0202E+00	6.7700E+02	5.9602E+02	2.5990E+01	7.5693E+03	2.7605E+00
54	413	1901	1951	6.0372E+01	3.6970E-03	4.9565E-03	3.8050E+00	2.0082E+00	6.7150E+02	5.9833E+02	2.5134E+01	7.6335E+03	2.7617E+00
55	413	2001	2052	6.0650E+01	3.7021E-03	4.9268E-03	3.8133E+00	2.0322E+00	6.7867E+02	5.9748E+02	2.6048E+01	7.5823E+03	2.7568E+00
56	413	2102	2152	6.0401E+01	3.7309E-03	4.9565E-03	3.9517E+00	2.0627E+00	6.9317E+02	5.9681E+02	2.5308E+01	7.7576E+03	2.7545E+00

TABLE 4-1 (Continued)

NO	DATE	TIME FIRST	TIME LAST	PMEAN	XD AMP	XP AMP	IMTR	IFIELD	OAD PWR	THD MEAN	A/F RAT	FIRERATE	LOAD RES
57	413	2202	2252	6.0483E+01	3.7351E-03	4.9275E-03	3.9317E+00	2.0653E+00	6.9517E+02	5.9823E+02	2.5433E+01	7.7592E+03	2.7496E+00
58	413	2303	2359	6.0448E+01	3.7803E-03	4.9745E-03	4.1144E+00	2.0644E+00	7.0711E+02	5.9753E+02	2.5843E+01	7.7253E+03	2.7478E+00
59	414	9	59	6.0550E+01	3.7813E-03	4.9653E-03	4.1250E+00	2.0613E+00	7.0417E+02	5.9602E+02	2.5410E+01	7.2979E+03	2.7462E+00
60	414	110	150	6.0503E+01	3.7974E-03	5.0091E-03	4.1200E+00	2.0616E+00	7.1100E+02	5.9618E+02	2.5943E+01	7.6846E+03	2.7561E+00
61	414	200	250	6.0538E+01	3.7743E-03	4.9313E-03	4.0323E+00	2.0700E+00	7.0667E+02	5.9577E+02	2.5540E+01	7.4314E+03	2.7487E+00
62	414	300	351	6.0708E+01	3.7981E-03	4.9556E-03	4.0900E+00	2.0668E+00	7.0483E+02	5.9597E+02	2.5833E+01	7.9945E+03	2.7520E+00
63	414	401	451	6.0686E+01	3.7936E-03	4.9551E-03	4.1017E+00	2.0652E+00	7.0217E+02	5.9598E+02	2.5269E+01	7.4076E+03	2.7519E+00
64	414	501	552	6.0790E+01	3.7677E-03	4.9320E-03	4.0767E+00	2.0583E+00	6.9633E+02	5.9344E+02	2.5790E+01	7.6328E+03	2.7474E+00
65	414	602	652	6.0650E+01	3.7926E-03	4.9669E-03	4.1117E+00	2.0585E+00	6.9967E+02	5.9164E+02	2.5783E+01	7.8819E+03	2.7428E+00
66	414	703	753	6.0638E+01	3.8033E-03	4.9610E-03	4.1100E+00	2.0667E+00	7.0900E+02	5.8918E+02	2.5777E+01	7.9234E+03	2.7498E+00
67	414	803	858	6.0736E+01	3.7330E-03	4.9188E-03	3.9133E+00	2.0523E+00	6.9023E+02	6.0153E+02	2.5623E+01	8.0611E+03	2.7491E+00
68	414	918	958	6.0556E+01	3.7086E-03	4.9565E-03	3.8280E+00	2.0210E+00	6.8900E+02	6.0381E+02	2.5274E+01	7.8129E+03	2.7516E+00
69	414	1008	1059	6.0471E+01	3.6871E-03	4.9304E-03	3.7400E+00	2.0083E+00	6.8167E+02	6.0049E+02	2.6092E+01	8.0880E+03	2.7514E+00
70	414	1101	1150	6.0730E+01	3.6837E-03	4.9390E-03	3.6980E+00	2.0034E+00	6.7540E+02	6.0405E+02	2.5700E+01	8.1658E+03	2.7589E+00
71	414	1200	1252	6.0802E+01	3.6816E-03	4.9629E-03	3.6867E+00	2.0013E+00	6.7733E+02	6.0097E+02	2.5617E+01	8.8539E+03	2.7557E+00
72	414	1302	1353	6.0577E+01	3.6404E-03	4.9523E-03	3.5883E+00	2.0075E+00	6.7300E+02	6.0002E+02	2.5598E+01	9.0894E+03	2.7551E+00
73	414	1403	1454	6.0664E+01	3.6081E-03	4.9139E-03	3.5550E+00	2.0032E+00	6.6067E+02	6.0218E+02	2.5343E+01	9.1600E+03	2.7555E+00
74	414	1504	1555	6.0548E+01	3.6133E-03	4.9245E-03	3.5533E+00	2.0023E+00	6.6617E+02	6.0147E+02	2.5870E+01	8.6521E+03	2.7558E+00
75	414	1605	1656	6.0510E+01	3.6194E-03	4.9061E-03	3.5850E+00	2.0092E+00	6.7017E+02	6.0313E+02	2.5894E+01	8.7422E+03	2.7558E+00
76	414	1706	1757	6.0748E+01	3.6604E-03	4.9452E-03	3.6417E+00	2.0063E+00	6.7650E+02	5.9612E+02	2.5521E+01	9.1993E+03	2.7586E+00
77	414	1808	1859	6.0651E+01	3.6845E-03	4.9603E-03	3.7117E+00	2.0040E+00	6.8150E+02	6.0104E+02	2.5527E+01	9.0221E+03	2.7534E+00
78	414	1909	1959	6.0609E+01	3.1848E-03	4.2063E-03	3.1800E+00	2.0058E+00	5.8517E+02	6.0209E+02	2.7814E+02	7.3548E+03	2.4609E+00
79	414	2000	2052	6.0686E+01	3.7130E-03	4.9641E-03	3.7217E+00	1.9988E+00	6.9050E+02	6.0378E+02	2.5519E+01	7.9930E+03	2.7521E+00
80	414	2102	2153	6.0699E+01	3.7005E-03	4.9627E-03	3.7083E+00	1.9933E+00	6.8583E+02	5.9777E+02	2.5617E+01	7.8364E+03	2.7512E+00
81	414	2203	2255	6.0511E+01	3.6833E-03	4.9554E-03	3.7083E+00	1.9912E+00	6.7667E+02	6.0076E+02	2.5660E+01	7.7905E+03	2.7585E+00
82	414	2305	2358	6.0742E+01	3.6747E-03	4.9040E-03	3.6657E+00	1.9876E+00	6.6700E+02	6.0297E+02	2.5779E+01	7.7791E+03	2.7538E+00
83	415	8	59	6.0583E+01	3.7439E-03	5.0214E-03	3.7850E+00	1.9903E+00	6.9983E+02	5.9979E+02	2.5988E+01	8.4830E+03	2.7578E+00
84	415	110	130	6.0441E+01	3.6958E-03	4.9502E-03	3.7567E+00	1.9977E+00	6.8800E+02	6.0749E+02	2.5592E+01	9.2818E+03	2.7437E+00
85	415	150	150	6.0708E+01	3.2781E-03	4.3077E-03	2.7700E+00	1.9960E+00	5.2600E+02	5.7304E+02	2.3957E+01	8.1394E+03	2.7516E+00
86	415	201	252	6.0740E+01	3.8881E-03	4.9971E-03	4.3283E+00	2.0023E+00	6.9483E+02	5.6887E+02	2.2579E+01	7.7660E+03	2.7497E+00
87	415	302	353	6.0749E+01	3.8803E-03	4.9217E-03	4.4933E+00	2.0435E+00	6.8683E+02	5.6917E+02	2.1423E+01	8.6283E+03	2.7429E+00
88	415	404	455	6.0615E+01	3.9093E-03	5.0779E-03	4.5483E+00	2.0630E+00	7.2283E+02	5.8863E+02	2.1406E+01	8.5400E+03	2.7520E+00
89	415	505	556	6.0672E+01	3.7203E-03	4.9608E-03	3.8033E+00	2.0618E+00	7.0317E+02	6.0468E+02	2.4417E+01	7.8297E+03	2.7521E+00
90	415	607	658	6.0781E+01	3.8122E-03	4.9587E-03	4.1700E+00	2.0682E+00	7.0567E+02	6.0410E+02	2.4823E+01	8.5771E+03	2.7472E+00
91	415	708	759	6.0760E+01	3.7969E-03	4.9429E-03	4.2300E+00	2.0632E+00	6.9150E+02	6.0131E+02	2.5531E+01	8.2542E+03	2.7480E+00
92	415	809	850	6.0744E+01	3.7769E-03	4.9021E-03	4.2400E+00	2.0197E+00	6.7400E+02	6.0691E+02	2.5471E+01	8.4939E+03	2.7455E+00
93	415	900	911	6.0745E+01	3.7222E-03	4.8648E-03	4.0850E+00	1.9980E+00	6.6550E+02	6.0200E+02	2.6218E+01	8.2519E+03	2.7430E+00
94	415	925	956	6.0476E+01	3.7502E-03	4.9308E-03	4.2600E+00	1.9970E+00	6.6500E+02	5.9983E+02	2.5767E+01	8.3649E+03	2.7534E+00
95	415	1006	1057	6.0876E+01	3.7410E-03	4.8811E-03	4.0800E+00	2.0067E+00	6.7217E+02	6.0278E+02	2.5294E+01	8.5175E+03	2.7522E+00
96	415	1106	1159	6.0912E+01	3.7360E-03	4.8857E-03	4.1363E+00	1.9930E+00	6.5963E+02	6.0524E+02	2.5974E+01	8.3319E+03	2.7500E+00
97	415	1209	1250	6.0661E+01	3.7253E-03	4.9027E-03	4.1520E+00	1.9902E+00	6.5720E+02	6.0258E+02	2.5670E+01	8.3934E+03	2.7572E+00
98	415	1300	1351	6.0970E+01	3.7069E-03	4.8934E-03	4.0617E+00	1.9890E+00	6.6683E+02	6.0111E+02	2.5331E+01	8.3974E+03	2.7468E+00
99	415	1401	1452	6.0917E+01	3.7191E-03	4.9457E-03	3.9650E+00	1.9938E+00	6.6450E+02	6.0200E+02	2.4114E+01	8.8125E+03	2.7581E+00
100	415	1502	1543	6.0961E+01	3.6880E-03	4.9336E-03	3.8980E+00	1.9890E+00	6.5760E+02	5.9976E+02	2.4896E+01	8.5625E+03	2.7577E+00
101	415	1551	1553	6.0482E+01	3.7731E-03	5.2424E-03	3.9150E+00	2.0015E+00	7.4050E+02	6.2757E+02	1.5646E+01	1.3448E+04	2.7527E+00
102	415	1603	1654	6.0497E+01	3.6373E-03	4.8983E-03	3.7533E+00	2.0245E+00	6.6200E+02	6.0352E+02	2.5990E+01	8.5366E+03	2.7660E+00
103	415	1705	1755	6.0309E+01	3.7165E-03	5.0397E-03	4.0400E+00	2.0220E+00	6.9233E+02	5.9969E+02	2.5796E+01	8.6477E+03	2.7619E+00
104	415	1805	1853	6.0612E+01	3.6102E-03	4.8[illegible]19E-03	3.6183E+00	2.0175E+00	6.4483E+02	6.0539E+02	2.5025E+01	9.1767E+03	2.7630E+00
105	415	1903	1924	6.0733E+01	3.3573E-03	4.6207E-03	2.9067E+00	2.0260E+00	6.0367E+02	6.2041E+02	2.4805E+01	8.3789E+03	2.761[illegible]

TABLE 4-2

CLEARANCE CHANGES BETWEEN INSPECTIONS NO. 1 AND 3

Item	Description	Diameter Clearance Change (in.)
7	Power Piston Seal	0.0002
8	Power Piston FWD Bearing	0.0001
9	Power Piston AFT Bearing	0.0001
26	Displacer Motor Seal	-0.0007
27	Displacer FWD Bearing	0.0002
28	Displacer AFT Bearing	0.0004
29	FWD Gas Spring Seal	0.0006
30	Displacer Bearing Seal	0.0002
31	AFT Gas Spring Seal	0.0001
32	Displacer Bearing Seal	0.0004

System bearing flow checks, pre- and post-test, indicated that the ΔP increased by 11% which is indicative of the flow and, hence, a slight increase in clearance. This increase in ΔP for a given inlet pressure increase is attributed to the power piston bearings, but has not been confirmed by inspection of hardware.

5.0 PHASE II - FULL-STROKE TESTING

5.1 Objective

The objective of the full-stroke test was to accumulate 300 operational test hours at 700°C mean heater head temperature and at 20mm (full stroke) power piston stroke. Full-stroke testing is representative of the most severe operating condition except for dry start/stop testing.

5.2 Conclusions

The EM endurance engine successfully completed the Phase II full-stroke test phase. The average power was ~1.5 kW. There were no appreciable changes in the hardware as determined by visual observation, flow test, and inspection of the hardware. Engine parameters remained constant throughout this phase with no indications of degradation. The chrome oxide surfaces are particularly durable and held up well, even without the gas bearings operating for a short time. Check out and initial unattended operation went very well, with only minor corrections needed to software and facility hardware. The engine hardware was judged acceptable for Phase III duty-cycle testing.

5.3 Discussion

5.3.1 Test Description

The critical seal and bearing clearances were inspected as described in Section 3.0.

The engine load for this phase of endurance testing was set to a constant resistance with the load variac (Figure 6-1). The load resistance was adjusted to give design piston stroke (20 mm) at maximum motor current level (6 amps). The heater head temperature was also set to a constant level (between 650 and 700°C). The resulting electrical power output was between 1300 and 1600 watts.

The only hardware change was the displacer motor liner, which was replaced with a new phenolic liner with nominal design displacer seal clearance. The liner seal clearance (item 26 of Figure 3-7) during the low-power test was 50% larger than design. It was expected that the reduced displacer seal clearance (to design values) would reduce the displacer motor current necessary to drive the displacer.

5.3.2 Test History

Limited full-stroke testing was initiated on 25 April 1983 but was suspended because of poor combustor durability and a lack of operating thermocouples on the heater head. Corrective action was taken to resolve these problems prior to restarting the full-stroke test. Combustor durability was improved by limiting the amount of combustor vibration by adding mass to the engine test stand. The heater head instrumentation was completely redone with 27 new thermocouples tack-welded to the heater head. With improved combustor durability and re-instrumented heater head, the engine was checked out during the first two weeks of July for full-stroke operation. An identified displacer rub was corrected by replacing the liner and stuffer assembly. This substantially reduced the required motor power for a given alternator load and stroke. On July 13, the 300 hours of full-stroke testing was started. For this test, the inertial mass was attached to the case to reduce combustor vibration.

The safety interlock system was fine-tuned early in this test and substantial time was accumulated without operator attention. The interlock system shutdown the engine a few times per day for various reasons. These were mostly "glitches" in the cell exhaust airflow switch or in the primary coolant flow switch. The air and water flow switch installation was modified to reduce errant shutdowns. During the course of the test, the bearing pressure transducer, the case accelerometer, and the engine pressure transducers failed. In each case, the transducer was replaced or repaired and the test continued. Several shutdowns were the result of very slow engine pressure leaks; the pressure would drop from 63 to 60.5 Bar in aproximately six hours. Pressures outside this band de-tune the engine system, resulting in excessive displacer motor current. A makeup system was installed for later tests.

The engine was run at an electrical output of ~1500 watts and ~20 mm piston stroke during this test.

The 300-hour full-stroke test phase was completed on 3 August 1983. At completion of the test, the engine was run accidentally without operating gas bearings for approximately three minutes. The engine was completely inspected between 5-15 August 1983.

5.3.3 Test Results

Engine parametric trends as a function of time during the 300-hour test phase are shown in Figures 5-1 through 5-10. Load power varied between 1.3 and 1.6 kW as shown in Figure 5-4. Displacer amplitude (Figure 5-2) was automatically adjusted to maintain the power output (Figure 5-4) in response to changes in pressure (Figure 5-1), changes in heater head temperature (Figure 5-7), and load resistance (Figure 5-9).

5.3.4 Post-Test Inspection

The engine was disassembled and inspected following the full-stroke test, and the inspection was completed by 15 August 1983. The engine was in excellent condition, there was no damage to any engine hardware. The bearings and seal surfaces showed normal polishing and evidence of minor rubbing, however, no damage to bearing surfaces was found. The dimensional inspection of the hardware showed clearance changes, which may be due to measurement technique rather than the actual changes since there is no consistent trend over the pre- and post-test inspections associated with the 100 hour test phase.

The results of flow tests completed before and after this test are shown in Table 5-1. The piston bearings (i.e., alternator and aft gas spring bearings) show no change in flow as indicated by the flow meter ΔP. The test does indicate a change in the displacer bearing flow of 31%. The equivalent clearance change required for this flow change is within the measurement uncertainty of normal instrumentation ±0.0007 in.

Surface scratches were visually observed in the area of the forward piston bearing. The scratches were very local and did not affect inspection dimensions, nor did they affect power piston flow checks. It is very likely that these scratches occurred during the short period of operation without the hydrostatic gas bearings at the end of the 300-hour full-stroke test. It does demonstrate that the chrome

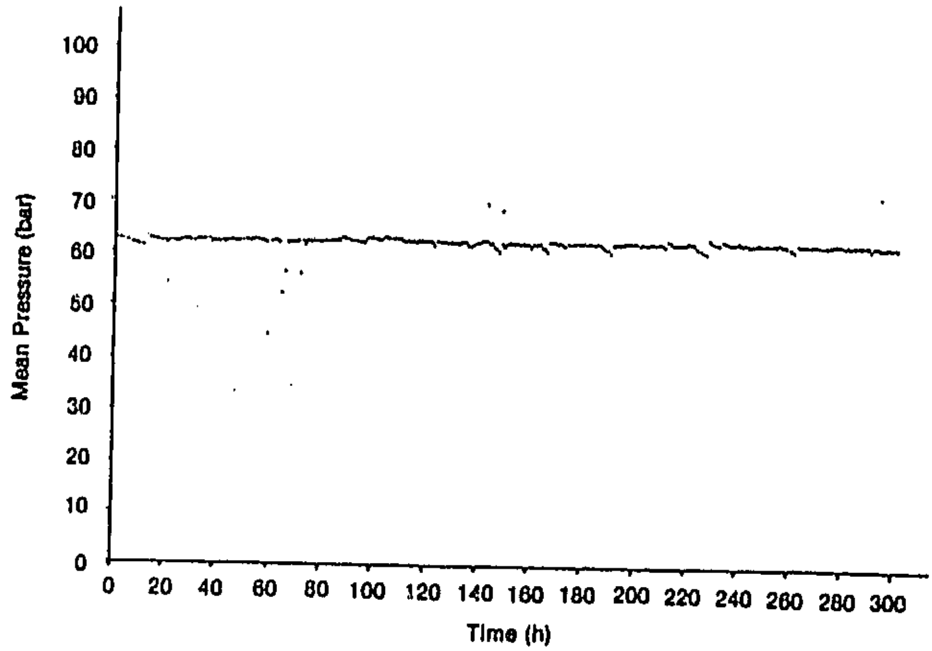


Figure 5-1 300-Hour Full-Stroke Test
Mean Pressure versus Time

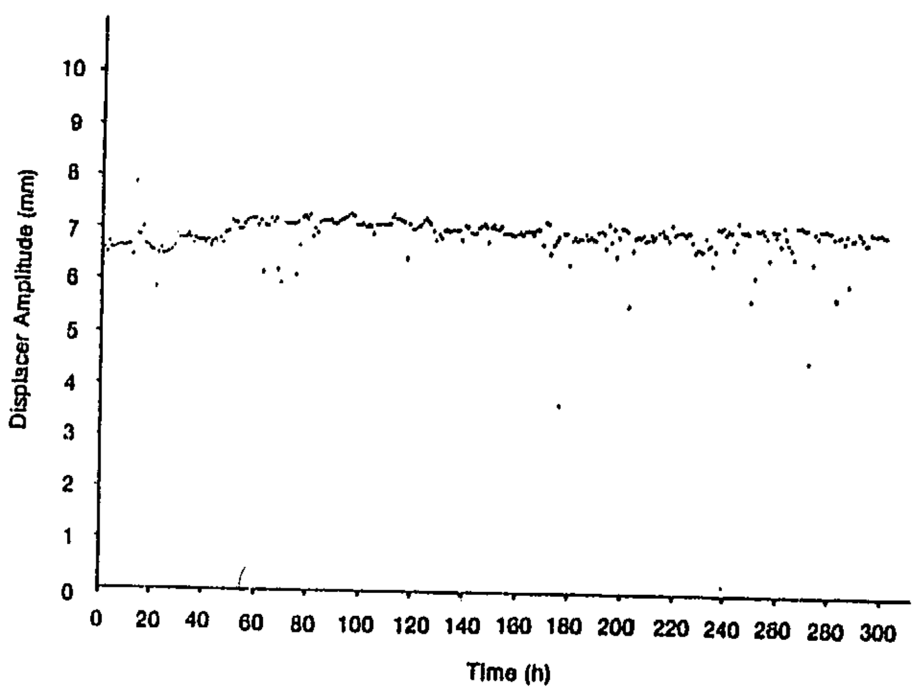


Figure 5-2 300-Hour Full-Stroke Test
Displacer Amplitude versus Time

ORIGINAL PAGE IS
OF POOR QUALITY

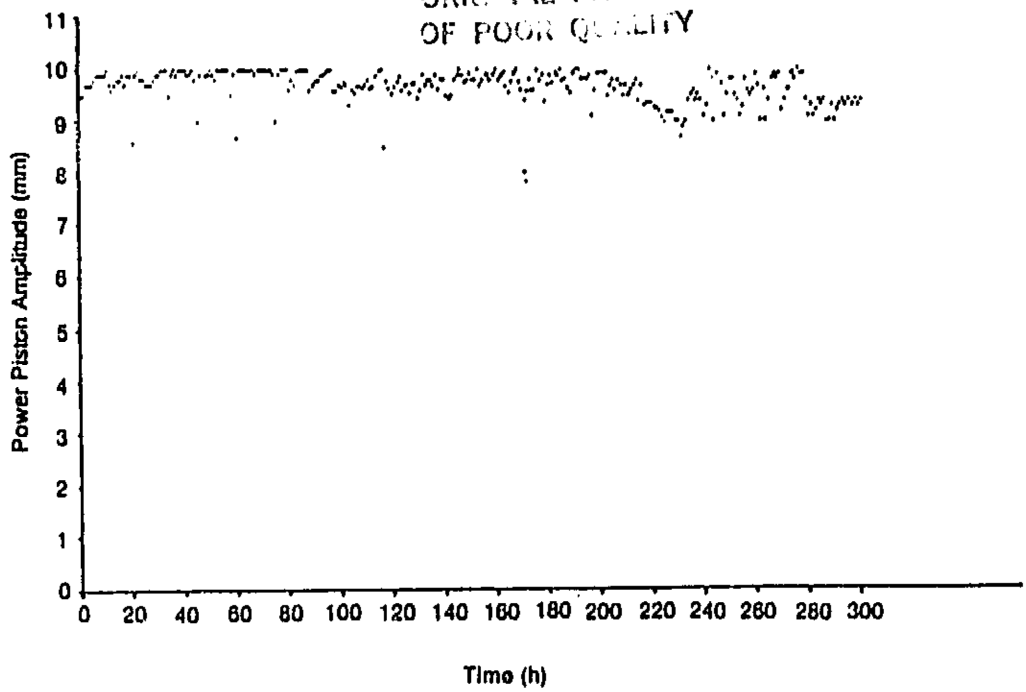


Figure 5-3 300-Hour Full-Stroke Test
Power Piston Amplitude versus Time

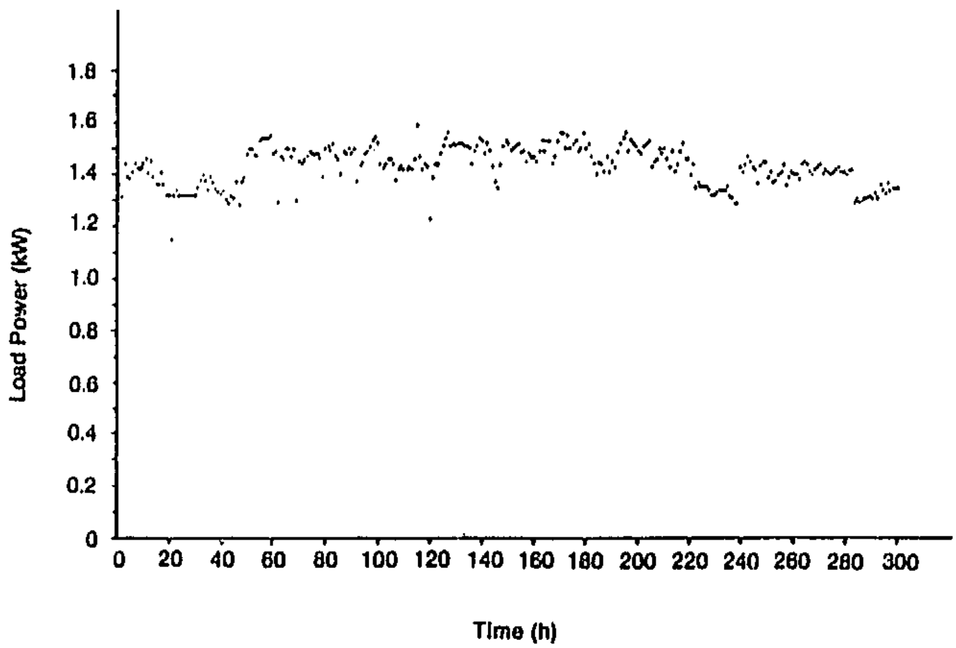


Figure 5-4 300-Hour Full-Stroke Test
Load Power versus Time

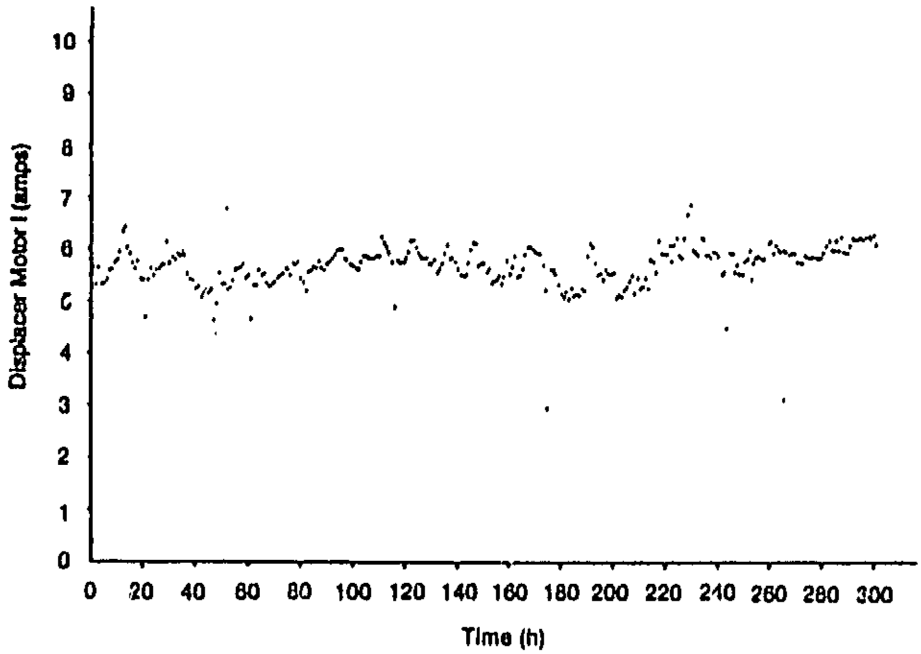


Figure 5-5 300-Hour Full-Stroke Test
Displacer Motor Current versus Time

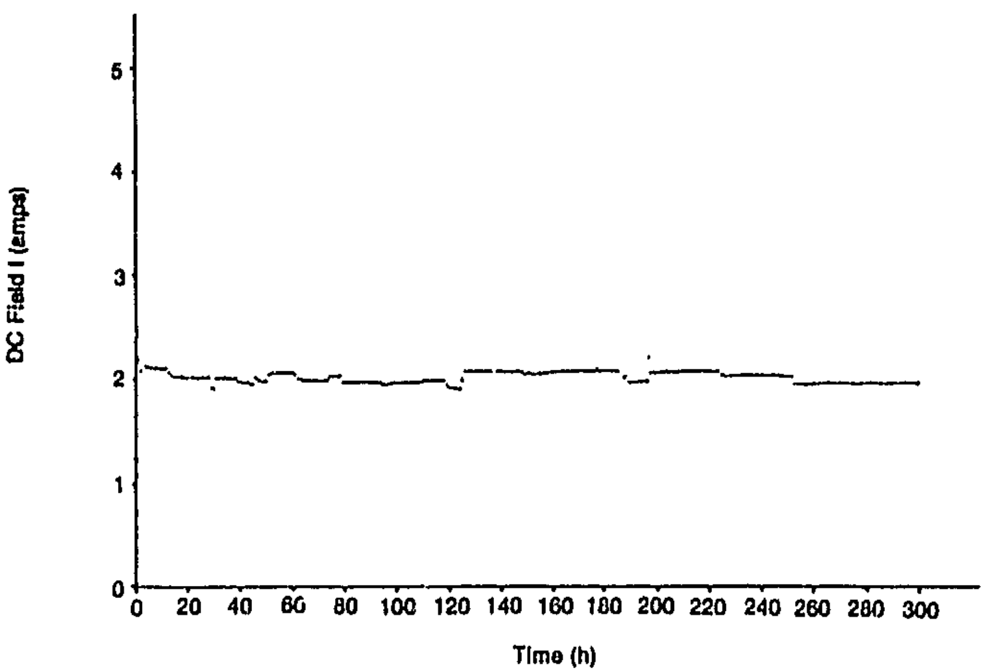


Figure 5-6 300-Hour Full Stroke Test
DC Field Current versus Time

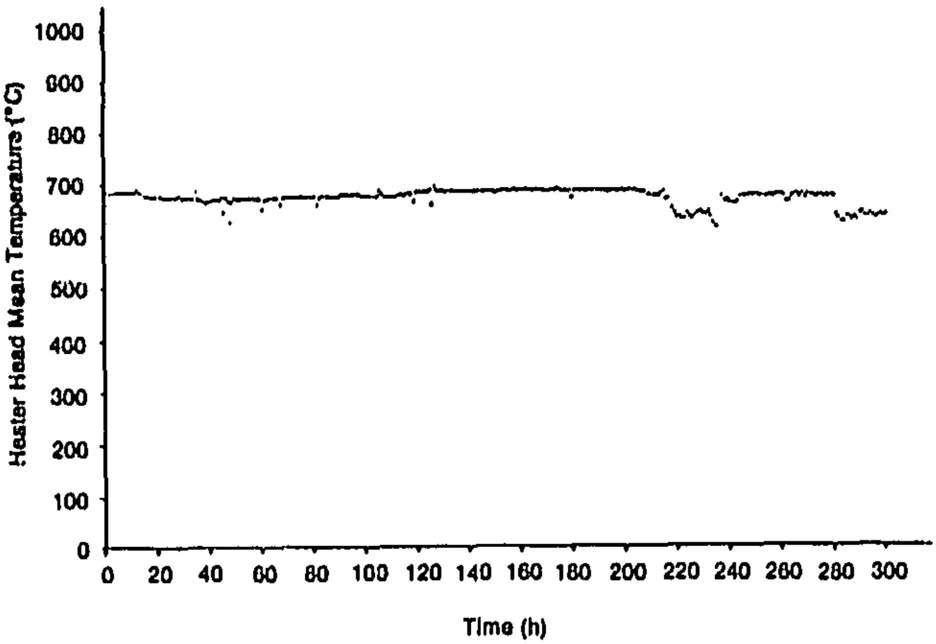


Figure 5-7 300-Hour Full-Stroke Test
Heater Head Mean Temperature versus Time

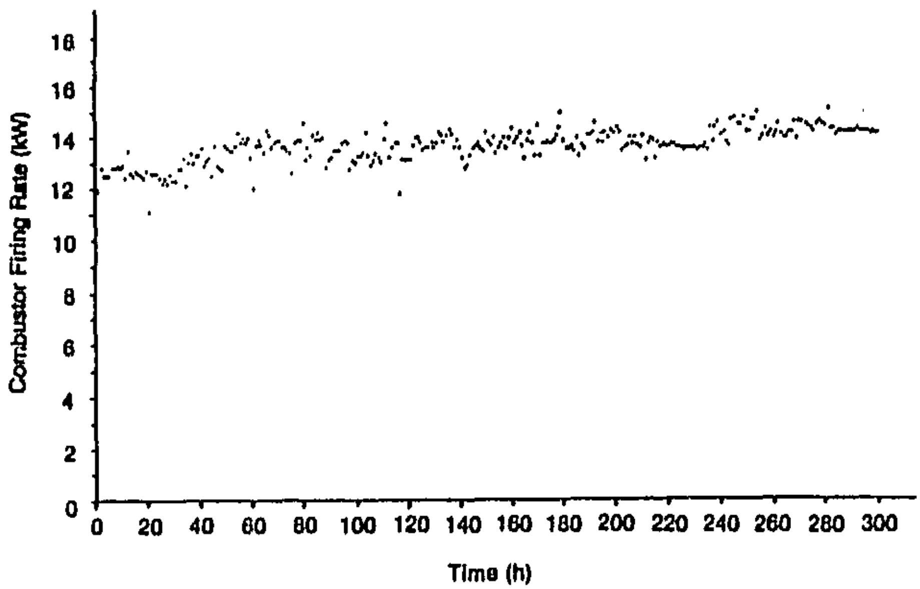


Figure 5-8 300-Hour Full Stroke Test
Combustor Firing Rate versus Time

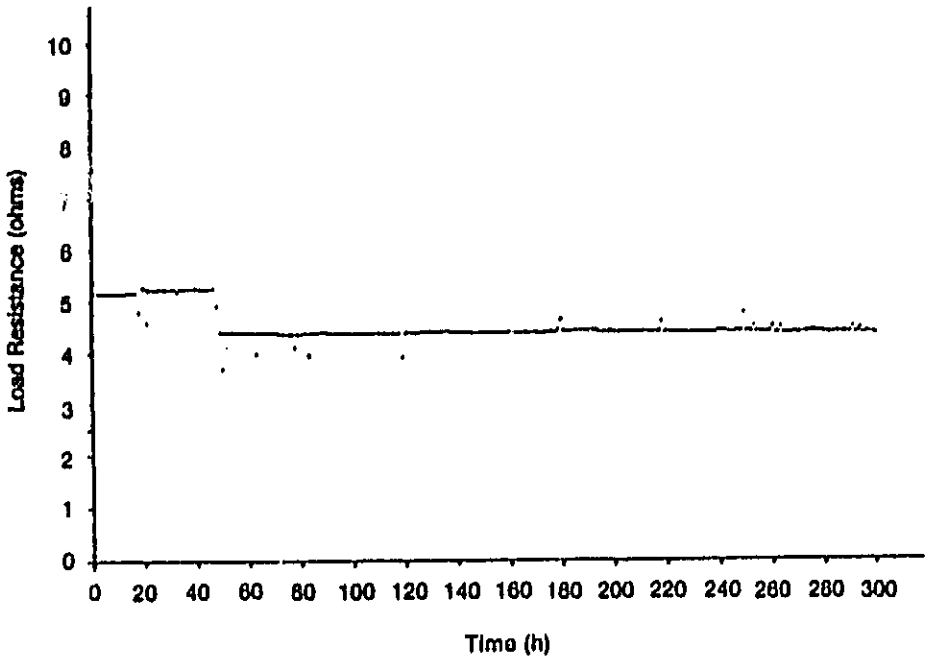


Figure 5-9 300-Hour Full-Stroke Test
Load Resistance versus Time

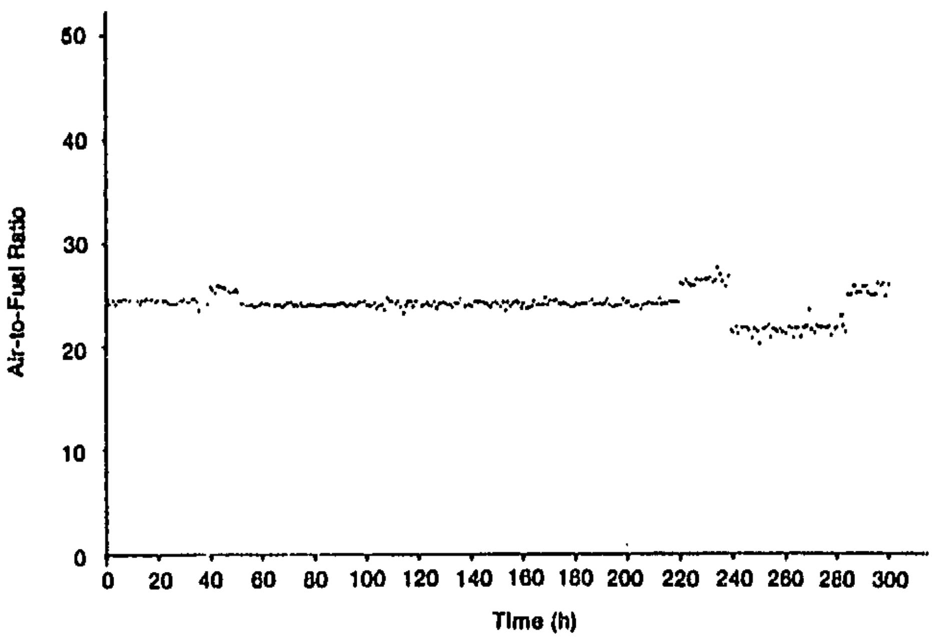


Figure 5-10 300-Hour Full-Stroke Test
Combustor Air to Fuel Ratio versus Time

TABLE 5-1

PHASE II - FULL STROKE TESTING BEARING FLOW CHANGES

	ΔP in H_2O at 20 psig Inlet Pressure	
	Pre-Test	Post-Test
Displacer Bearing	6.5	8.5
Alternator Bearing	5.0	5.0
AFT Gas Spring	5.1	4.9

oxide surfaces incorporated on the moving surfaces do provide a tough, durable surface coating that can protect against surface contact due to shock or momentary wear or, as demonstrated later in this test program, dry (no bearing) start-up.

6.0 PHASE III - DUTY-CYCLE TEST

6.1 Objective

The original objective of the duty-cycle test was to accumulate 300 operational hours at loads between 0.5 and 2.5 kWe, and 700°C mean heater head temperature. This objective was modified with NASA approval to extend the accumulated hours to 600.

6.2 Conclusions

The EM successfully completed 691 hours of duty-cycle operation. The one major engine failure (displacer magnet dislodgement) was not related to the duty-cycle operating mode.

6.3 Discussion

6.3.1 Test Description

The critical seal and bearing clearances were inspected as described in Section 3.0.

The electrical engine load was modified by the addition of a parallel clock-driven resistive load, shown in Figure 6-1. Manual relays were also installed to allow for use of the original "fixed" resistance load. The variac used to adjust the "fixed" resistance load provided the flexibility of proportionally adjusting the duty-cycle load.

The duty-cycle load was designed to change the engine load to one of three levels for a given alternator voltage every 1/2-hour according to the schedule shown in Figure 6-2. The resistances are switched such that the load is at one of three levels, 100%, 60%, and 20%, for a period of 1/2-hour, and the cycle repeats every two hours. The power dissipated in the load will also depend on the engine output voltage, which for this test was set by a power control that senses the load voltage and adjusts the displacer motor voltage to produce the required output voltage.

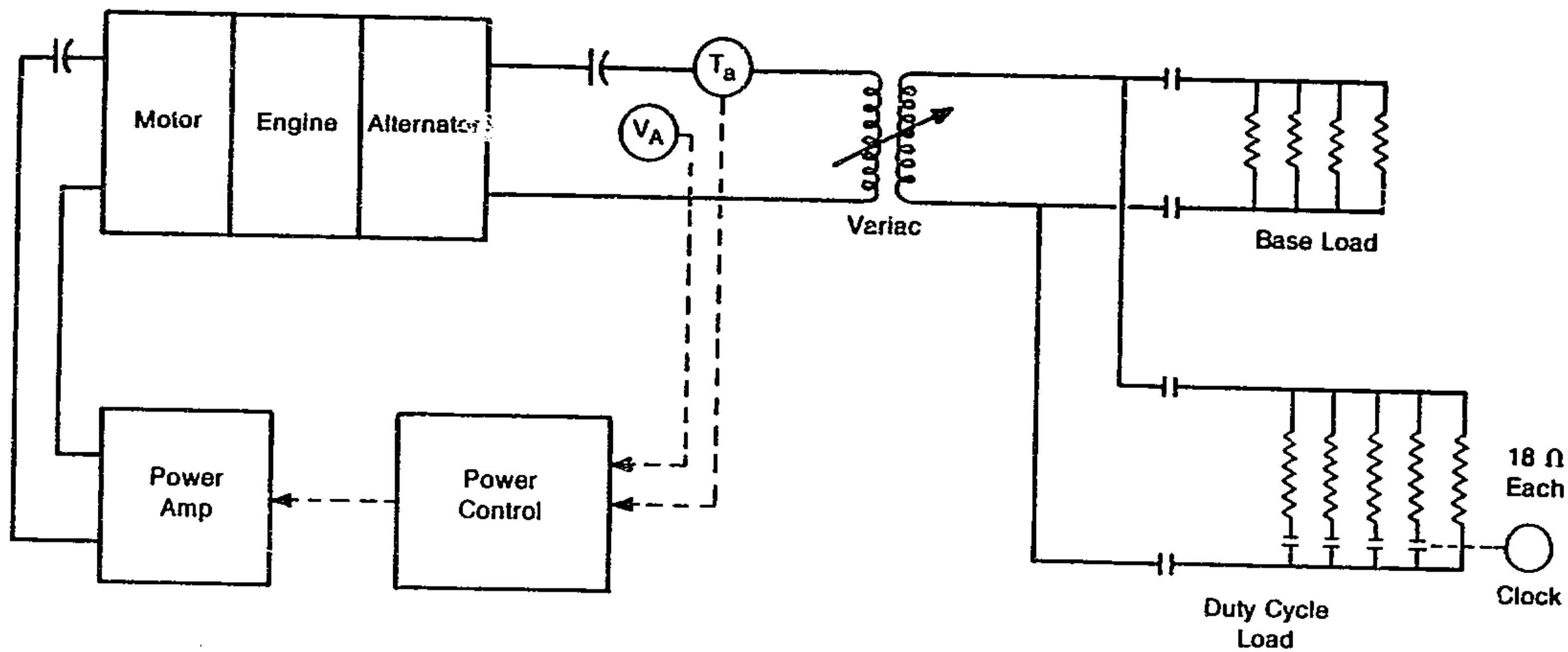


Figure 6-1 Duty Cycle Load Schematic

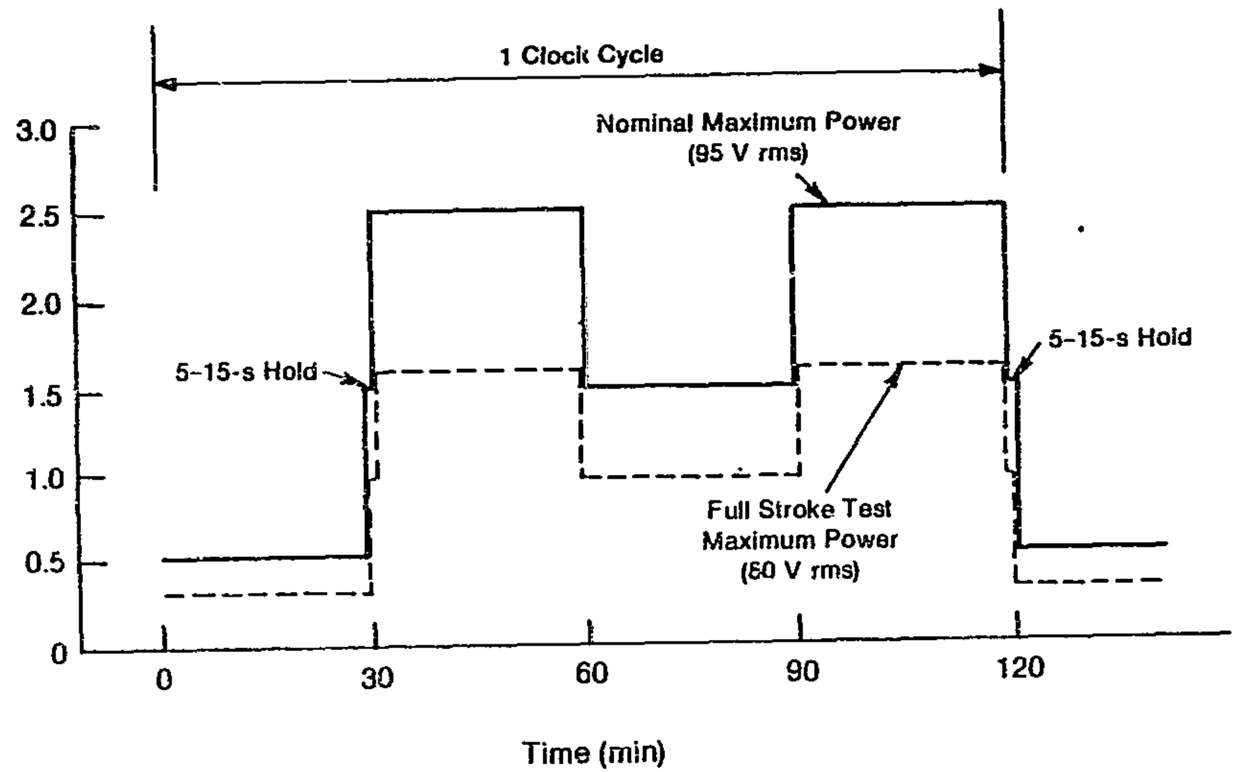


Figure 6-2 Duty Cycle Test Cycle

The large load changes (20 to 100% and 100 to 20% steps) are provided with a 5-15 second delay at the 60% load level. This reduced the impact of these large load changes. The engine and control responded very well to the duty-cycle load changes. The output voltage was maintained very consistently, with little or no overshoot during load change .

The power levels at which the duty-cycle test was run were lower than the design values to limit the motor input current. The available motor power supply was limited to $\sim$6-7 amps RMS; therefore, the load was adjusted to limit the motor current to about 6 amps. The previous full-stroke testing was run at $\sim$1600 watts and was not increased prior to the duty-cycle test; therefore, the load was set to the dashed curve in Figure 6-2.

The engine DAS was improved for this test. This involved implementing a program which could take wave form data from the endurance cell No. 6 with the HP1000 DAS. Though the number of channels was limited to four, the basic engine dynamic (X_D and X_P) and thermodynamic pressure wave (P_C) could be measured on a routine basis. With these measurements, the piston PV power was calculated and direct comparisons with the first-order thermodynamic analysis could be made.

6.3.2 Test History

The 691 hours of duty-cycle testing was begun on 17 August 1983. The displacer magnet failure described in Section 3.0 was the only major engine related failure which occurred during this phase of endurance testing. Shortly after the engine was re-started, one stringer, which attaches the engine to the inertia mass, failed. This caused a combustor failure. Both were repaired and the testing continued smoothly until 600 hours of duty-cycle testing were completed on 10 September 1983. The goal of 1000 hours of endurance testing was accomplished.

The engine was then separated from its inertia mass in order to accumulate hours on the combustor at high ($\sim$7 g's) vibration levels. The engine was run in this configuration for 91 hours.

6.3.3 Test Results

The analysis was compared to test results to establish the empirical factors needed to obtain an agreement in terms of the dynamic engine performance. In general, empirical factors applied to total volume and seal leakage are necessary to obtain an agreement in terms of dynamic engine performance. In general, empirical factors applied to total volume and seal leakage are necessary to obtain an agreement with test results (Table 6-1). Volume adjustments of 8 and 14% are typical for FPSE's, and are perhaps indicative of needed improvements in the analysis. Seal leakage adjustments, on the other hand, may be more attributable to the difficulty of accurately measuring small clearances of relatively large diameters. In this respect, EM No. 1 hardware was in very good condition, and a 3% increase in the seal clearances could account for the observed differences. EM No. 2 hardware was in somewhat worse condition, so a 28% increase in seal clearance would be required to account for the observed differences.

Performance of the two EM engines is compared in Figures 6-3 through 6-17 at various power levels. EM No. 2 was operated at constant load voltage and various load impedances (Figure 6-3), while EM No. 1 was operated at a constant load impedance and various voltage levels. The power piston amplitudes necessary to produce the desired output voltages (Figure 6-4) indicate a resonable agreement between the physical hardware and the model. The piston stroke versus power curves are different for two reasons: 1) different loading conditions; and, 2) the hardware differences in the two alternators (i.e., EM No. 2 has fewer AC turns than EM No. 1).

The pressure amplitude and phase (Figures 6-5 and 6-6) provide the force to drive the alternators and determine the basic PV power delivered to the load by the cycle (abscissa of Figures 6-3 through 6-9). The PV power, rather than total cycle power, was selected for comparison since it could be easily measured on the test engine. The cycle power delivered to the displacer is relatively constant over the test range. The pressure force must balance all other forces acting on the power piston and is, therefore, indicative of any deviations between the modeled load on the thermodynamic system and physical reality. Deviations of less than 3% are observed in the pressure amplitude where the worst case is at the low power point for EM No. 2. Also, deviations on the order of 0.5 degrees are

TABLE 6-1

COMPARISON OF DATA TO CODE PREDICTIONS EM's #1 and 2

	EM #1		EM #2	
	Data	Calc.	Data	Calc.
Frequency (Hz)	58.1	58.1[a]	60	60[a]
Pressure (Bar)	59.9	59.9[a]	62	62[a]
Heater Temp (°C)	710	710[a]	680	680[a]
Cooler Temp (°C)	32	32[a]	37	37[a]
Disp. Amp. (mm)	6.82	6.87	6.48	6.47
Disp. Phase (°)	67.7	67.8	59.0	58.6
Piston . np. (mm)	9.95	9.94	8.75	8.76
Pressure Amp. (Bar)	9.57	9.55	7.63	7.64
Pressure Phase (°)	-11.0	-11.1	-7.96	-7.98
PV Power (watts)	3410	3420	1800	1800
Heat Rej. (watts)	7610	6310	5650	5840
PV Efficiency	0.309	0.351	.242	.236
Dead Volume Factor	1.0	1.08	1.0	1.14
Seal Leakage Factor	0.82[b]	0.90	1.52[b]	3.15

[a]measured operating condition
[b]calculated from measured geometry

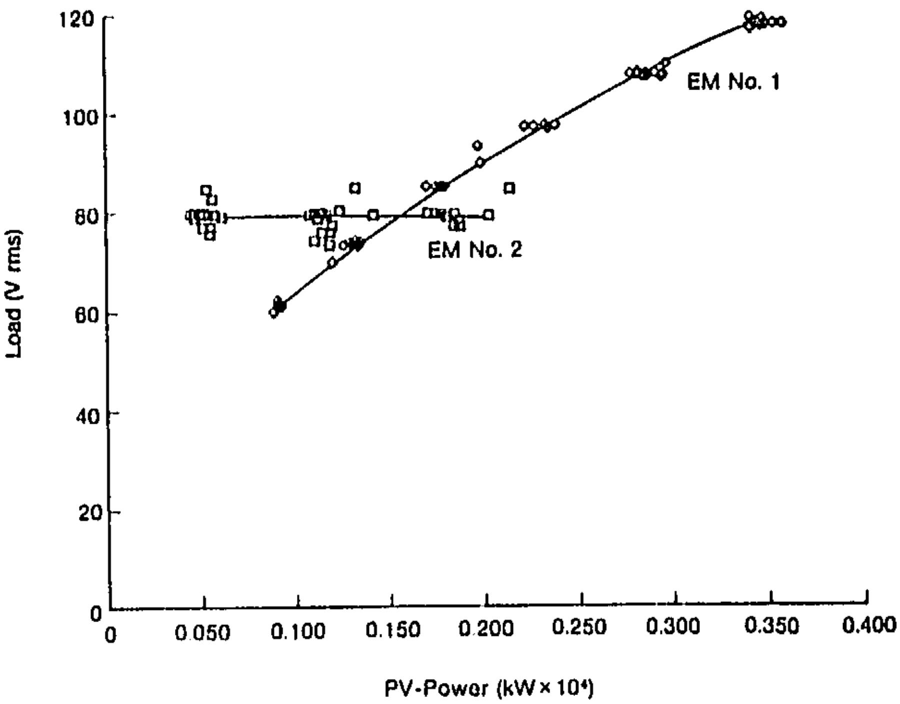


Figure 6-3 EM #2 Operation - V_{Load} versus PV Power

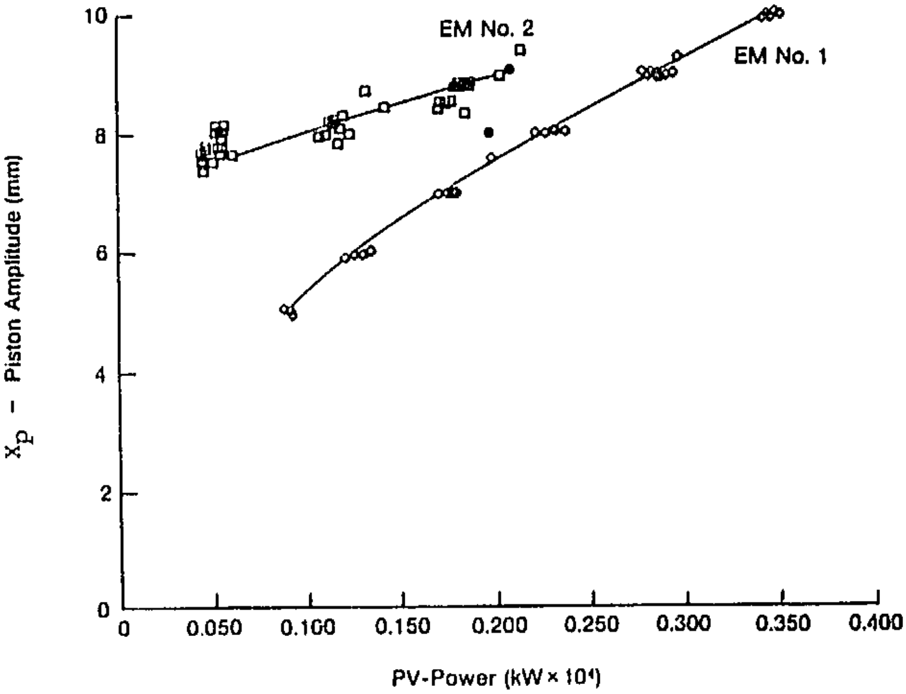


Figure 6-4 EM #2 Operation - X_p versus PV Power

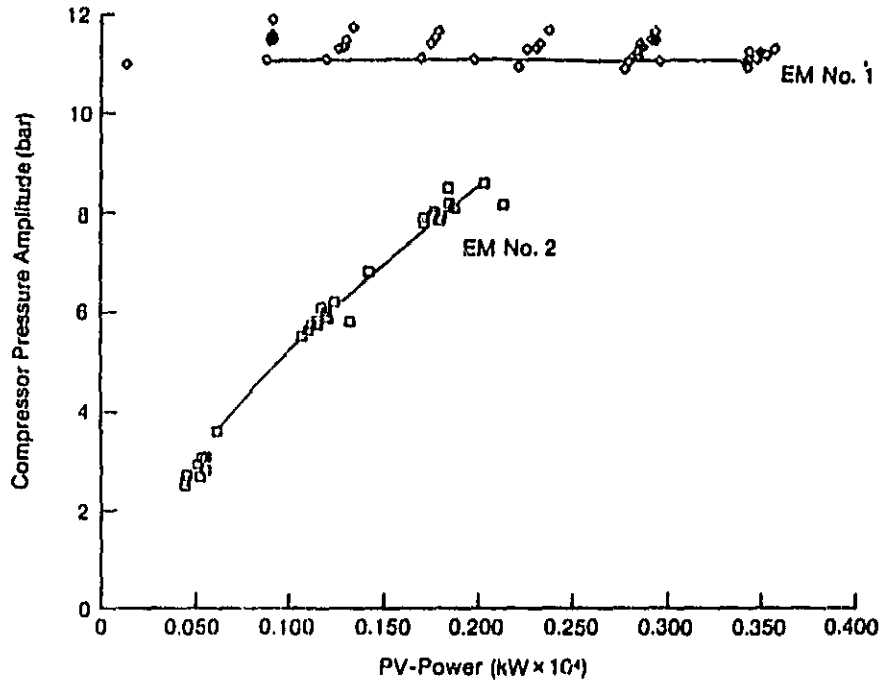


Figure 6-5 EM #2 Operation - Pressure Amplitude versus PV Power

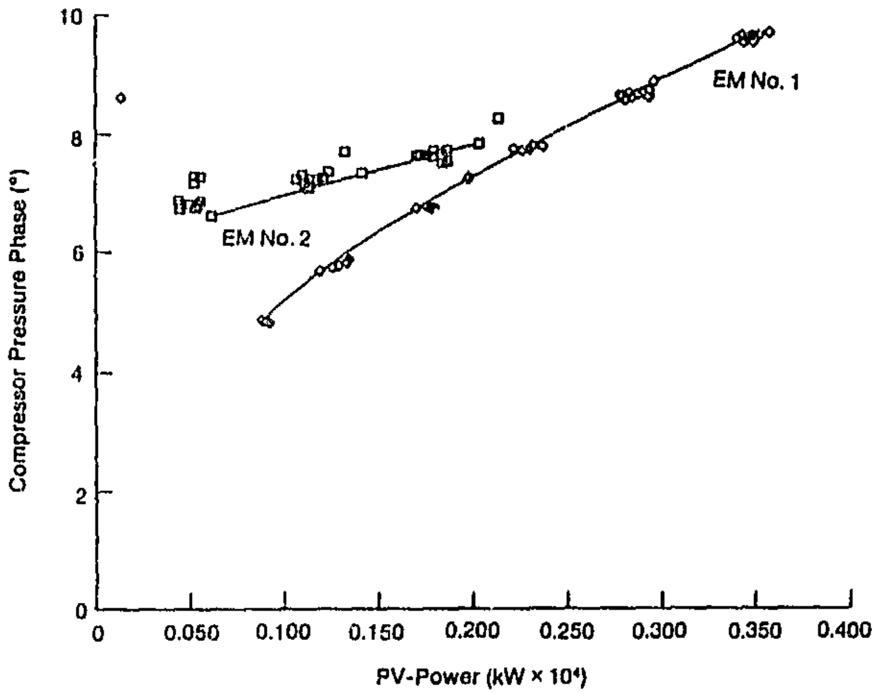


Figure 6-6 EM #2 Operation - Pressure Phase Angle versus PV Power

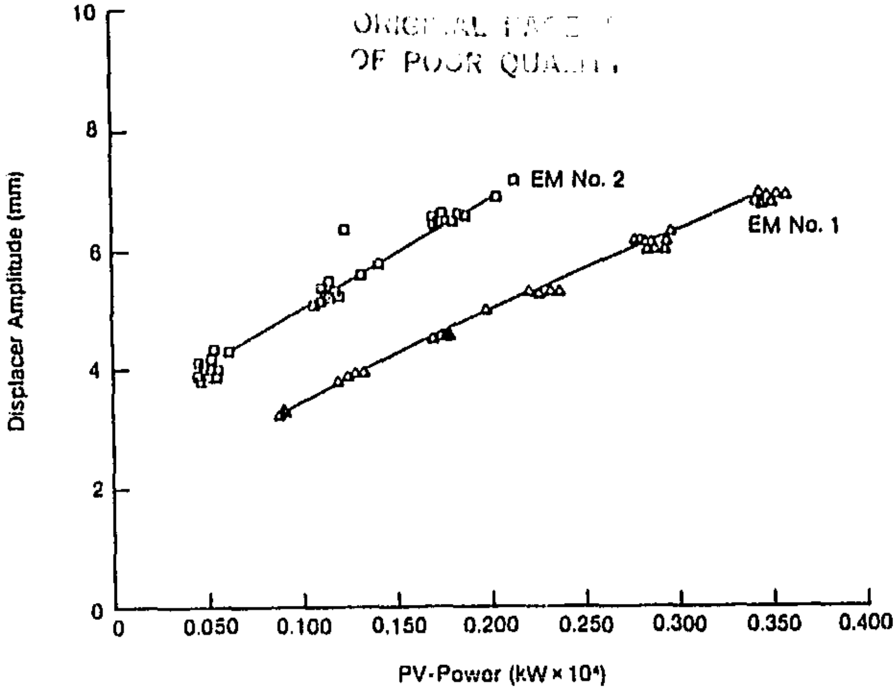


Figure 6-7 EM #2 Operation - Displacer Amplitude versus PV Power

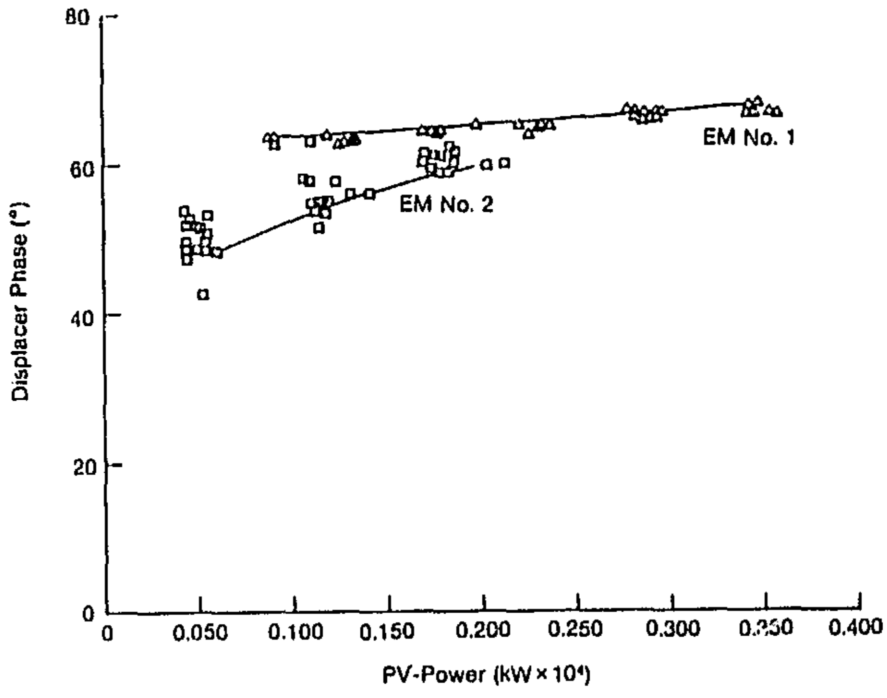


Figure 6-8 EM #2 Operation - Displacer Phase K versus PV Power

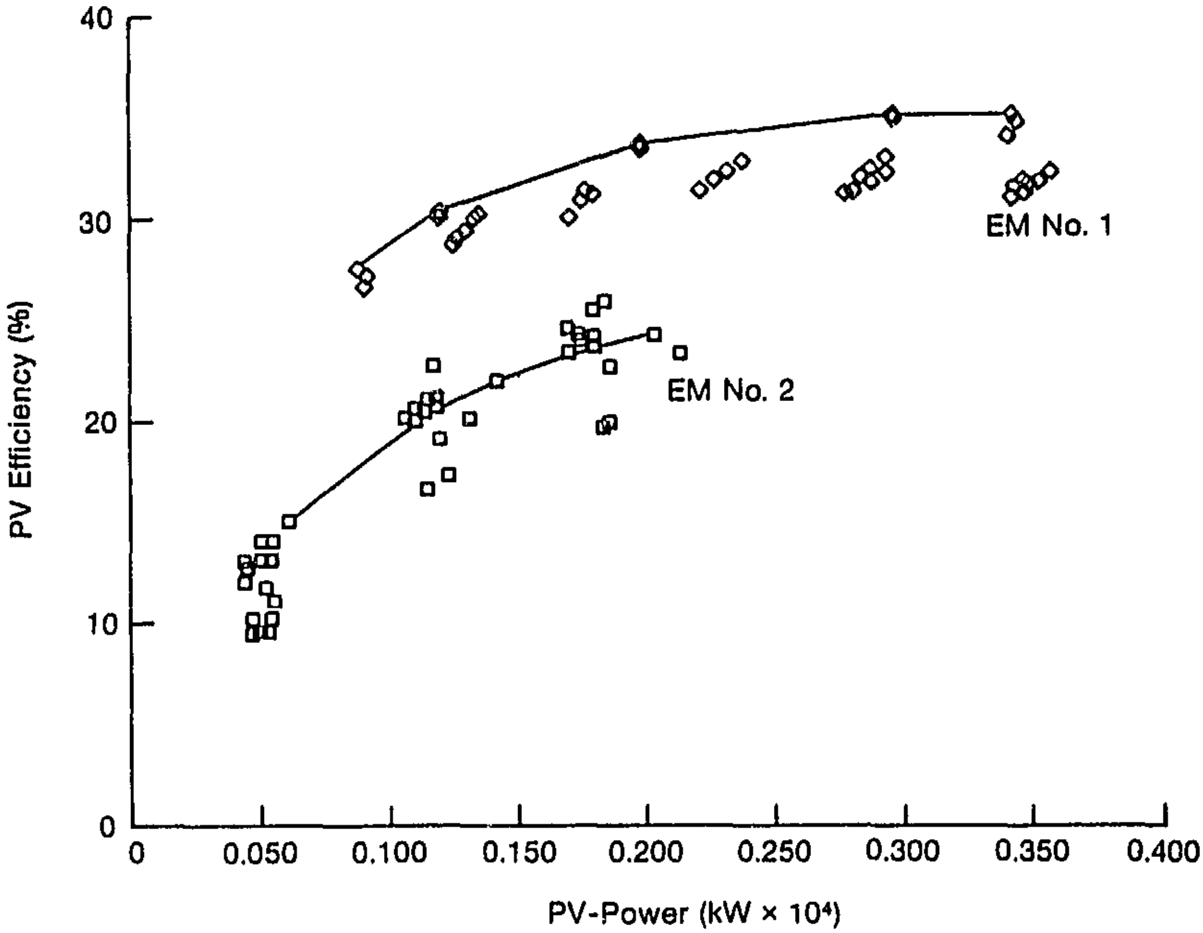


Figure 6-9 EM #2 Operation - PV Efficiency versus PV Power

observed in the EM No. 1 pressure phase, indicating variations in the alternator load or bounce-space loss.

The displacer amplitude and phase for the EM engines is directly influenced by the effective impedance of the engine working space in addition to the piston dynamics and load. The effective working-space impedance is a direct result of the thermodynamic engine behavior and, therefore, of all parameters that influence thermodynamic performance. The displacer dynamics (Figures 6-7 and 6-8) show an agreement between test and analysis, indicating that the harmonic thermodynamics analysis is a good model of the physical processes. The thermodynamic efficiency is, after engine power, the most important engine performance parameter. The PV efficiency used for comparison is defined as:

PV Efficiency = PV Power/PV Power + Heat Rejected

This was selected since the measured efficiency on this basis is well defined, and would, therefore, provide a well defined comparison with the calculated efficiency. This definition was selected over those defined by Crowley[1], since, in this case, his definition would involve the addition of terms which could not be directly measured. The PV efficiency of the EM engines is compared to corresponding calculated values in Figure 6-9. The data from EM No. 2 was in agreement with predictions across the power range tested. Considerable scatter is seen in this test data, may be due to the transient nature of the duty-cycle test from which the data was obtained. The data from EM No. 1 follows the trend predicted by the harmonic analysis; however, it is two to four points lower than the prediction, particularly at higher power. The running test results are also shown in Figure 6-10 through 6-17. This data indicates that the engine performance was not affected by the duty-cycle load changes.

[1] Crowley, J.L., "ORNL/CON-131 Efficiency Terms for Stirling Engines

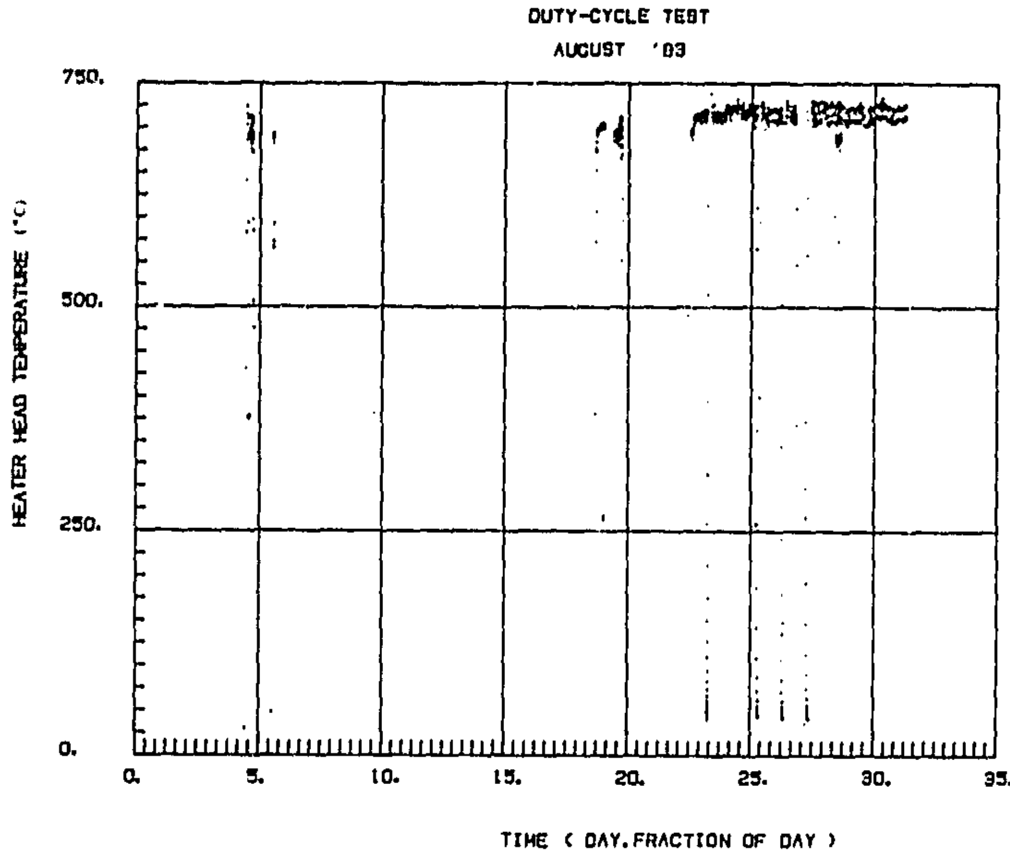


Figure 6-10 Heater Head Temperature versus Time

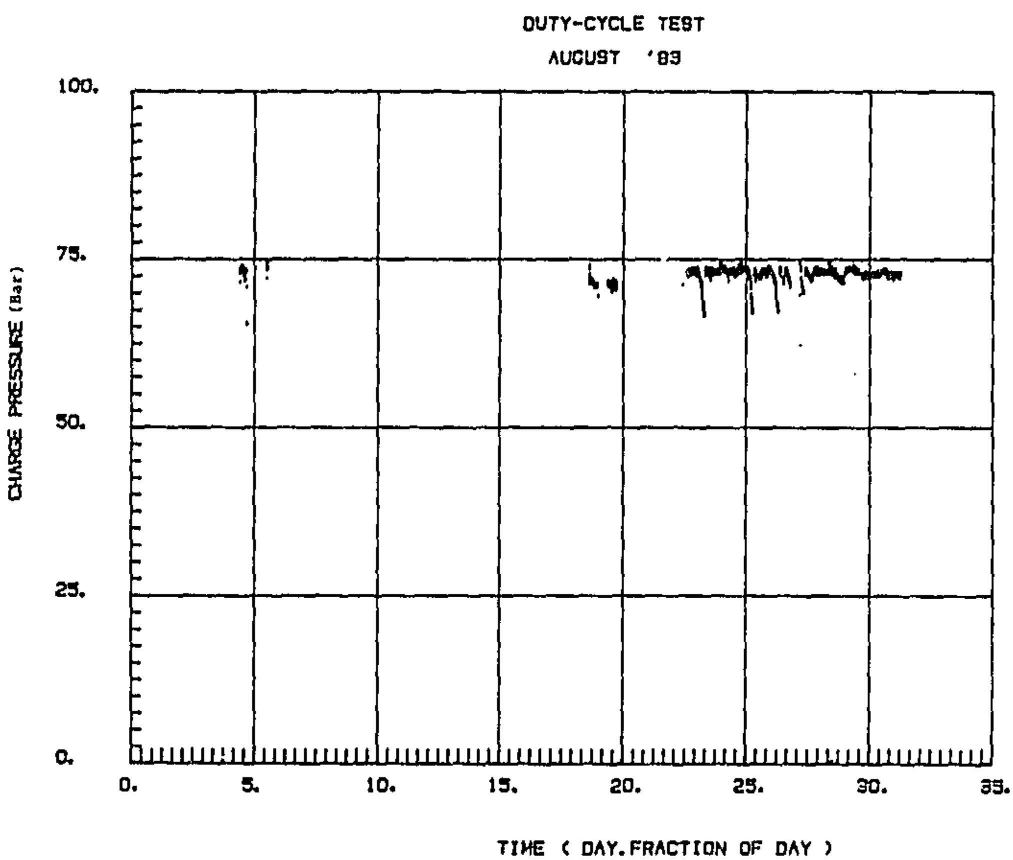


Figure 6-11 Charge Pressure versus Time

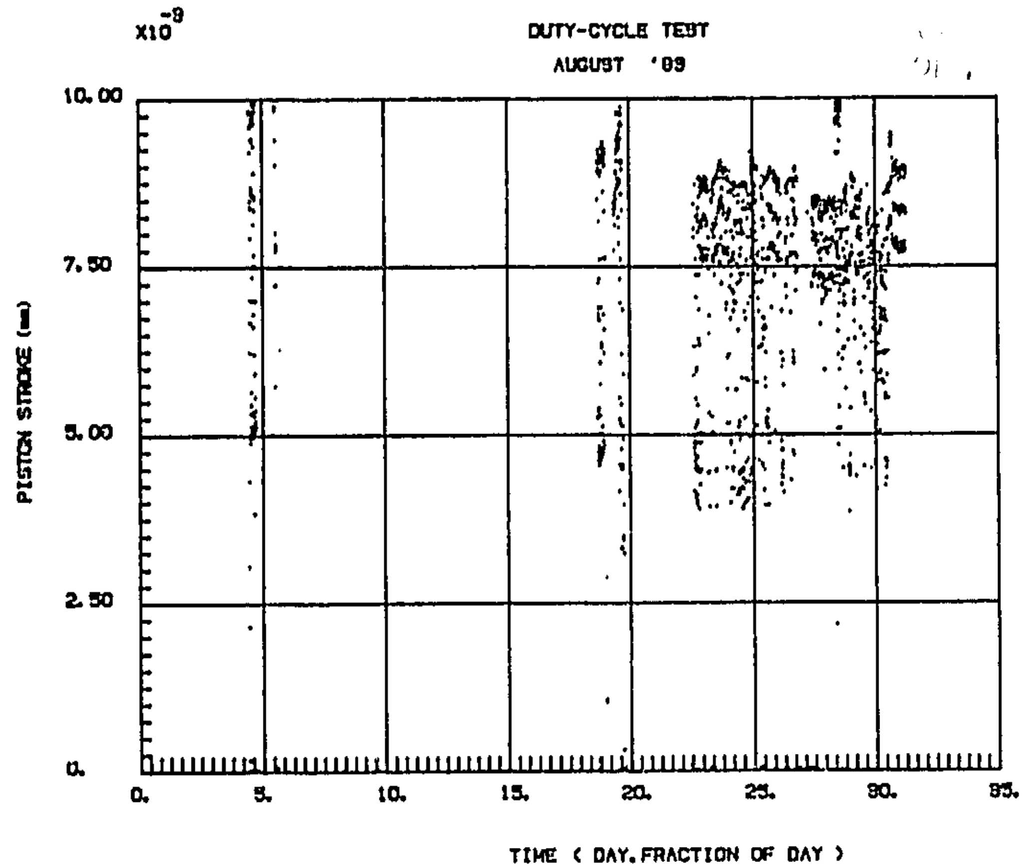


Figure 6-12 Piston and Displacer Stroke versus Time

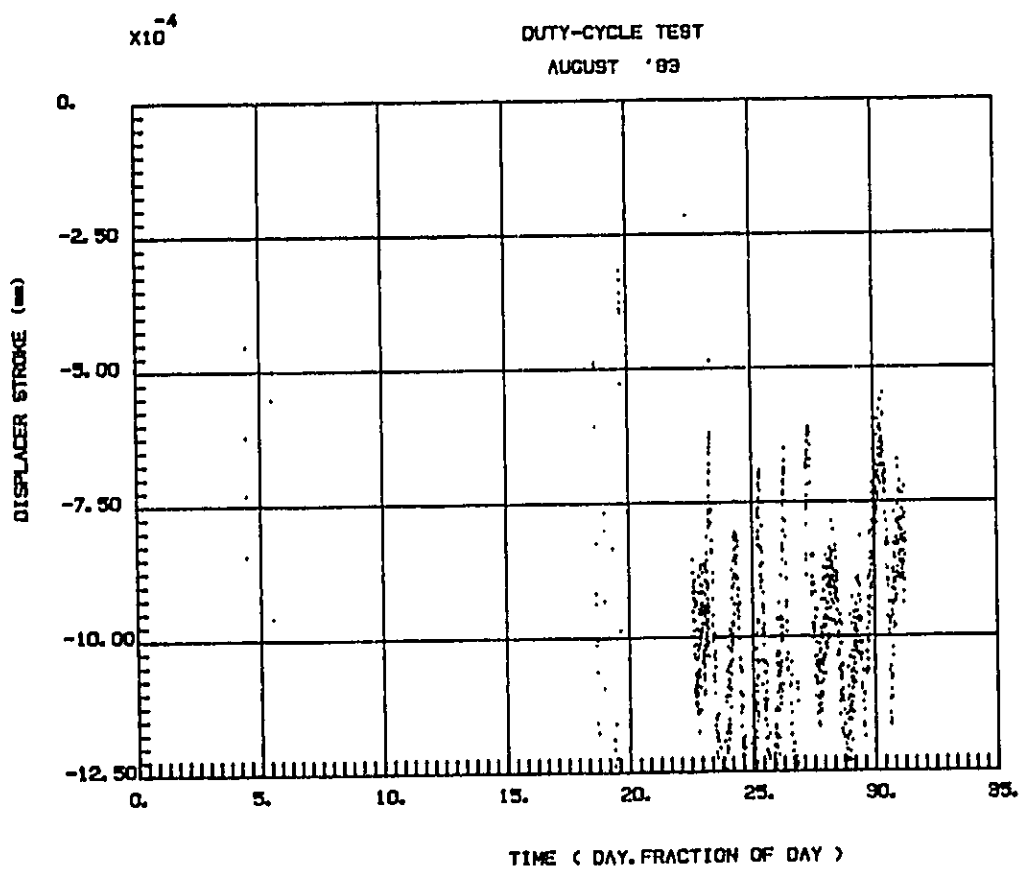


Figure 6-13 Piston and Displacer Stroke versus Time

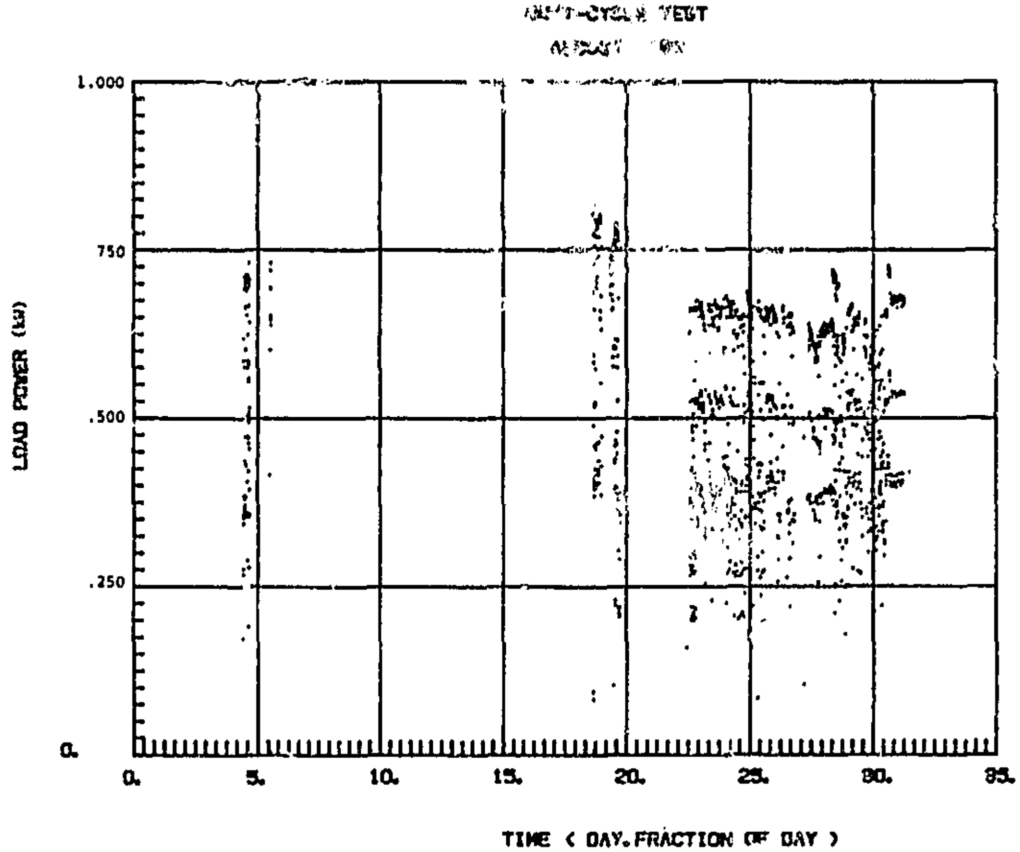


Figure 6-14 Load Power versus Time

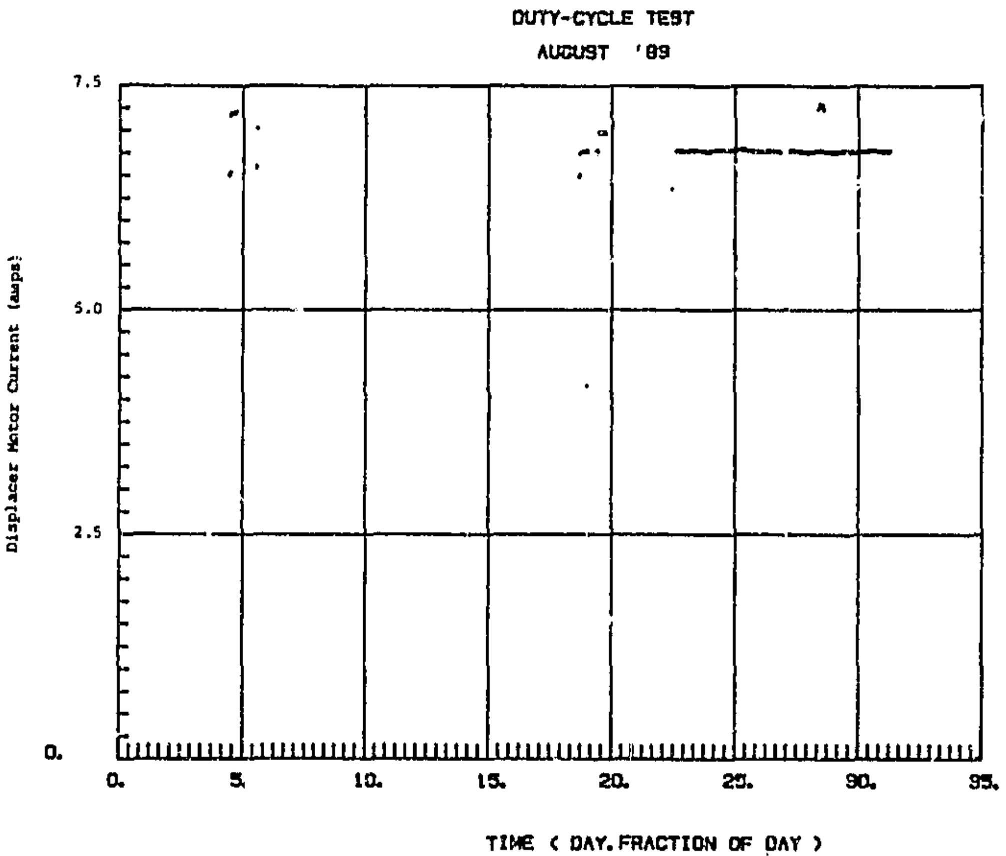


Figure 6-15 Motor Current versus Time

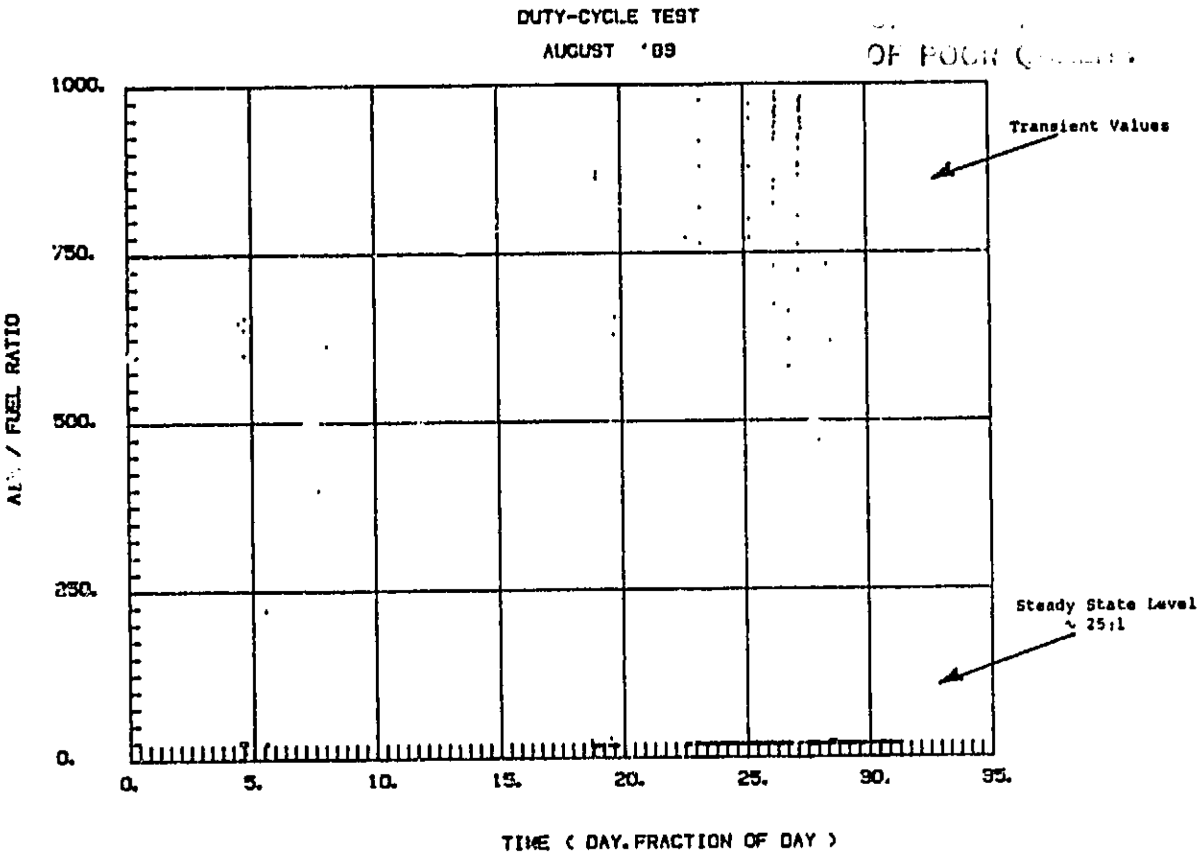


Figure 6-16 A/F Ratio versus Time

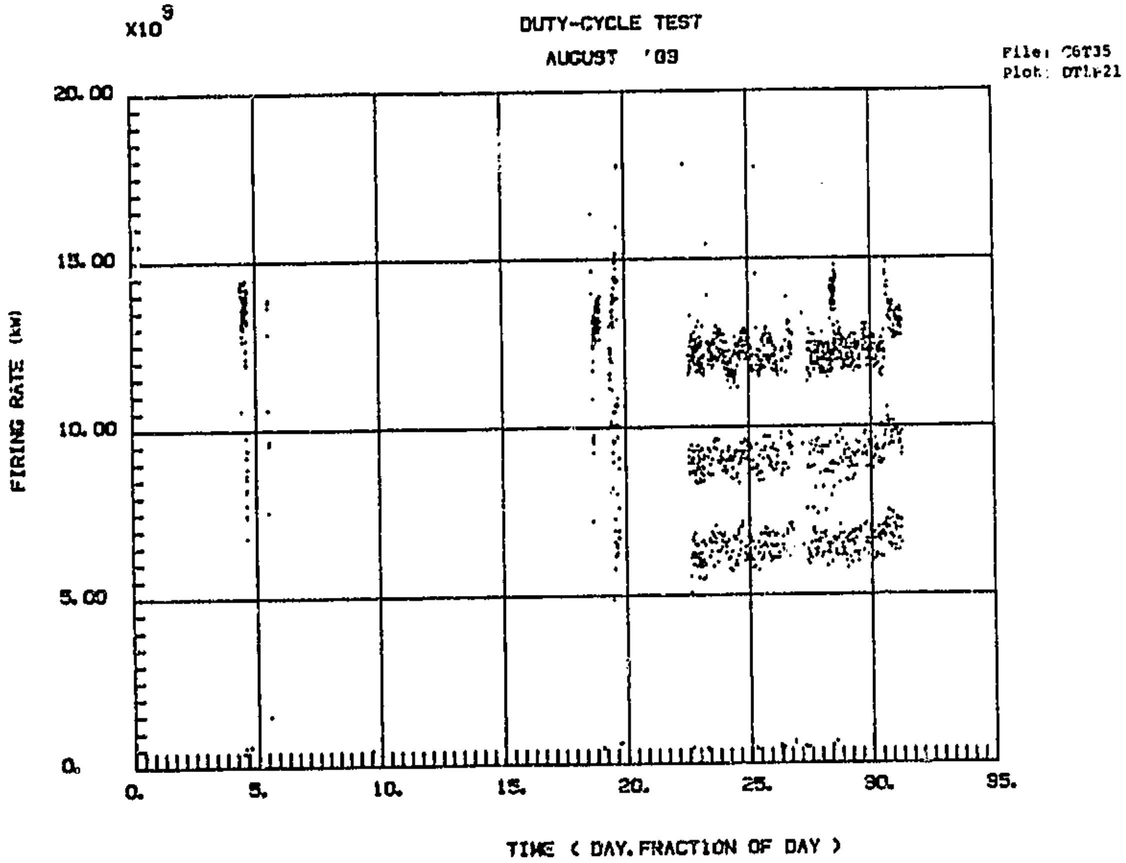


Figure 6-17 Firing Rate versus Time

7.0 PHASE IV - START/STOP TEST

7.1 Objective

The original objective of the start/stop test was to accumulate 300 test hours while performing 1000 start/stop tests of the engine system. The engine was to be cycled on and off approximately every 15 minutes, with load between zero power power and the power point defined in Phase II. This task objective was modified with approval from NASA to accumulate a minimum of 100 start/stop tests. The engine was to be cycled on and off approximately every 5 minutes.

7.2 Conclusions

The EM engine successfully completed 262 start/stop cycles. While there was no significant degradation of engine operating performance, there were subtle indications of engine degradation. On inspection of the bearings and seals, no damage was observed in the seals or piston bearings, however, minor damage of the displacer rod was noted.

7.3 Discussion

7.3.1 Test Description

The critical seal and bearing clearances were inspected as described in Section 3.0.

The test procedure was designed to demonstrate the most critical phase of engine start-up relative to wear and durability of the engine proper. The start procedure was abbreviated to obtain as many start/stop cycles as possible and to demonstrate the basic durability of the engine bearings and seals. To this end, the engine heater/combustor was operated continuously as was the engine cooling system. The combustor control maintained the heater temperature at the set point of 650-700°C by automatically controlling firing rate and airflow (Figure 7-1). The cooling flow in the primary and secondary loops were maintained at constant flow rates. The coolant inlet temperature is controlled by the temperature of a large storage tank, which is cooled by a cooling tower. The inlet temperature

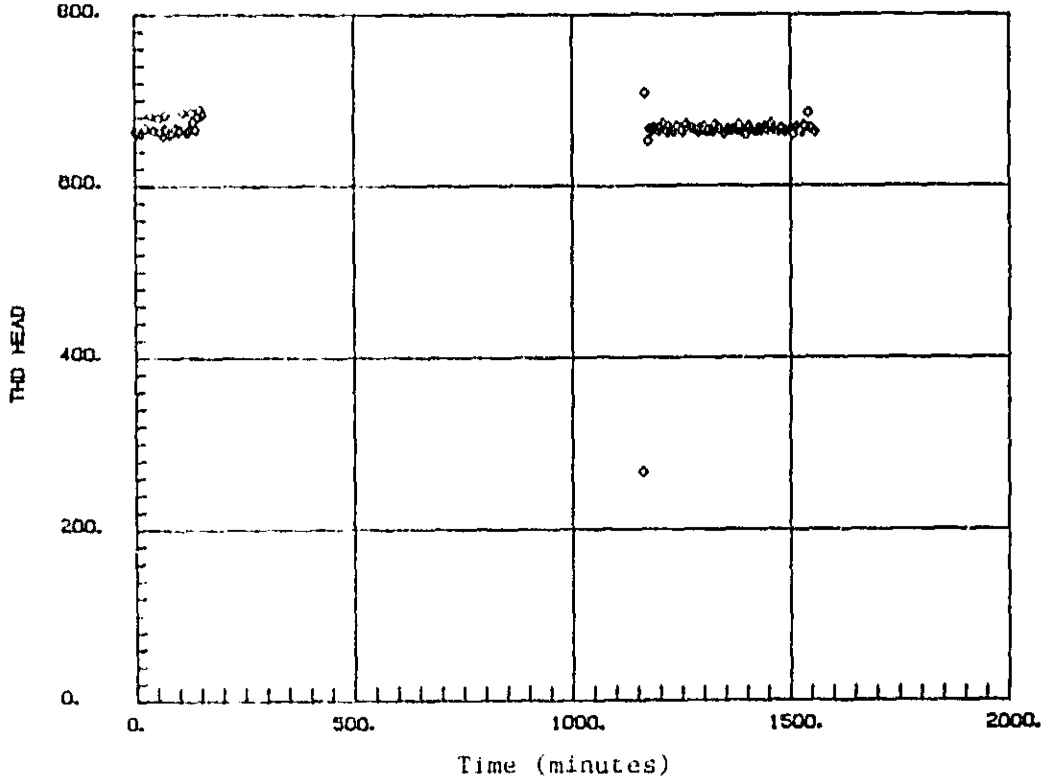


Figure 7-1 T_{read} Operating Range

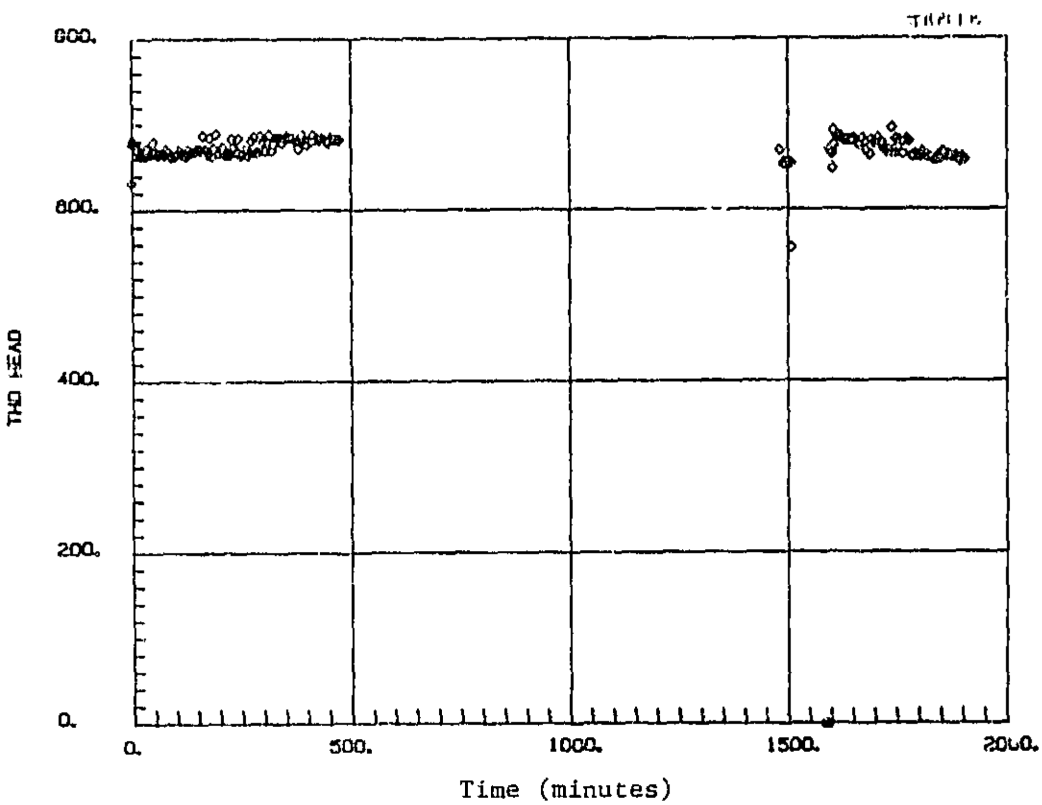


Figure 7-1 Continued

cycled between 28 and 33°C (Figure 7-2) once the cooling system came up to temperature at the beginning of each day's testing. The engine outlet temperature followed the inlet temperature with a constant ΔT ($\sim$13°C), Figure 7-2.

7.3.2 Test History

The start/stop test was begun following the demonstration of internal bearing operations described in Section 4.0. The test was started on 13 February 1984 and was completed on 21 February 1984, with a total accumulation of 262 "dry" (no external pressure) bearing starts.

7.3.3 Test Results

The engine started easily during this test, achieving steady-state piston stroke, displacer stroke, and bearing supply pressure in less than one second. A typical start-up cycle (Figure 7-3) shows the displacer stroke comes up to 75% of the steady level in three engine cycles, then stabilizes. The piston stroke and compression space pressure amplitude oscillates at a low amplitude for $\sim$20 cycles, at which point the piston and pressure amplitude increases rapidly for several cycles (five), then increases slowly for another 25 cycles when full piston stroke is achieved. The bearing supply pressure (ΔP bearing) came up to its steady level as the piston stroke achieved its steady state level. Also, once the piston stroke begins coming up to full stroke, the load on the displacer drops and the displacer stroke increases to steady-state levels.

The delay in the piston stroke, and thus pressure amplitude, in coming up to stroke is due to the additional leakage loss of the mid-stroke ports. When the stroke increases to the point where the ports begin to close, the leakage loss drops relative to the stroke and reduces the load on the thermodynamic cycle, thus making more energy available for driving the power piston.

The steady state bearing ΔP (Figure 7-4) was relatively constant during the first three days. On 21 February 1984, the bearing check valve system was modified to improve the tuning, and thus the bearing supply pressure. The bearing pressure was increased from 5.7 to 6.1 Bar.

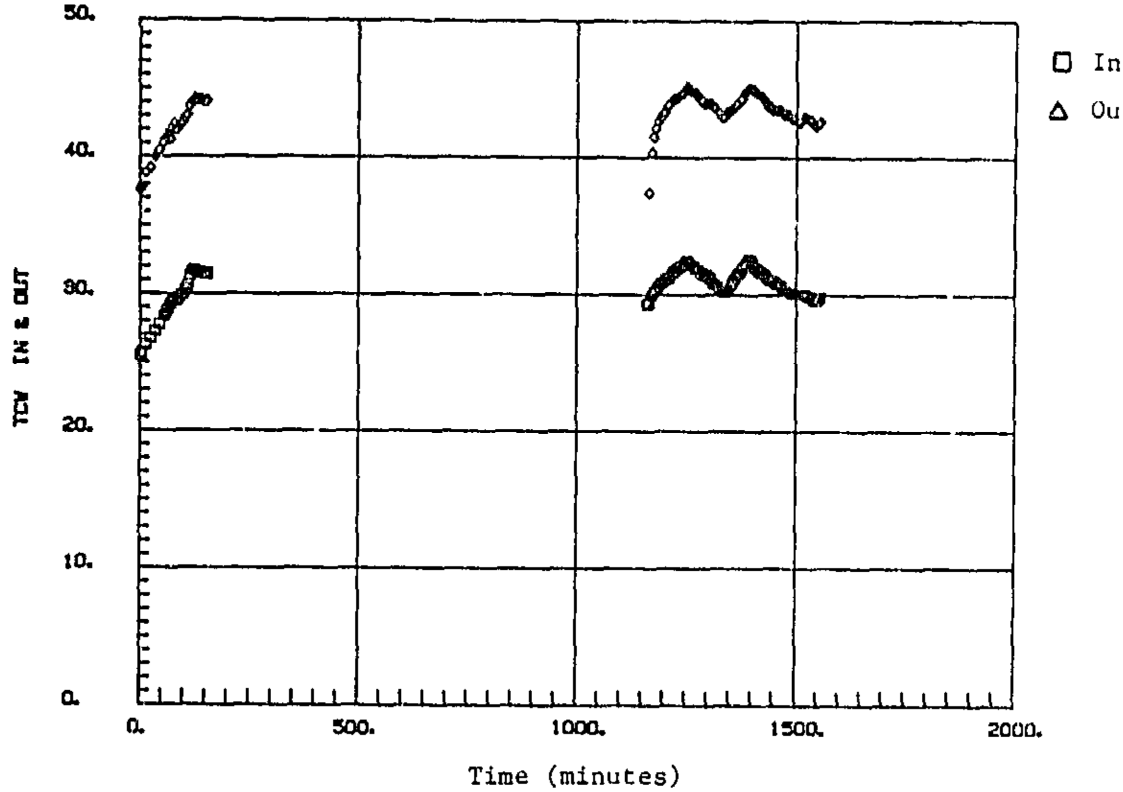


Figure 7-2 Cooling Water Temperature and Difference Operating Range

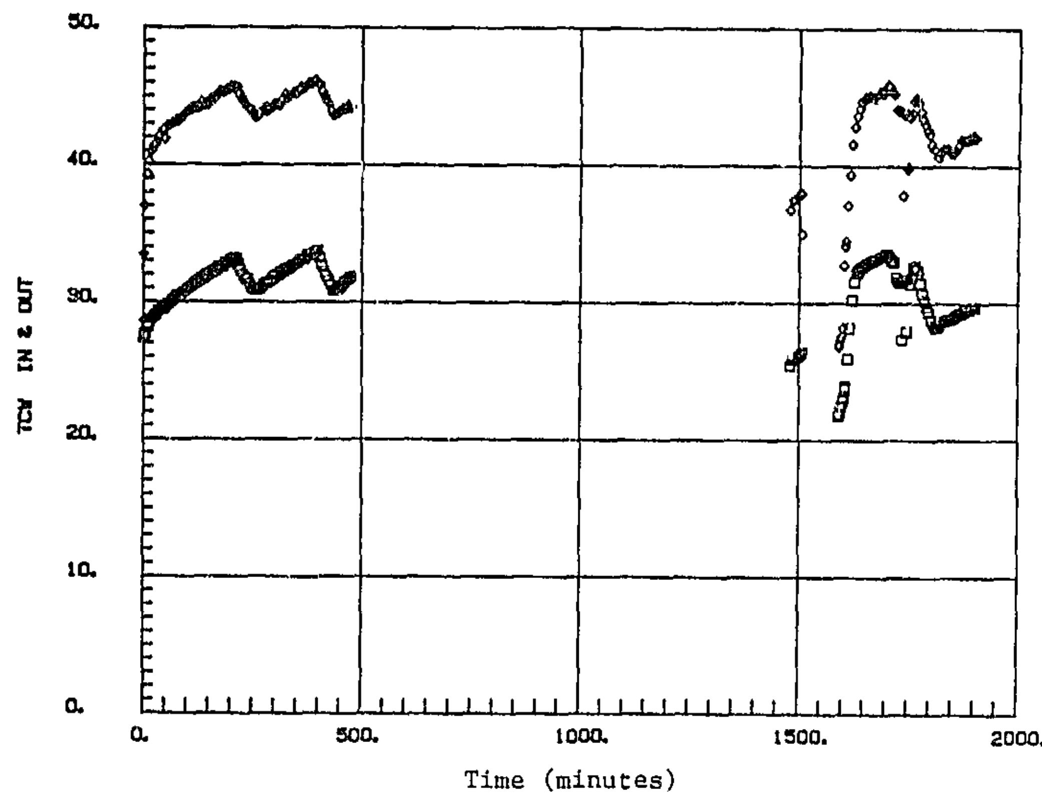


Figure 7-2 Continued

ORIGINAL PAGE IS
OF POOR QUALITY

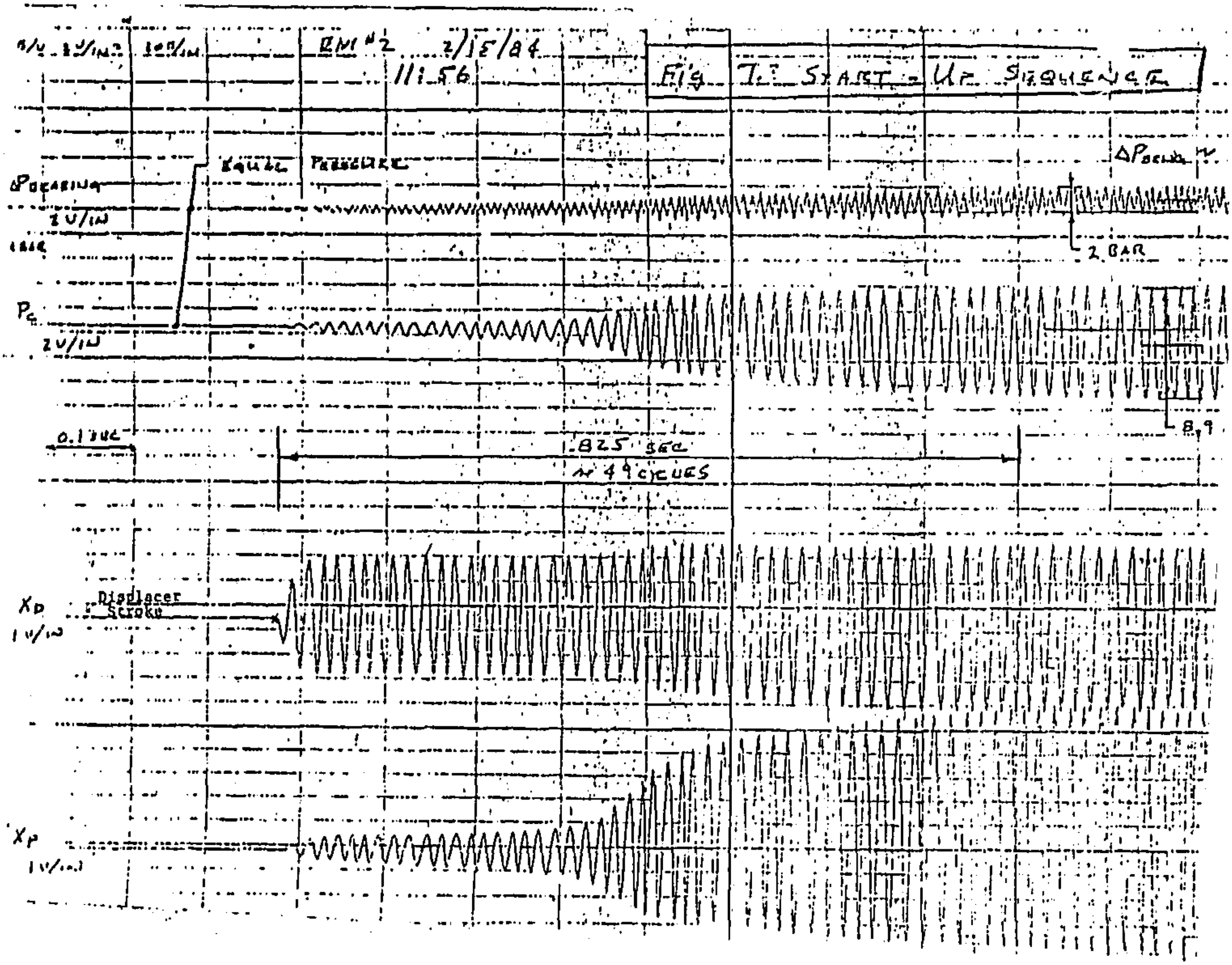
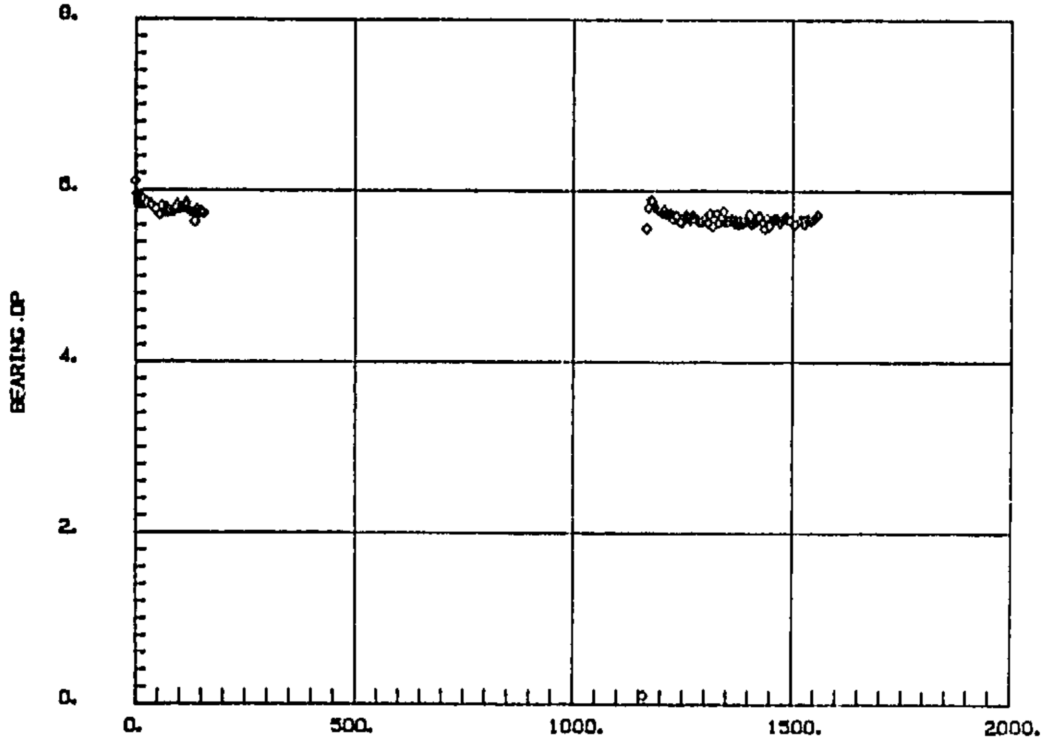
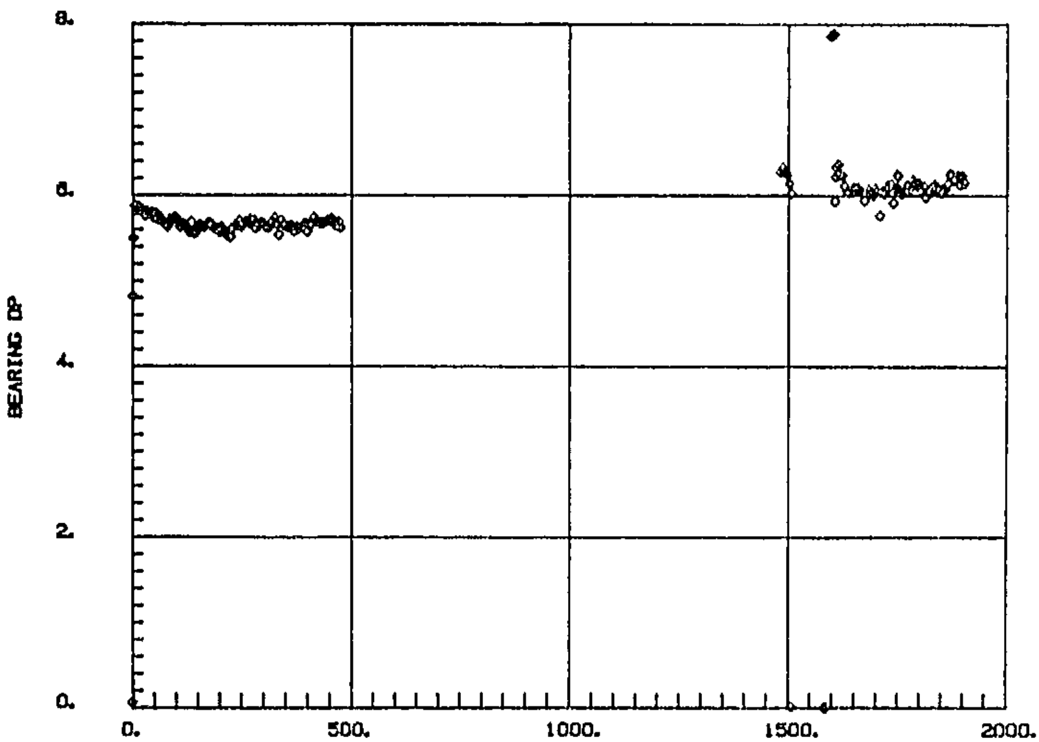


Figure 7-3 Start-Up Sequence



Time (minutes)

Figure 7-4 $\Delta P_{\overline{bearing}}$ Operating Range



Time (minutes)

Figure 7-4 Continued

ORIGINAL PAGE IS
OF POOR QUALITY

The bearing pressure dropped 0.1 to 0.2 Bar in the first hour of running each day, then stabilized. This is may be due to cold-start thermal transients, which are affecting either the bearing clearance or the internal check-valve compressor operation.

The piston and displacer amplitudes were maintained at a constant level during the entire test (Figure 7-5). The consistency of the piston and displacer amplitudes indicates that thermodynamic performance and losses are not changing over time.

The motor current (Figure 7-6) is proportional to the force that the motor imposes on the displacer and is the most sensitive to changes in dynamic or thermodynamic losses. This is evident by the scatter in the current during the first three days of testing compared to other parameters, such as piston and displacer amplitude. The data from 15 February 1984 indicates a potential increase in losses during the first hour of operation, after which the current dropped to the same as the previous two days of testing. The data from 21 February 1984 exhibits more scatter than was observed on 13-15 February 1984. This may be an indication of intermittent increases in losses which may be an early indication of engine degradation. Subsequent engine inspection indicated rubbing between the displacer rod and the bearing it runs in, and could explain the intermittent high current observed in the test data.

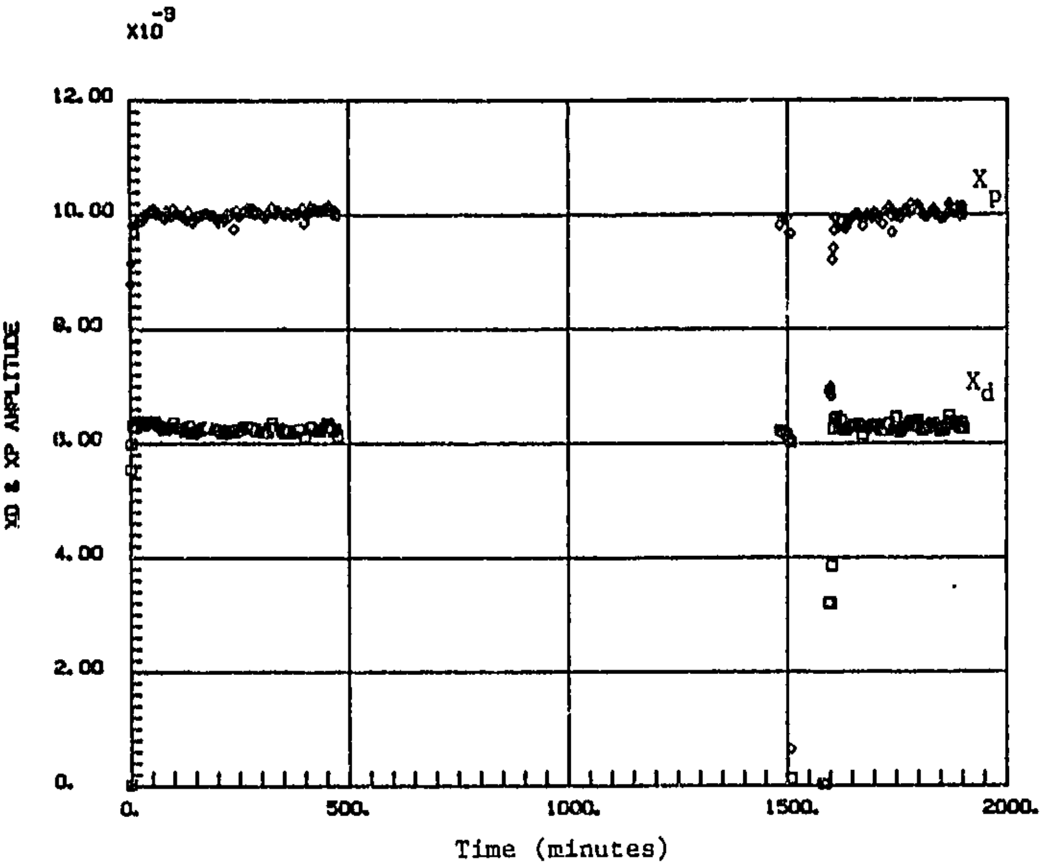


Figure 7-5 Displacer (X_d) and Power Piston (X_p) Amplitude Operating Range

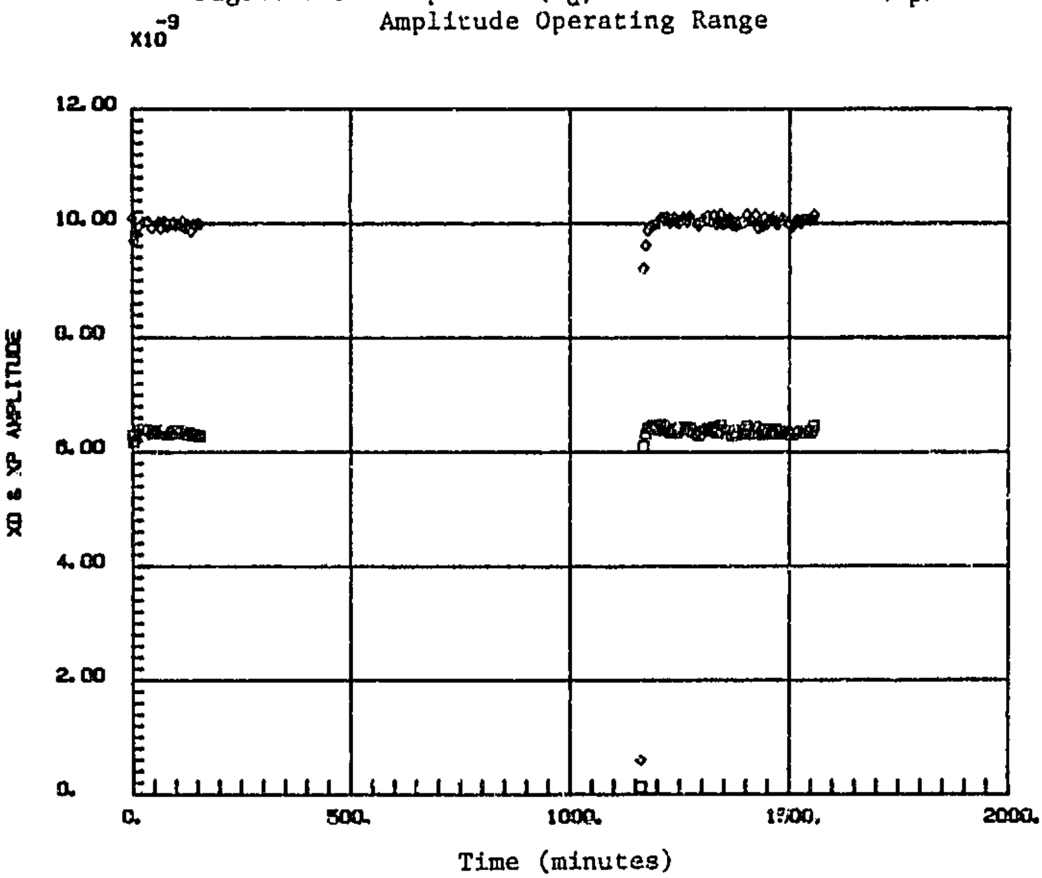


Figure 7-5 Continued

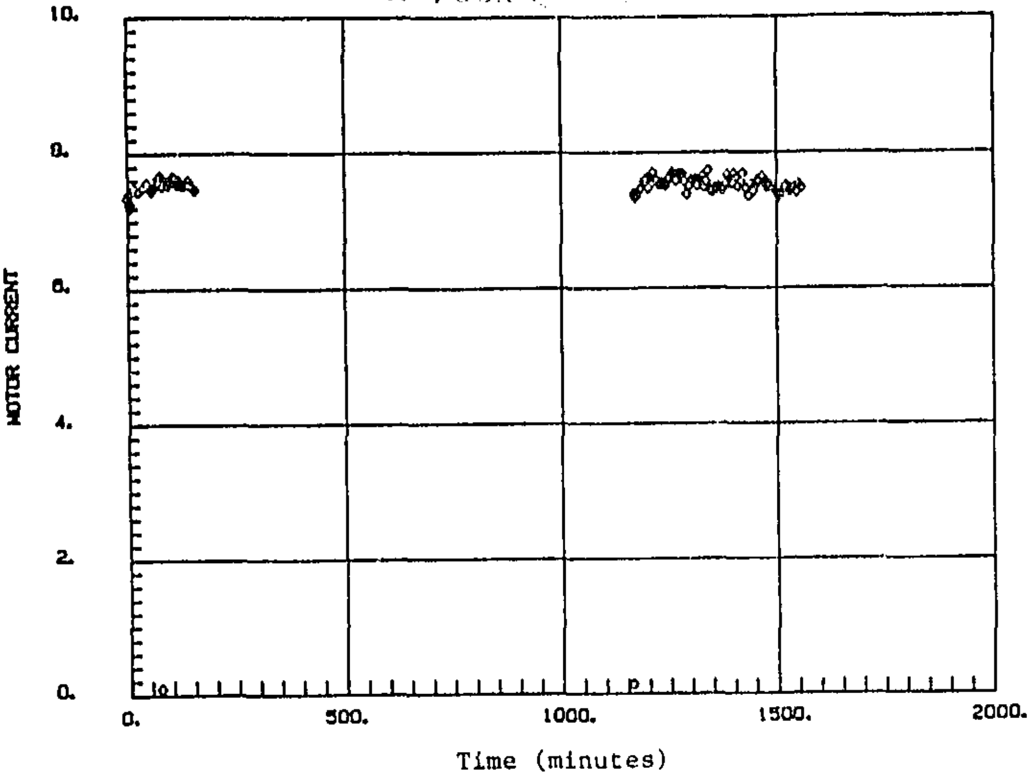


Figure 7-6 Displacer Motor Current Operating Rnage

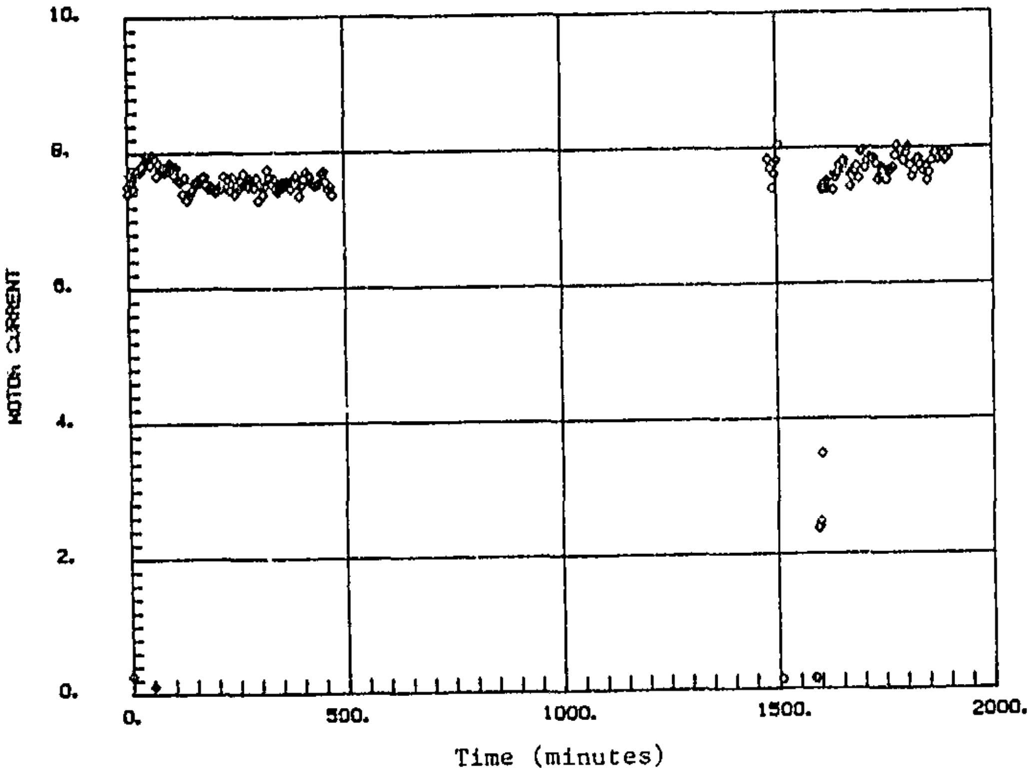


Figure 7-6 Continued

APPENDIX A

SYMBOLS
STANDARD MEASURED DATA AND CALCULATED RESULTS

Standard Measured Data

P_{mean}	- mean engine pressure
P_{brng}	- bearing supply pressure
f_{eng}	- engine frequency
$X_{d\ mean}$	- mean displacer position
$X_{d\ amp}$	- displacer amplitude
$X_{p\ mean}$	- mean piston position
$X_{p\ amp}$	- piston amplitude
$P_{dgs\ 1\ M}$	- mean pressure of displacer gas spring 1
$P_{dgs\ 2\ M}$	- mean pressure of displacer gas spring 2
$P_{c\ M}$	- mean pressure of compression space
$P_{dgs\ 1\ A}$	- pressure amplitude of displacer gas spring 1
$P_{dgs\ 2\ A}$	- pressure amplitude of displacer gas spring 2
$P_{c\ A}$	- pressure amplitude of compression space
V_{mtr}	- input motor voltage (RMS)
I_{mtr}	- input motor current (RMS)
MTR Pwr	- input motor power (watts)
V_{field}	- alternator field voltage (PC)
I_{field}	- alternator field current (PC)
V_{load}	- alternator load voltage (RMS)
I_{load}	- alternator load power (watts)
Load Pwr	- alternator load power (watts)
dP_{fuel}	- differential pressure of fuel laminar-flow element
P_{fuel}	- fuel supply pressure
T_{fuel}	- fuel supply temperature
dP_{ambair}	- differential pressure of air laminar-flow element
P_{ambair}	- combustion air supply pressure
T_{ambair}	- combustion air supply temperature
T_{cwin}	- engine cooling water inlet temperature
T_{cwout}	- engine cooling water outlet
$Flow_{cw}$	- engine cooling water flow rate
T_{hd}	- head temperatures up to 27 locations
T_{amb}	- combustion temperatures up to 10 locations

Standard Calculated Results

T_{ctrlmn} - mean control temperature, average of heater thermocouples used for temperature control (°C)

T_{hd} Mean - mean head temperature (°C)

Fire Rate - gross heat input to combustor (watts)

A/F R_{tio} - combustor air/fuel ratio

Load Res - calculated load resistance (Ω)

Field Pwr - power input to alternator field (watts)

Field Res - resistive independence of alternator field coil (Ω)

Field Temp - estimate of mean field coil temperature based on coil resistance (Ω)

Ht Rej - heat rejected to engine cooling water (watts)

Brng dP - pressure difference across gas bearings

Gross Eff - gross engine efficiency defined as electrical power at the load/ gross heat input to combustor.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-174771		

4. Title and Subtitle

Free-Piston Stirling Engine/Linear Alternator 1000-Hour Endurance Test

5. Report Date

March 1985

6. Performing Organization Code

7. Author(s)

Jeffrey Rauch and George Dochat

8. Performing Organization Report No.

10. Work Unit No.

9. Performing Organization Name and Address

Mechanical Technology Incorporated
968 Albany-Shaker Road
Latham, New York 12110

11. Contract or Grant No.

DEN 3-333

13. Type of Report and Period Covered

Contractor Report

12. Sponsoring Agency Name and Address

U.S. Department of Energy
Office of Building and Community System
Building and Equipment Division
Washington, D.C. 20545

14. Sponsoring Agency Code

DOE/NASA/0333-1

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AI05-82OR1005. Project Manager, Donald Alger, Power Technology Division, NASA Lewis Research Center Cleveland, Ohio 44135.

16. Abstract

The Free-Piston Stirling Engine (FPSE) has the potential to be a long-lived, highly reliable, power conversion device attractive for many product applications such as space, residential or remote-site power. The purpose of endurance testing the FPSE was to demonstrate its potential for long life. The endurance program was directed at obtaining 1000 operational hours under various test conditions: low power, full stroke, duty cycle and stop/start. Critical performance parameters were measured to note any change and/or trend. Inspections were conducted to measure and compare critical seal/bearing clearances. The engine performed well throughout the program, completing more than 1100 hours. Hardware inspection, including the critical clearances, showed no significant change in hardware or clearance dimensions. The performance parameters did not exhibit any increasing or decreasing trends. The test program confirms the potential for long-life FPSE applications.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Stirling engines; Free-piston Stirling engines; Endurance test; Linear alternator	Unclassified - unlimited STAR Category 44 DOE Category UC-95

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	100	A05

*For sale by the National Technical Information Service, Springfield, Virginia 22161

☆ U.S. GOVERNMENT PRINTING OFFICE: 1985—559—109/10439

END DATE
SEP. 13, 1985