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EVALUATION OF REQUIREMENTS FOR MILITARIZATION OF 3-kW FREE-PISTON STIRLING ENGINE GENERATOR SET

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The design evaluation study assessed the capability of the free-piston Stirling engine (FPSE) to meet requirements for military mobile electric ground power. Operational requirement parameters included physical, thermodynamic, audio, material, operational, and electrical. Test data and design calculations indicated that, with continued development, the FPSE can meet or exceed all of the military requirements for 3 kW silent tactical generators operating on military logistic fuels.

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EXECUTIVE SUMMARY

Free-piston Stirling engines (FPSE) are advanced conversion power systems that operate with two moving parts to produce electrical power from most any fuel source, with high efficiency and high reliability. Mechanical Technology Incorporated (MTI) is developing the FPSE for stationary commercial applications in the size range below 10 kW. Because of the potential strategic and logistics advantages offered by these machines, the U.S. Army Mobility Equipment Development Command has contracted MTI to project the capability of the FPSE to meet requirements for military ground power. This report documents the results of that study.

The methodology employed in this study involves the comparison of test data and design calculations with military requirements and standard documents. Because the current development is oriented toward commercial applications, engineering projections were made to evaluate the feasibility of adapting the FPSE for military use.

Operational requirement parameters were divided into six categories: physical, thermodynamic, audio, material, operational, and electrical. The results of the ensuing parametric assessment are summarized in the table that follows.

Parameter	Meets or Exceeds Requirements	Below Requirements	Comments
Physical		X	Component Technology Advancement Required to Meet Weight Specifications
Thermodynamic	X		
Audio	X		
Materials	X		
Operational	X		
Electrical	X		

Of the six categories assessed, only the physical requirement for low system weight would demand additional technological development for FPSEs to have the capability for complying with military specifications. In all other regards, the FPSE was found to have the capability for meeting or exceeding the requirements. Further, when comparing the projected militarized FPSE generator system with alternative generators from the existing standard family, the FPSE was determined to be potentially superior in all aspects.

The specific conclusions that were drawn from the study are stated as follows:

- The state of the art of FPSEs allows for current commercial hardware designs to achieve a significant portion of the military requirements and standards.
- Engineering projections show that, in the near term, the FPSE can be developed to comply with all military requirements for ground power.
- Present FPSE hardware designs compare most favorably with alternative generator sets now in the standard family.
- Advanced FPSEs will surpass the operational characteristics of alternative standard family generator sets in all respects.
- The operational and developmental testing of a FPSE generator operating with military logistics fuel capability could be established by 1984.
- A system development program needs to be implemented in order to adapt commercially oriented FPSE technology for military application.

PREFACE

The work completed under this study was authorized by the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, under contract number DAAK70-81-C-0115. This volume documents the entire program effort associated with Task 1, Design Evaluation. A program plan was prepared and submitted separately in fulfillment of the requirements for Task 2, Development Plan. This document comprises the Scientific and Technical Report as required by the Contract Data Requirements List DD Form 1423 (article A002).

The author gratefully acknowledges the enthusiastic support provided by the Contracting Officer's Technical Representative, Mr. Paul Arnold. Additionally, the following technical contributors are listed for recognition of their efforts in this project: Dr. R. Ackermann, Dr. Suresh Bhate, Mr. G. Dochat, Mr. R. Farrell, Mr. B. Goldwater, Mr. J. LaPointe, and Mr. N. Vitale.

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SECTION 1.0

INTRODUCTION

1.0 INTRODUCTION

This document comprises the final report of a study to project the capability of free-piston Stirling engine (FPSE) generators to meet military requirements for mobile electric power. The study was conducted by Mechanical Technology Incorporated (MTI) for the Army's Mobility Equipment Research and Development Command (MERADCOM) under contract DAAK70-81-C-0115. The conclusion of this report is that the FPSE can, with continued development, meet or exceed all of the military requirements for 3 kW silent tactical generators operating on military logistic fuels.

1.1 Background

In 1969, MERADCOM published a report detailing the results of a survey that was conducted "to critically review the entire silent, power generation technology field."[1] The purpose of the survey was to provide guidance for program planning in the early development of reliable and silent military ground power sources. A Stirling-cycle engine-generator was among the candidate energy conversion systems considered in the survey. Regarding Stirling engines, the report commented that "the hardware is a complex mechanical system requiring strong design discipline in order to seal the working fluid and maintain good control over the system under dynamic operating conditions."

Since 1969, significant advances have been accomplished in Stirling engine technology that address the identified limitations reported. Most notably, the reduction to practice of the FPSE in the early 1970s provided a simple, hermetically sealed, gas lubricated design with the potential for a long life and high reliability. Additionally, the FPSE is characterized by the same attractive operating features that are common to most Stirling engines: high efficiency, multifuel capability, and quiet operation.

1.2 Technical Concept

MTI is developing the FPSE for a variety of commercial product applications. The basic design approach for FPSE integrates power cycle machinery and load devices within a single hermetically sealed unit. Integration of the engine

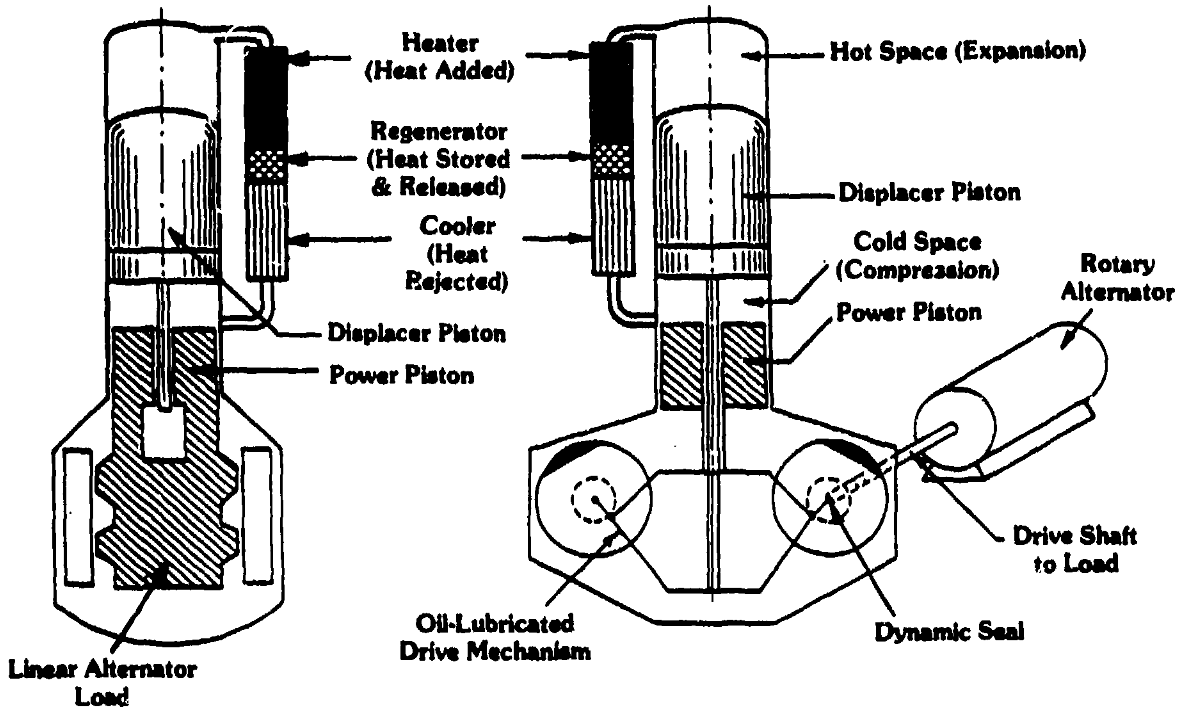
[1] "A Silent, Electric Power Generator for Tactical Applications Special Study," US MERDC, Ft. Belvoir, Virginia, June 1969, Report 1954.

section with a linear alternator load is illustrated in Figure 1-1(a) and is compared with the more conventional Stirling engine rotary alternator configuration shown in Figure 1-1(b). FPSE generator configurations operate with only two moving parts that utilize working fluid gas springs to control their prescribed motions. These two dynamic components, the displacer piston and the alternator piston, are supported on gas bearings. The gas bearings provide a working fluid gas lubrication for the moving surfaces. As a result, all surface contact is eliminated during engine operation. These design features provide the FPSE with an inherent potential for achieving long life with a high degree of reliability. Figure 1-2 schematically illustrates the engine's reliability-oriented features.

In addition to an inherent potential for durability, the FPSE achieves high efficiency over a broad operating range. Theoretically, the power cycle efficiency is equal to the Carnot efficiency for an equivalent set of operating temperatures. In practice, nearly 70% of Carnot efficiency can be realized through good design technique. In the low-power range (<10 kW), the FPSE offers a definite efficiency advantage over alternative power conversion devices.

The FPSE utilizes helium as a working fluid in a closed-cycle operation. Energy is input to the engine at high temperature through the engine hot side heat exchanger known as the heater head. Because the heat input is accomplished external to the engine's hermetic encasement, the FPSE can efficiently utilize a variety of high-temperature energy sources such as combustible gases, liquid fuels, biomass solids, nuclear radiation, and concentrated solar radiation.

Because the FPSE operates both efficiently and reliably irrespective of the energy source, these attractive power converters are being developed for a variety of system applications. Some examples of the applications under consideration include residential, heat-activated heat pumps and total energy systems, stationary and mobile battery chargers, portable electric power systems, solar thermal power units, and remote-site electric generators.



(a) Free-Piston Stirling (b) Conventional Stirling

Fig. 1-1 Alternative Configuration for Stirling Engines

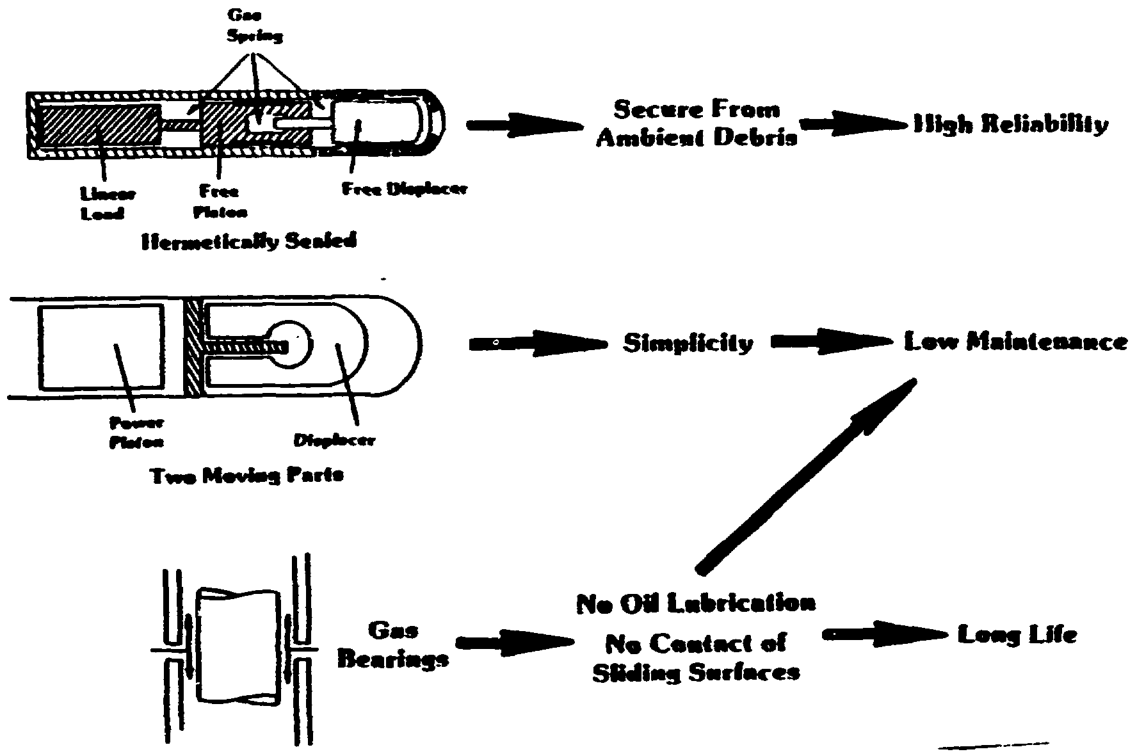


Fig. 1-2 FPSE Reliability-Oriented Features

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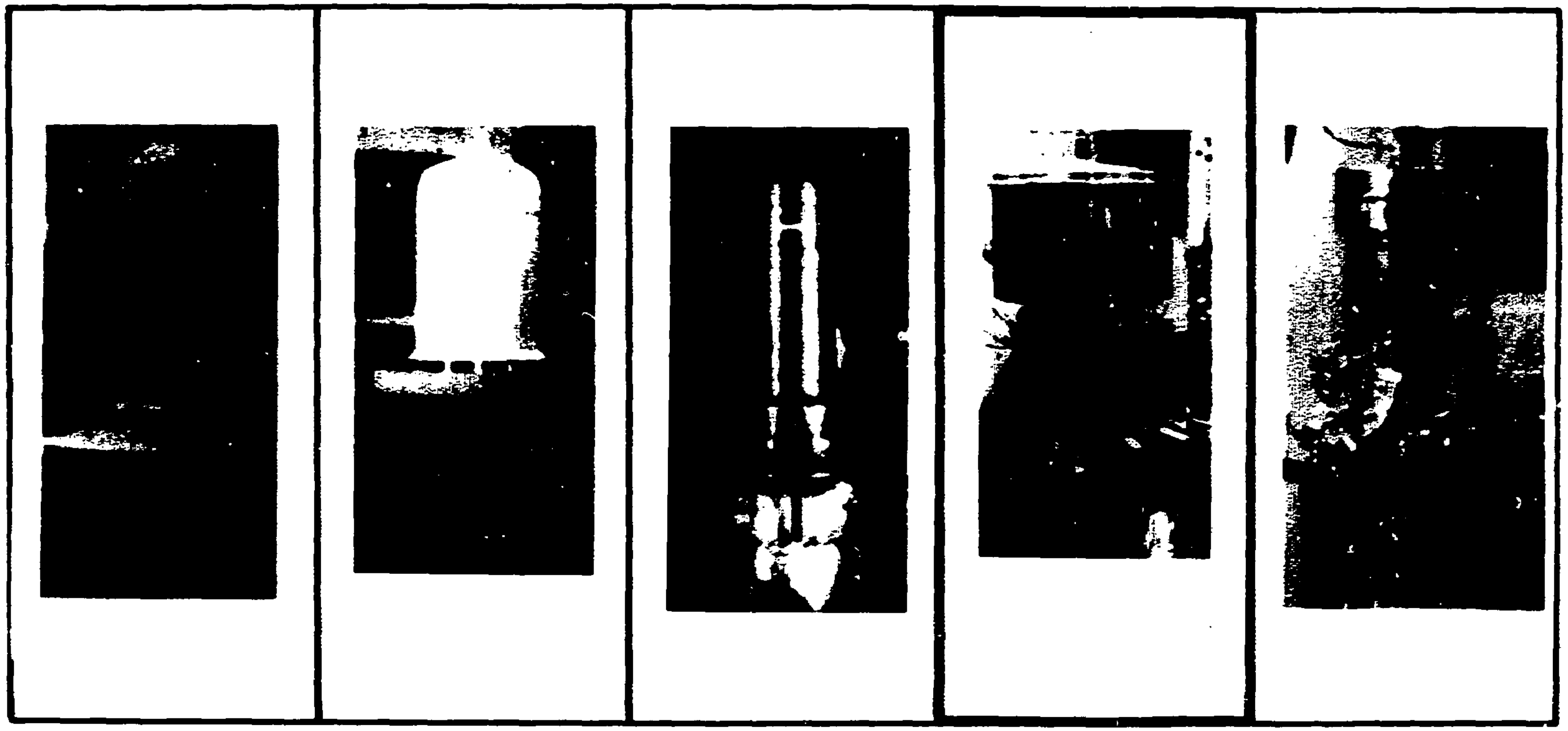
A number of FPSE units have been developed and tested at MTI since the mid 1970s. Some of these units are shown in Figure 1-3. The state of the art of the FPSE is MTI's 3 kW Engineering Model Engine Generator. The Engineering Model can currently be classified as a nonsystem advanced development prototype.

1.3 Militarization Study

By virtue of its unique operational capability, the FPSE offers potential advantages of a strategic and logistic nature to users of mobile power equipment in a military environment. For this reason, MERADCOM contracted MTI to perform an assessment study of the suitability of the FPSE for meeting the military's need for ground power. The program objective was to utilize test data and design calculations to project the capability of the FPSE to meet military requirements for tactical generator sets. The work scope consisted of two major tasks:

Task 1.0 Design Evaluation
Task 2.0 Development Plan

The purpose of Task 1.0 was to compare FPSE test and design data with suitable military standards and specifications. Task 2.0 involved the preparation of a development plan to achieve full demonstration of FPSE generator systems operating on military logistic fuels to provide the electrical power output performance as defined in MIL-STD-1332B. The study was accomplished in four months. The following sections detail the methodology that was employed and the results that were achieved.



YEAR	1976	1978	1980	1981	1982
SIZE	0.5 kW	0.9 kW	>1.0 kW	3 kW	3.3 kW
PURPOSE	Demo/HAHP	Demo/Solar	Technology	Generator/HAHP	Generator Set
PROGRAM	Private	JPL	DOE	Private/DOE	Product
PERFORMANCE*	.22	.34	.38	N/A	.40**

*Engine thermodynamic efficiency
**Predicted

Fig. 1-3 FPSE Units Developed and Tested at MTI

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SECTION 2.0

METHODOLOGY

2.0 METHODOLOGY

The Task 1.0 effort comprised the major portion of the study. As stated, the task objective was to compare FPSE test and design data with existing military standards and specifications. The following military documents were considered:

1. Purchase Description For Low Noise 3.0 kW Stirling Engine Power Plant, MERADCOM, March 28, 1974. Included were the following reference documents:

   MIL-G-3056: Gasoline, Automotive, Combat

   MIL-T-5624: Jet Fuel, Grades JP-4 and JP-5

   MIL-STD-810: Environmental Test Methods for Aerospace and Ground Equipment, Miscellaneous

   MIL-STD-1472: Human Engineering Design Criteria for Systems, Equipment, Facilities

   MIL-STD-1474: Noise Limits for Army Materiel
   VV-F-800: Fuel Oil, Diesel

2. MIL-STD-1332B. Definitions of Tactical, Prime, Precise and Utility Terminologies for Classification of the DOD Mobile Electric Power Engine Generator Set Family, March 13, 1973. The following reference documents were considered:

   MIL-STD-633: Mobile Electric Power Engine Generator Set Family Characteristics Data Sheets

   MIL-STD-705: Generator Sets, Engine Driven, Methods of Tests and Instructions

Appendix A contains a replication of these documents. For the purpose of this study, all information that was derived from the above documents was categorized as a military requirement even though, as in the case of the Purchase Description Document, the term requirement is not exact.

The following three subsections contain a description of the approach that was used to complete each of the following subtasks:

Subtask 1.1 Test Data Comparison with Requirements

Subtask 1.2 Design Data Comparison with Requirements

Subtask 1.3 Projected Design Comparison with Requirements.

2.1 Test Data

The primary sources of FPSE test data for Task 1.1 were MTI's Technology Demonstrator Engine (TDE), MTI's "Prototype Engine", and component test rigs. Each of these hardware systems was used for exploratory development at MTI, and they formulated the state of the art for the FPSE during the course of the study.

2.1.1 Technology Demonstrator Engine (TDE)

The TDE is MTI's 1.0 kW FPSE research engine. The engine was developed under a contract with DOE and is currently used as a test bed engine to advance the state of the art of FPSEs. By far, the greatest amount of test data obtained for this study was from the TDE.

The TDE, shown schematically in Figure 2-1, consists of the following major components:

- Free-piston Stirling engine (FPSE)
- Natural gas-fired external heat system
- Linear alternator
- Controls and auxiliaries.

The TDE was designed to meet the following specifications:

- Electrical power output = 1.0 kW
- Operating frequency = 45 Hz
- Engine shaft efficiency ≥ 30%.

This engine system was originally designed and built during 1978-1979 and is equipped with the extensive instrumentation necessary for engine performance evaluation. Figure 2-2 shows the TDE on its test stand.

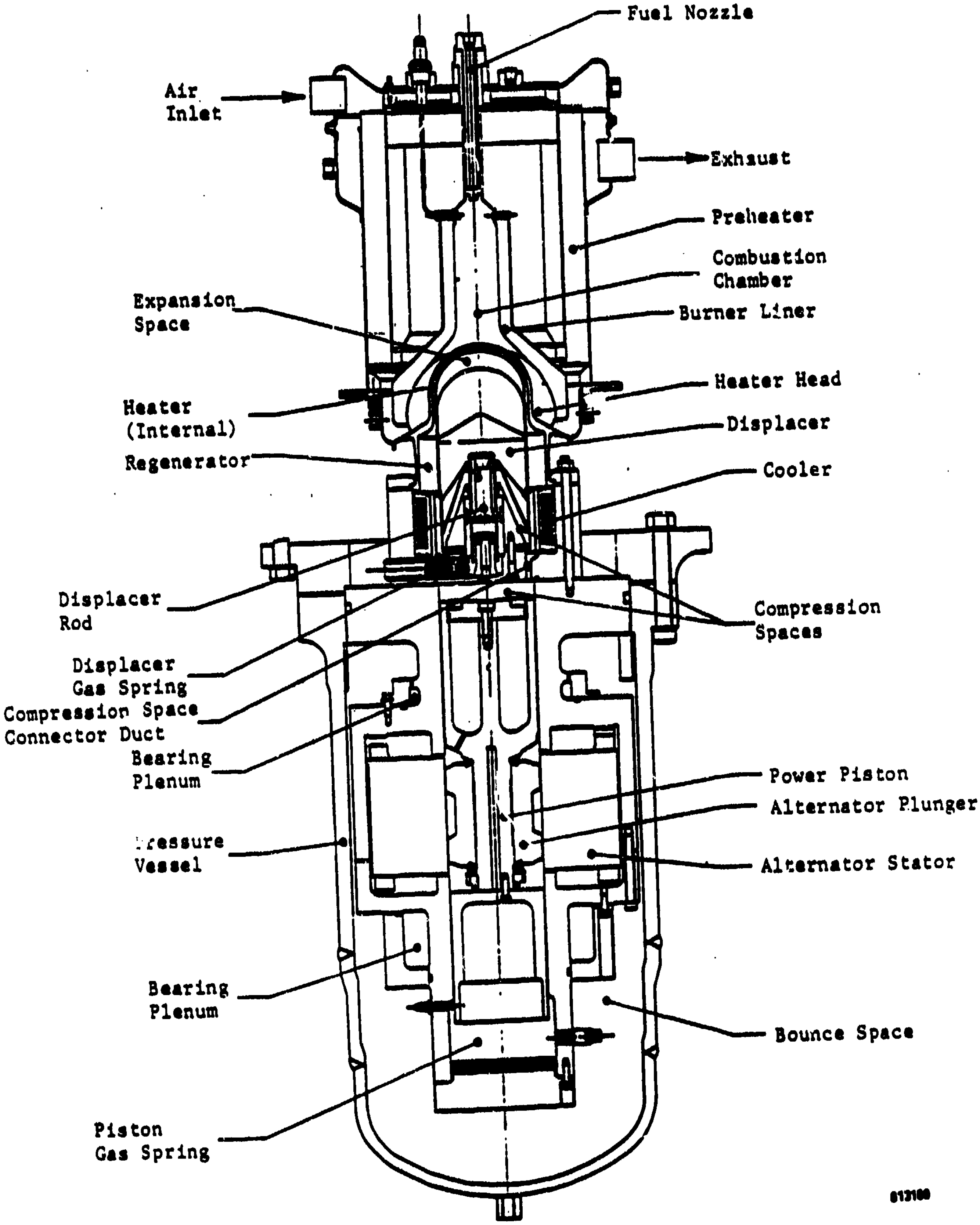

Fig. 2-1 Technology Demonstrator Engine Layout

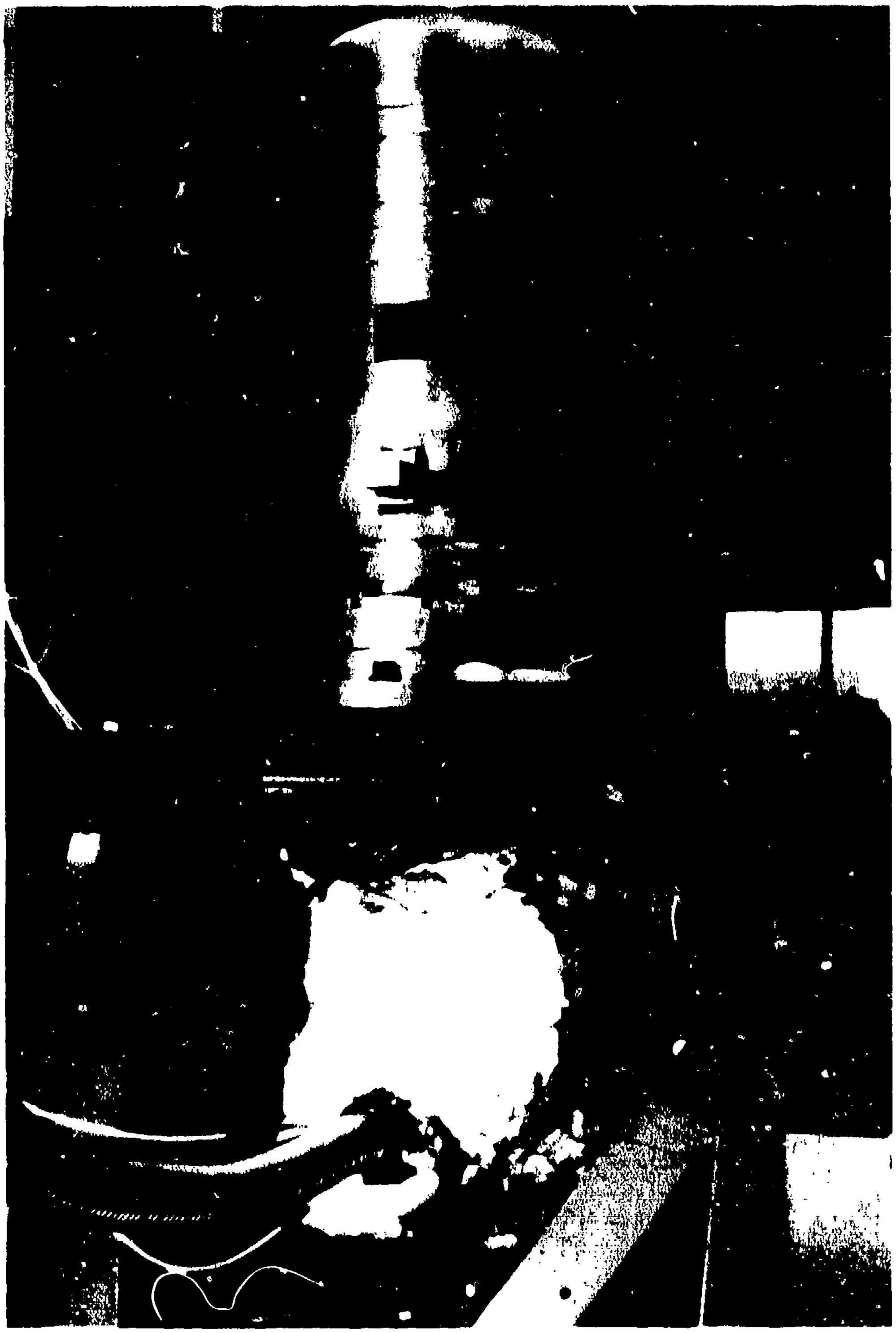

Fig. 2-2 MTI 1-kW_e Technology Demonstrator Engine

2.1.1.1 Engine. The TDE is a free-piston displacer type, or gamma engine, which is thermodynamically similar to conventional Stirling engines except that the piston and displacer motions are controlled by the resonant spring-mass system rather than a fixed mechanical linkage.

Thermodynamics

The thermodynamic elements of the engine consist of an expansion space and a compression space that are connected by three heat exchangers: the heater, regenerator, and cooler. The function of the thermodynamic system is to convert thermal energy into mechanical energy at high efficiency. The expansion space is the volume enclosed by the displacer hot end and cylinder head. The compression space is actually two contiguous volumes. In one, the displaced volume is due to motion of the displacer cold end; in the other, the displaced volume is due to piston motion. The compression space is "isolated" from the expansion space by a clearance seal at the cold end of the displacer and from the "bounce" chamber by clearance seals around the power piston and displacer rod.

Heater

The heater head is a monolithic pressure vessel design which is integral with the annular regenerator pressure wall; see Figure 2-3. This design requires no high-temperature structural weld or brazed joints.

The internal heater is immediately adjacent to the expansion space. Rectangular flow passages and fins are machined into the inside heater pressure wall to enhance the heat transfer process. The inner heater wall is a thin shell which separates the heater from the expansion space. This liner extends past the regenerator down to the cooler. The outside of the pressure wall has been finned to augment combustion gas heat transfer to the head.

Regenerator

The regenerator is an annular porous ring located between the heater and cooler. The regenerator removes and stores thermal energy from the gas as

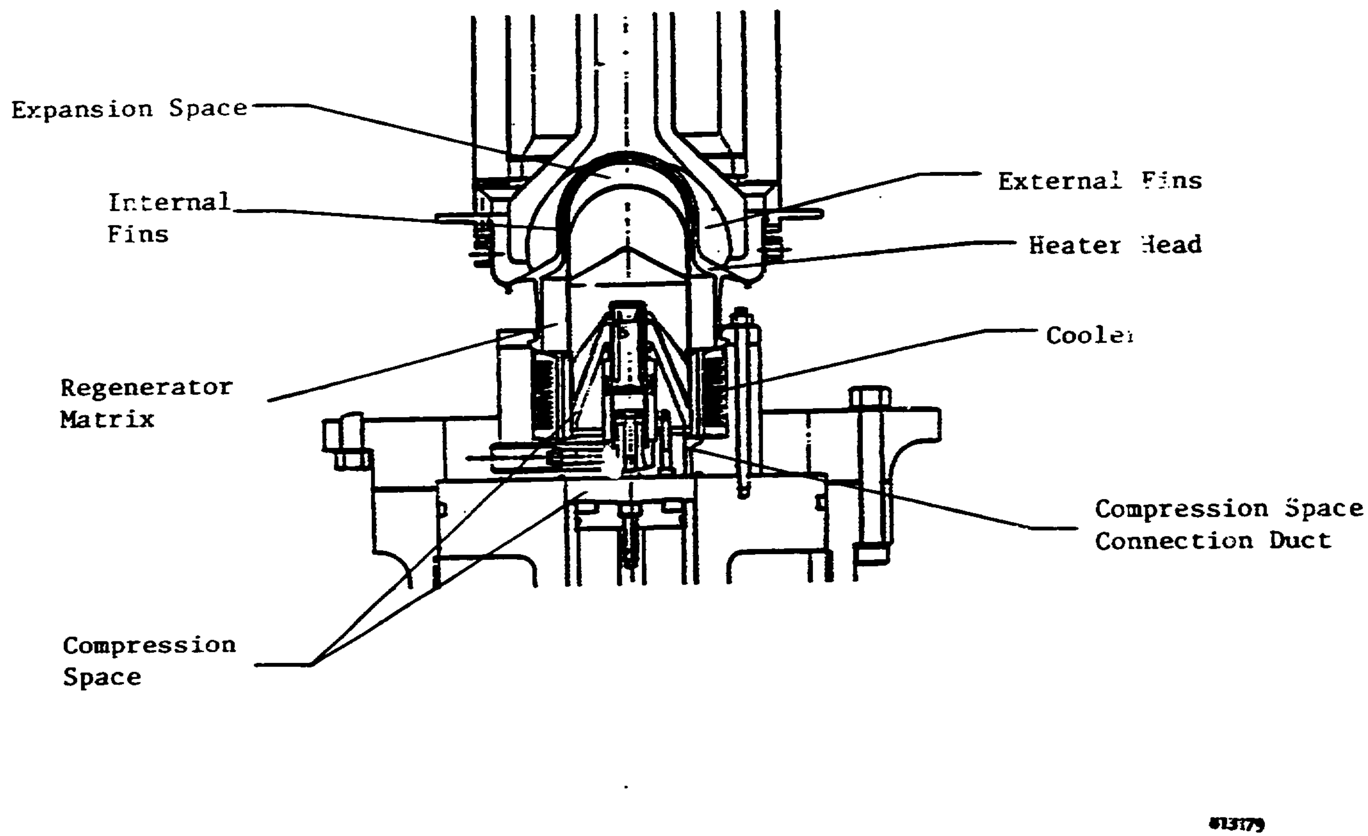

Fig. 2-3 Heat Exchanger Layout

it flows from the heater to the cooler and adds energy to the gas as it flows from the cooler to the heater. The outside regenerator wall is part of the engine pressure vessel and is, therefore, subject to high internal pressure. There is a large thermal gradient along the length of this wall which contributes to the stress level. The wall is tapered to reduce conduction losses by taking advantage of higher material strength at the cold end of the wall. The annular regenerator matrix is made up of individual woven screens made of 1 mm wire and 100-by-100 mesh. The inside wall (displacer cylinder wall) is a thin walled tube which is designed to prevent short circuiting of the heater and regenerator.

Cooler

The cooler, located in an annulus between the regenerator and compression space, rejects heat from the thermodynamic cycle to a closed loop hydronic radiator. The cooler has finned flow passages on the helium side and on the water side. The water side fins also transmit the helium working pressure to a structural cylinder, thus reducing the required thickness and causing a temperature drop in the wall. The cooler helium volume is connected to the compression space volume through the compression space connecting duct.

Dynamics

The TDE has two dynamic components: the displacer and the piston. The dynamic components impose volumetric boundary conditions on the thermodynamic working space, while the thermodynamics impose pressure forces on the dynamic elements.

Displacer

The displacer is guided in the engine cylinder by a gas bearing on the displacer rod. The displacer gas bearing system has demonstrated noncontacting operation between the rod and bearing sleeve. The displacer mass is dynamically coupled to the engine frame by a gas spring designed to balance the net displacer inertia. The pressure difference across the heat exchangers impose a load on the displacer. The power required to drive the displacer is supplied by the thermodynamic cycle pressures acting on the displacer rod area.

Power Piston

The power piston subassembly is the remaining major dynamic element and consists of an engine piston, alternator plunger, gas spring piston, and gas bearing journals. Most of the engine thermodynamic power is delivered to the alternator via the power piston. A piston gas spring is designed to balance the net inertia of the piston subassembly. The power piston is radially supported on either side of the alternator plunger by inherently compensated hydrostatic gas journal bearings.

Gas Springs

The power piston and displacer gas springs provide a portion of the spring force required to resonate the piston and displacer mass at the desired frequency. The gas springs, to the first order, undergo adiabatic processes, although thermal hysteresis, seal leakage, and mid-stroke port leakage result in nonideal spring behavior and losses. The gas springs are provided with mid-stroke ports that provide make-up of net seal leakage flow. These mid-stroke ports stabilize the axial locations of the displacer and power pistons.

The capability of the power piston gas spring to function as the bearing supply compressor is included in the design. A check valve is located between the gas spring and the bearing supply plenum. As the pressure in the gas spring rises above the bearing plenum pressure, the valve opens, supplying gas to the plenum. The gas removed from the spring is made up by mid-stroke port flow.

2.1.1.2 Combustion System. The combustor system consists of the following major components: (See also Figure 2-4)

- Preheater
- Fuel nozzle/swirler cup
- Combustion chamber liner
- Igniter
- External heater head.

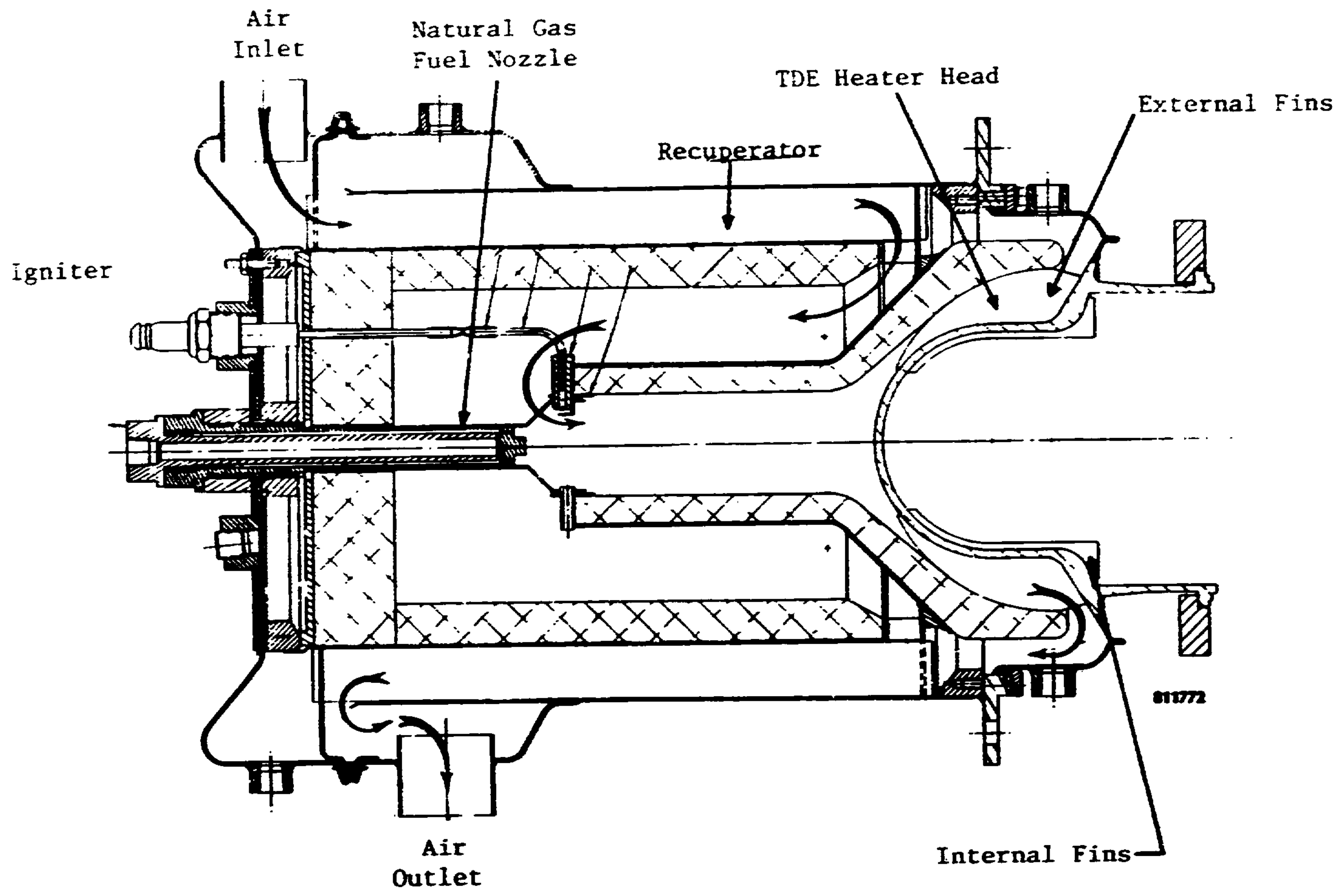

Fig. 2-4 Combustor System Layout

The fuel and air are supplied to the combustor from an external fuel/air control system. The inlet air is preheated by the combustion exhaust in a folded foil preheater. The preheated air enters the combustion chamber through a swirler cup to create a turbulent mixing zone. The fuel is injected through the center of the swirler cup into the combustion zone. The current combustor system is designed to burn natural gas at a peak firing rate of 60K Btuh.

2.1.1.3 Alternator. The alternator, which provides the mechanical piston load, is a flux-switching linear alternator. The basic alternator design is an adaptation of several linear motor designs developed for other MTI projects. The DC coil in the stator provides the basic circulating flux. The moving plunger completes the magnetic path around the DC coil and switches the flux across the double-slot AC coils. The compensating coil in the pole tips on the plunger reduces the AC flux in the plunger, which reduces the inductive reactance of the machine.

The magnetic iron in this machine was fabricated of radially oriented laminations made of Hyperco-50. This material saturates at a higher flux density and has lower eddy losses than conventional magnetic iron. The Hyperco-50 was selected to provide alternator efficiencies in excess of 90%. This high level of operating efficiency was required for the originally intended application - isotope source space power systems.

2.1.1.4 Controls. During normal operations, the engine/alternator system is controlled by two primary control systems: the heat input, or combustor control system; and the power output, or field control system. The former is used to control heater head temperature and the latter to control engine stroke. Both control systems are used for experimental purposes and operate manually.

2.1.2 "Prototype Engine"

The "Prototype Engine" was built under MTI's privately funded product development program. The engine is shown on its test stand in Figure 2-5. The prototype engine incorporated a unique design approach involving a diaphragm

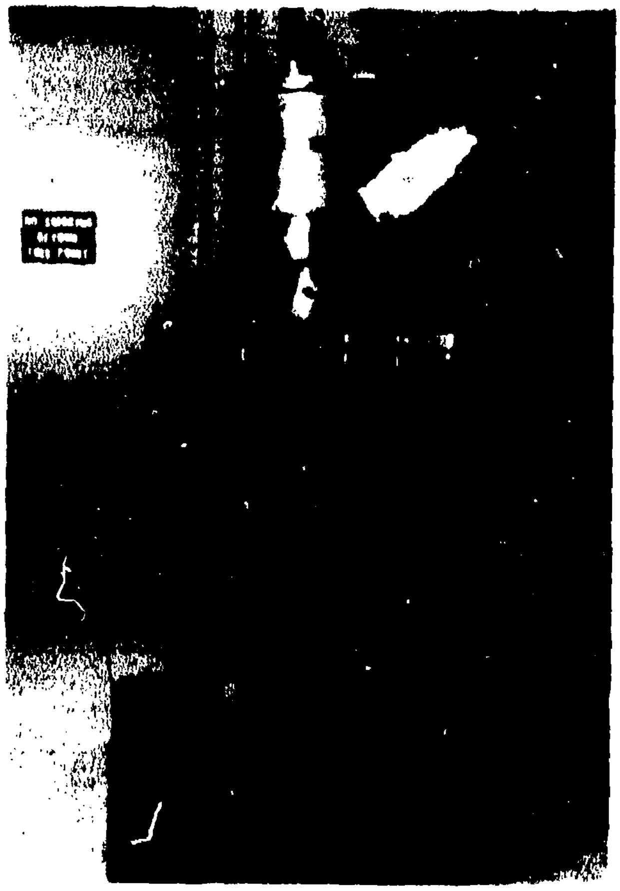

Fig. 2-5 MTI 3-kW_e Prototype Engine

displacer drive system. Unfortunately, the engineering difficulties encountered, while attempting to achieve reasonable levels of power output, more than offset the intended enhancement in engine reliability. Some of the problems associated with diaphragm displacer engines include unavoidably large dead volumes, large heater head structures, and excessive material cost - to name a few. Originally designed to be a 3 kW engine, it failed to develop rated power due to the inherent difficulty associated with scaling diaphragm displacer engines. Furthermore, cost projections showed that engine manufacture would be expensive. Based on this experience, the diaphragm engine design approach was determined by MTI to be inappropriate for power levels above 1 kW, and was subsequently abandoned. The "prototype" engine did, however, operate successfully at part load and as such operational and design characteristics of the "Prototype Engine" are cited in the test comparison results listed in Section 3.0.

2.1.3 Component Test Rigs

Two major component test rigs are used to support FPSE development at MTI. One of these rigs supports combustion system development and the other, alternator development.

The combustion rig, shown in Figure 2-6, consists of a fully instrumented free burning combustor test stand that is used to evaluate combustion processes and characteristics such as efficiency, temperature profile, emissions, and flame stability.

The alternator test rig is a vibration motion amplifier that has the capability to test alternators up to 20 hp and at strokes of 1.0 inch at frequencies of up to 60 Hz. A picture of the alternator test rig is shown in Figure 2-7.

2.2 Design Data

Under its FPSE product development program, MTI is developing an advanced development prototype system called the Engineering Model (EM). During the course of this study, most of the EM component designs were completed, some were already fabricated, and still others were undergoing initial testing.

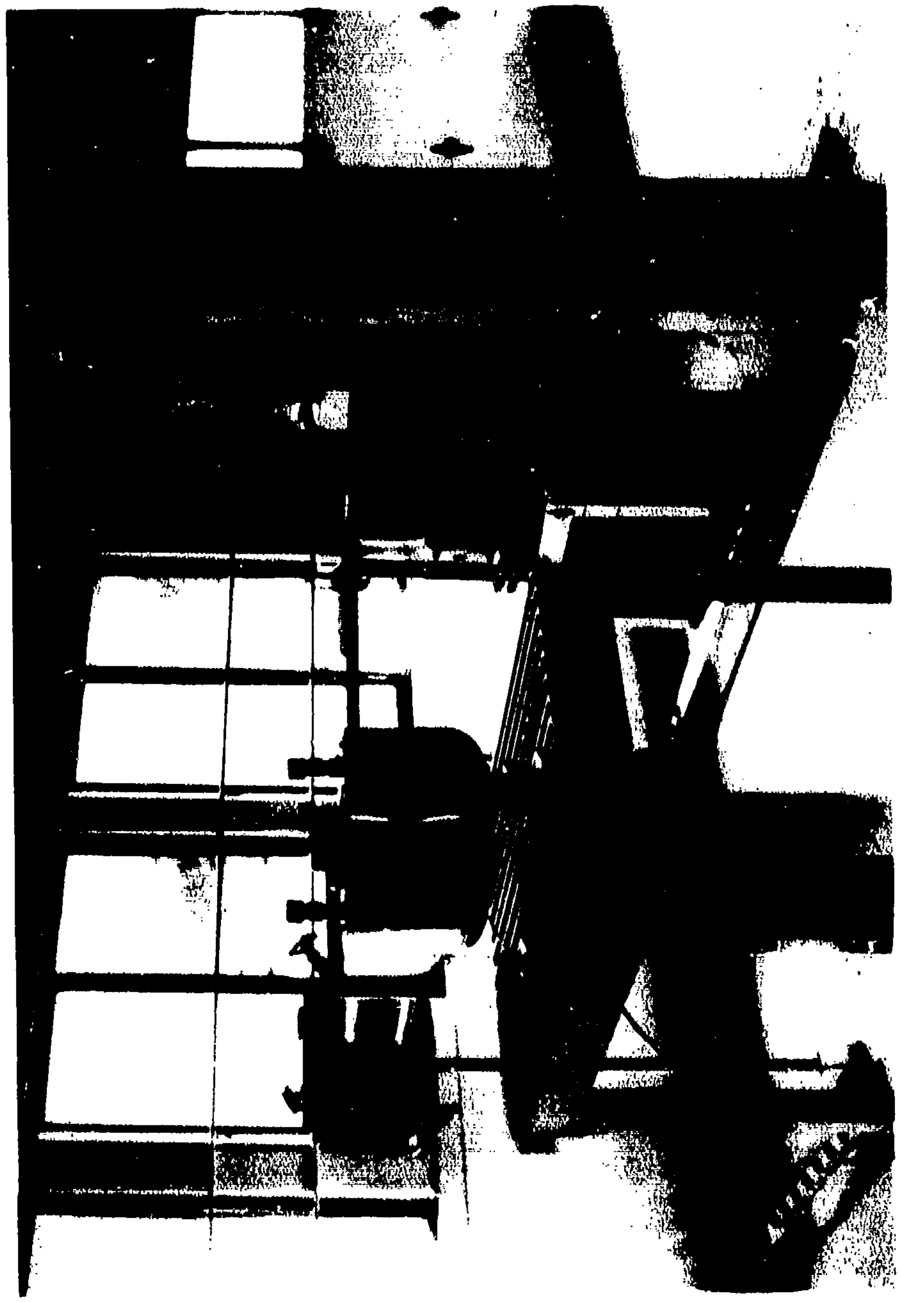

Fig. 2-6 Combustion Rig

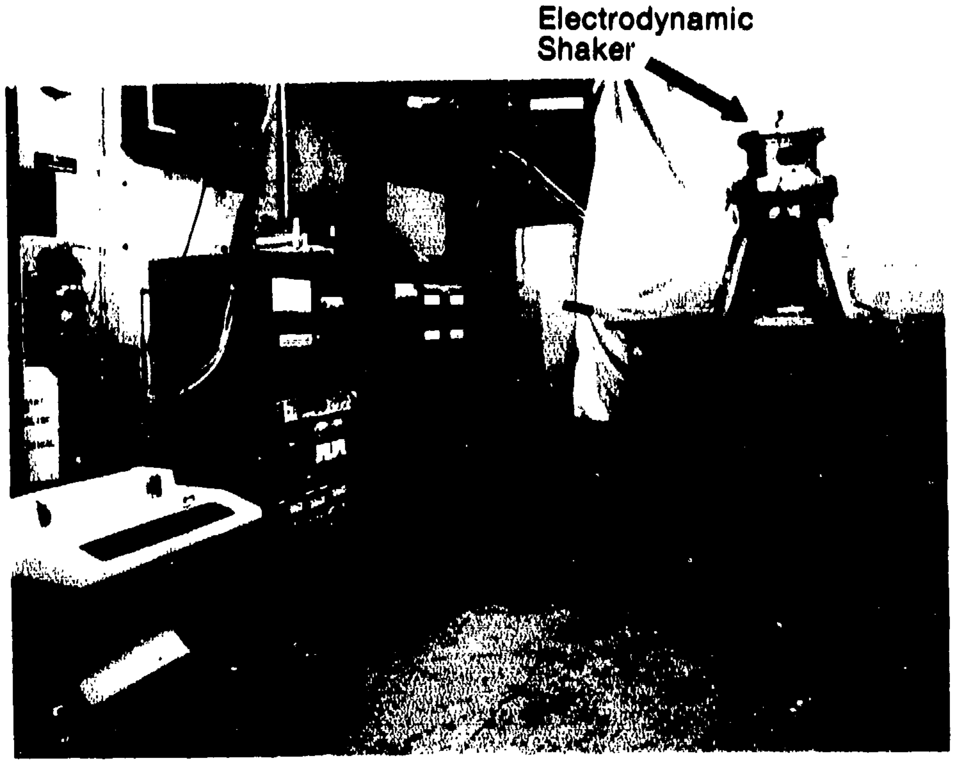

Fig. 2-7 Linear Motor/Generator Test System

The EM, therefore, represents the state of the art in FPSE design and was used as a source of design data for comparison under Task 1.2 of this study. Furthermore, since the EM design is fixed but not yet fully fabricated, it formulates a precise definition of the term "design data", as interpreted in this study. Additionally, it provides a clear distinction between the design data and the design projection evaluated under Task 1.3.

2.2.1 The Engineering Model System

2.2.1.1 The Engineering Model Engine/Alternator System. The Engineering Model is a full packaged self-contained 3 kW diesel fuel fired generator system built around the engineering model engine/alternator unit. The system is designed to provide 120 V, 1ϕ, 60 Hz power quietly, reliably, efficiently, and with excellent regulation. Ease of operation, ruggedness, and minimal maintenance are specified design goals. The power control system, a critical element of any free-piston generator system, is designed to provide the transient response and steady-state regulation capabilities. The system includes the following major subsystems:

- Combustor
- Combustor control system
- Engineering Model engine/alternator unit
- Cooling system
- Power control system.

The EM system is envisioned in its packaged configuration in Figure 2-8. A description of the engine/alternator unit and the power control system are provided below.

The EM Engine/Alternator Unit

The EM engine/alternator unit is a single cylinder free-piston displacer type engine driving a "partially saturated plunger" linear alternator. The EM is shown with a temporary, oversized combustor unit in Figure 2-9. The complete EM will have a compact combustor and will be about two thirds the length of the unit shown in Figure 2-9. The engine utilizes only hydrostatic gas bearings and clearance seals in its displacer and piston drive system for long life and high reliability. The basic engine layout and

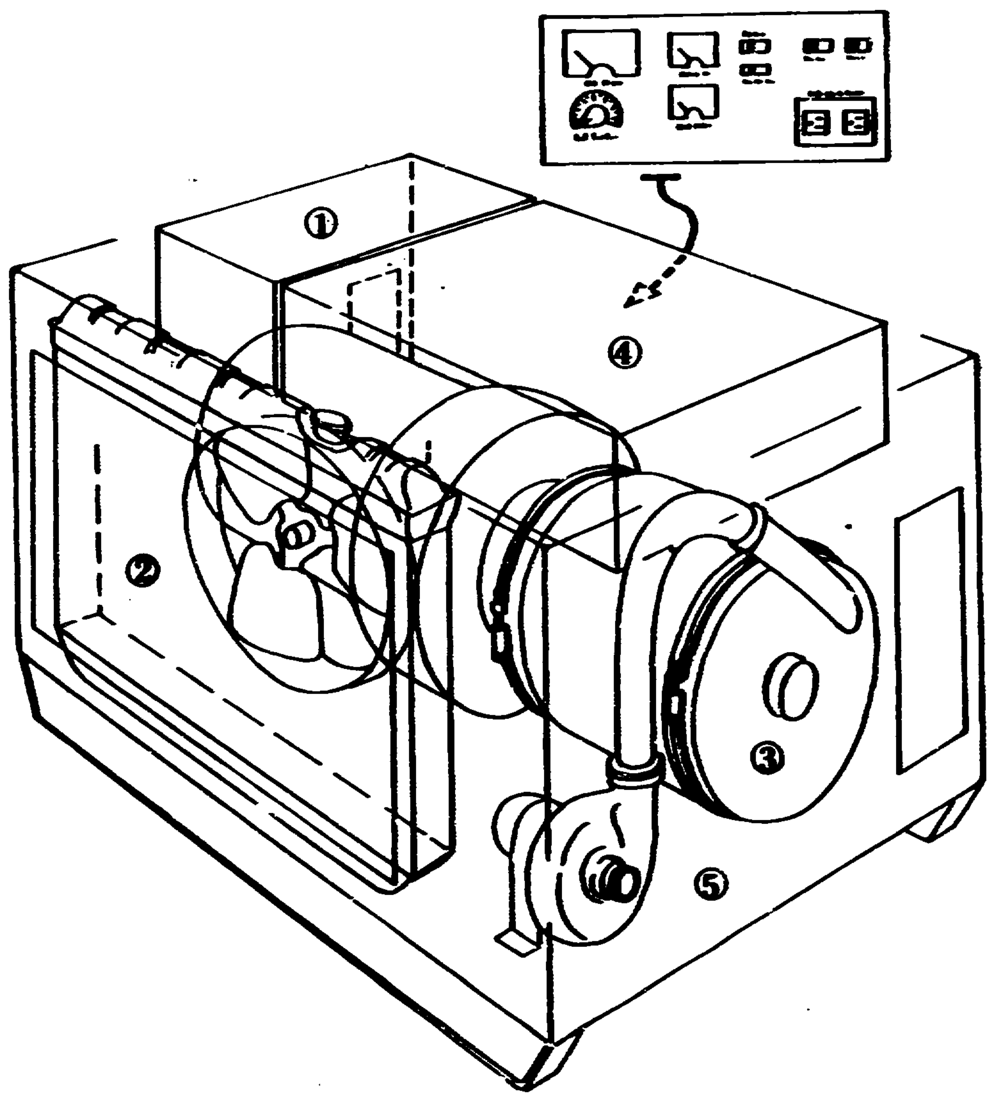

Fig. 2-8 Engineering Model in a Package Unit

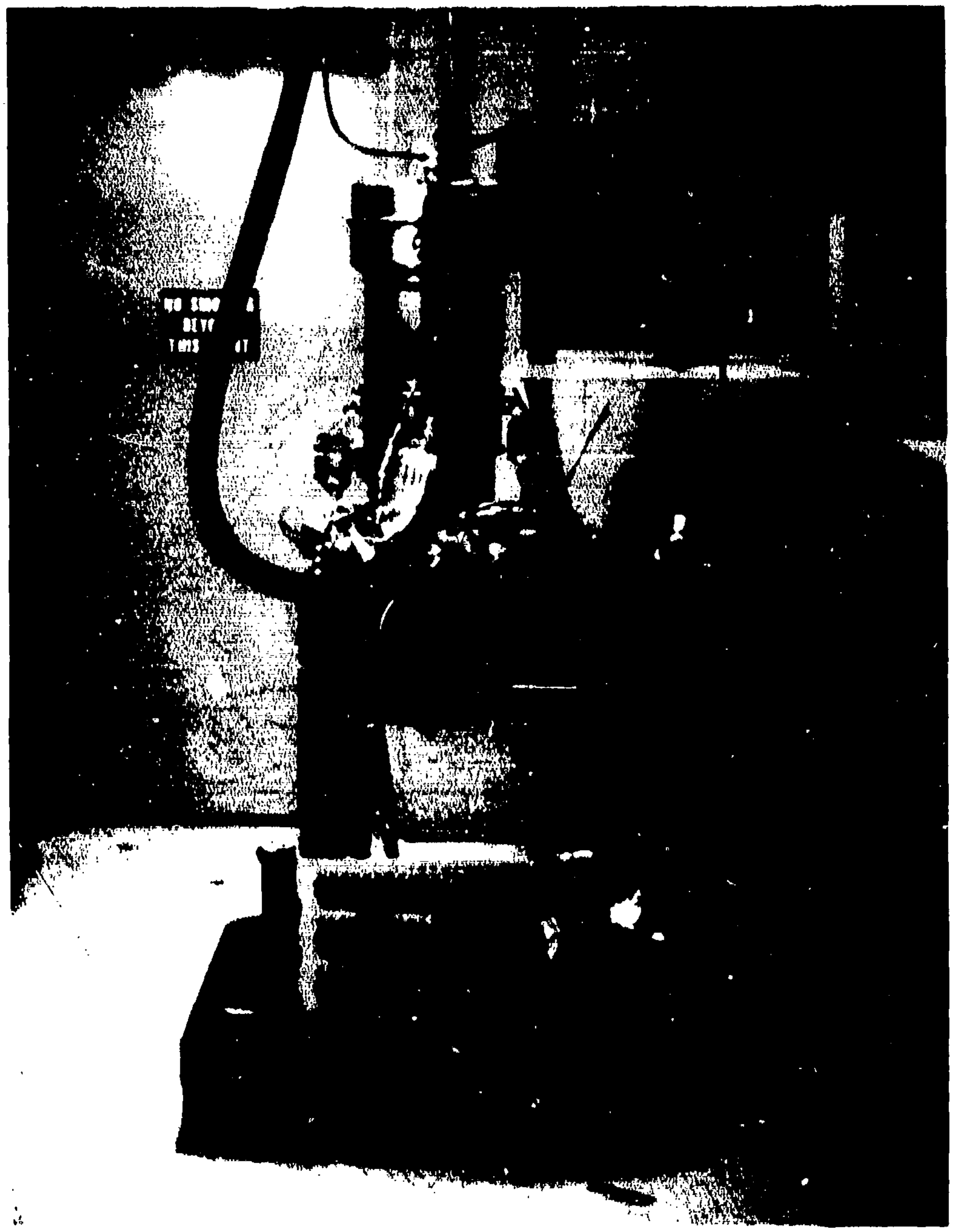

Fig. 2-9 EM Engine/Alternator on Test with Temporary Combustor

structure are extensions and improvements of the work accomplished with the Technology Demonstrator Engine. The engine is composed of three major components and subsystems:

- Heater head
- Displacer system
- Alternator system.

The heater head for the engineering model is a monolithic nickel-based alloy casting with integral internal and external fin geometries. It is a simple rugged component designed to provide a rated power operating life of greater than 10,000 hours.

The displacer drive consists of the displacer body and dome, fully gas bearing displacer rod, and displacer gas springs. The displacer body contains the displacer cylinder clearance seal. The displacer drive system and the resulting dynamics are critical to the performance of the engine power control system. As such, a proprietary design innovation has been implemented to ensure that the displacer achieve a desirable dynamic state.

The linear alternator consists of a 0.5 inch thick cylindrical plunger which reciprocates between inner and outer cylindrical stators. A DC field coil generates a toroidal flux path linking both the inner and outer stators. The toroidal flux path passes through the two magnetically active rings on the plunger in passing into and out of the two stators. Consequently reciprocating the plunger causes the flux toroid to move axially along the stator. As it does so, its sinusoidally links and unlinks four physically separate AC output coils. The AC coils are electrically connected and act as one single output coil providing alternating AC voltage and power.

This above linear alternator configuration is referred to as a "partially saturated plunger" alternator because of the magnetic characteristics of the plunger design. It was chosen for the engineering model because it is relatively rugged and has a low plunger weight. The light plunger weight allows operation of the EM at 60 Hz without the use of an auxiliary piston gas spring, resulting in the potential for achieving a higher overall efficiency.

As configured for testing during the 1982 time frame, the EM will have the following specifications:

- Overall efficiency = 25%
- Rated net electrical power output = 3.0 kW
- Charge pressure = 60 bar
- Heater head temperature = 1400°F
- Ambient air temperature = 95°F.

2.3 Projected Design

As stated, the EM represents the state of the art of FPSE technology that has yet to be verified through system testing. The EM, however, was designed for civilian commercial applications and could not be expected to meet military requirements for ground power in every respect. The variance, then, between the EM and military requirements formulates the basis for making design projections to determine the level of difficulty involved in modifying the EM system to meet those requirements. Hence, all projected design calculations were based on using the EM as a reference design to which evolutionary changes or design extensions could be made. Items involving significant technical advancements are identified as such. The projected design is referred to as the Advanced Development Prototype (ADP).

SECTION 3.0

PARAMETRIC COMPARISON WITH REQUIREMENTS

3.0 PARAMETRIC COMPARISON WITH REQUIREMENTS

The military requirements for ground power were identified from each of the referenced standards and specifications documents, and were further assembled into the following separate categories:

- Physical
- Thermodynamic
- Audio
- Material
- Operational
- Electrical.

Suitable parameters were then selected for each category to enable a quantifiable evaluation of test data, design data, and design projection to be made relative to the requirements. This section details the results of that parametric comparison.

SUBSECTION 3.1

PHYSICAL PARAMETERS

3.1 Physical Parameters

Physical parameters were identified as the nonoperational system parameters including size, weight, orientation, and shock and vibration. A summary of the physical parameters comparison is listed in Figure 3-1. As indicated, both the system size and weight would have to be reduced for the projected Advanced Development Prototype (ADP). In fact, technology advancement is required to advance the state of the art of linear alternators to achieve lightweight design capability.

3.1.1 Size

Requirements

The purchase description for a 3 kW Stirling engine power plant requires that the total system volume not exceed 12 cu. ft.

Test Data

The 1 kW TDE is not a fully packaged system. However, the combustor/engine/alternator unit has an overall length of 53 in. and an overall diameter of 19 in. yielding a total volume of 8.7 cu. ft.

The 3 kW "Prototype Engine" has an overall length of 40 in. and an overall diameter of 12 in.

Design Data

The EM system, as configured in Figure 3-2, has an overall volume of 14.5 cu. ft. The EM, however, is being designed for laboratory development requiring easy access of components and space for instrumentation.

The orthogonal views depicted in Figure 3-3 indicate the locations and relative sizes of the major system components. The engine unit and control system, which account for the largest single volume elements, are 2.5 cu. ft. and 2 cu. ft respectively. The coolant system radiator has dimensions of 24 in. x 17 in. x 2.25 in., accounting for an additional 0.5 cu. ft.

Parameter	Test Data[2]	Design[1]	Projection[1]	Requirement
Size	40 in. × 12 in. dia.	28 in. × 32 in. × 26 in. 14.5 cu ft	11.5 cu ft	12 cu ft
Weight	466 lb_m	485 lb_m	411 lb_m[3] 300 lb_m[4]	300 lb_m
Orientation	Tested Flame Up and Flame Down	Operational up to 41°	Operational up to 38°	31° from Horizontal
Mechanical	N/A	Mounts and Frame Designed to Meet Specifications	Mounts and Frame Designed to Meet Specifications	18 in. Drop 6 in. Drop

[1]Total system
[2]3-kW engine/alternator component (PE)
[3]With lightweight control systems
[4]With lightweight alternator

Fig. 3-1 Comparison of Physical Parameters

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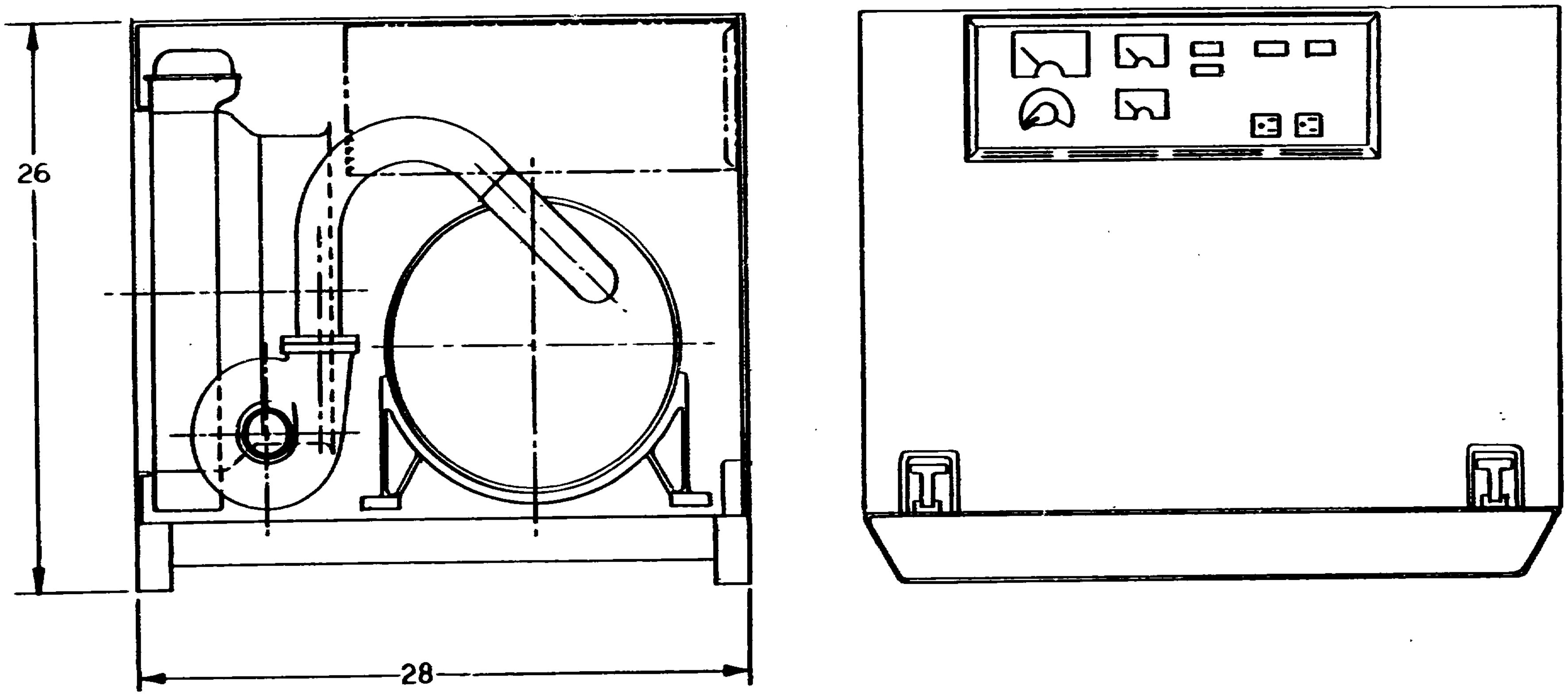


Fig. 3-2 MTI 3-kW Engineering Model System

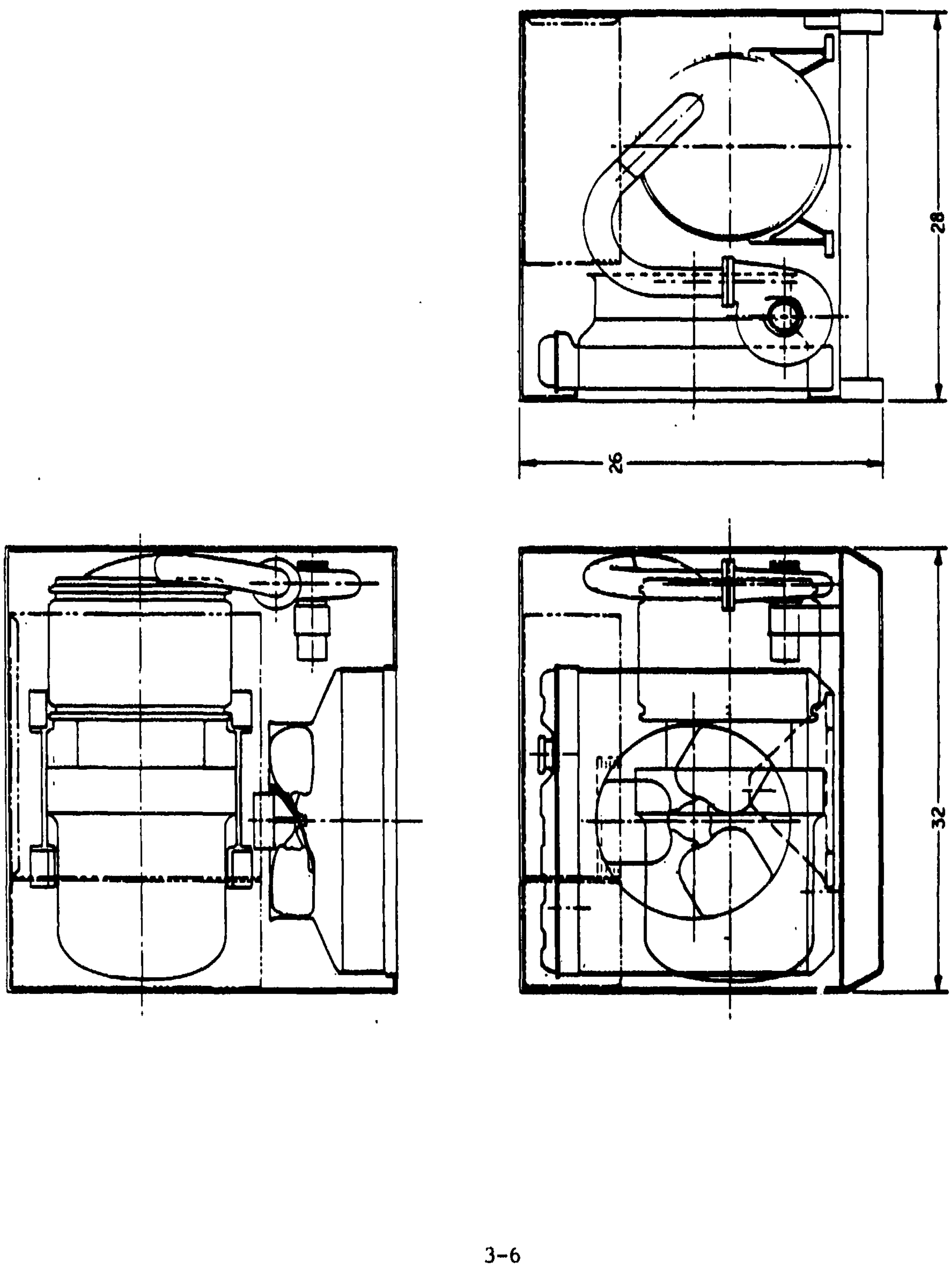


Fig. 3-3 Major Components of EM System

Projected Design

A volume of 11.5 cu. ft. is projected for the ADP. This projected volume reduction was accomplished by improving the design of the coolant radiator and control system, and by implementing a packaging scheme that is more appropriate for a commercial system. Details of the cooler radiator system redesign are given in Table 3-1. An air-cooled engine design is also being considered. As indicated, the size improvement is achieved at the sacrifice of additional parasitic power required. Improvements to the control system are listed under the next section discussion on system weight. The projected system configuration for the ADP is depicted in Figures 3-4 and 3-5.

3.1.2 Weight

Requirements

MIL-STD-1332B requires that the maximum dry weight for a 3 kW generator set not exceed 300 lb. (Maximum dry weight is the weight of the generator set less fuel, coolant, lubricant, electrolyte, and optional equipment as specified in MIL-STD-633.)

Test Data

The 1 kW TDE has an overall (nonsystem) weight of 482 lb. The subassembly weights are:

Combustor	42 lb	
Engine	365 lb	
Alternator	75 lb	(including the alternator pressure vessel)
Total	482 lb	

The 3 kW "Prototype Engine" has an overall weight of 466 lb. The subassembly weights are:

Combustor	71 lb	
Engine	130 lb	
Alternator	265 lb	(including the alternator pressure vessel)
Total	466 lb	

TABLE 3-1

COOLING SYSTEM SPECIFICATIONS

Parameter	Engineering Model	Advanced Development Prototype
Heat Rejection Rate	20,000 Btuh	20,000 Btuh
Peak Water Temperature	125°F	125°F
Ambient Temperature	90°F	90°F
Radiator Specifications		
No. of tube rows	29	29
Tubes per row	3	3
Tube width	0.625 in.	0.625 in.
Tube height	0.076 in.	0.076 in.
No. of fins per inch	13	13
Fin thickness	0.0025 in.	0.0025 in.
Fin height	0.5 in.	0.5 in.
Core dimensions	17 in. x 24 in. x 2.25 in.	17 in. x 17 in. x 2.25 in.
Weight	13 lb	13 lb
Radiator Fan	TORIN N-1424-3 (A = 14 in., B = 2.97 in.)	TORIN N-1624-4 (A = 16 in., B = 3.5 in.)
Speed	1140 rpm	1140 rpm
Head	0.2 in. H_2O	0.27 in. H_2O
Air Flow	640 cfm	1142 cfm
Fan motor power	75 W	180 W
Water Pump		
Water flow	13.26 gpm	13.26 gpm
Head	3.5 psi	4.0 psi
Pump/motor efficiency	25%	25%
Pump motor power	90 W	105 W

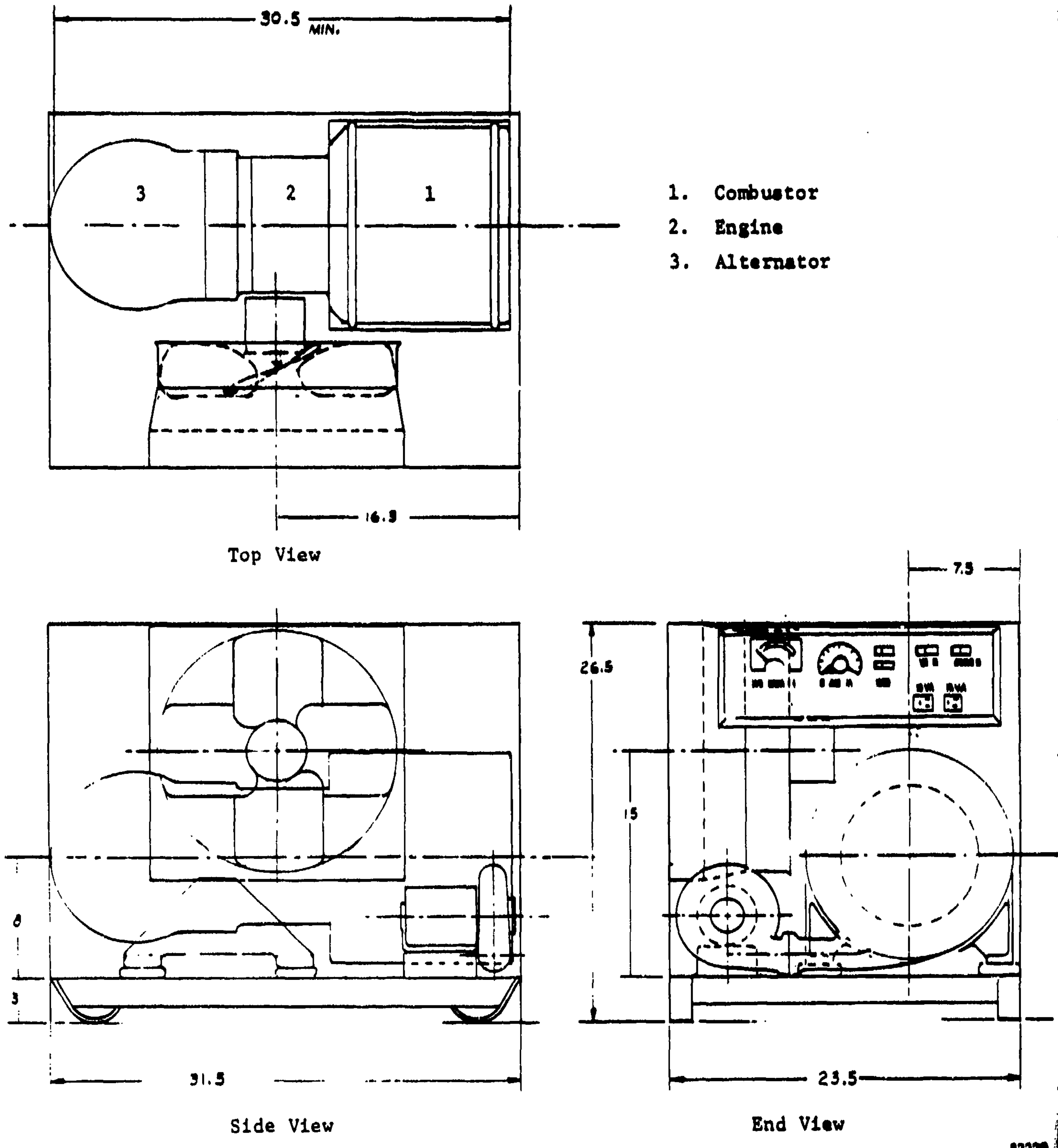


Fig. 3-4 ADP Projected System Configuration

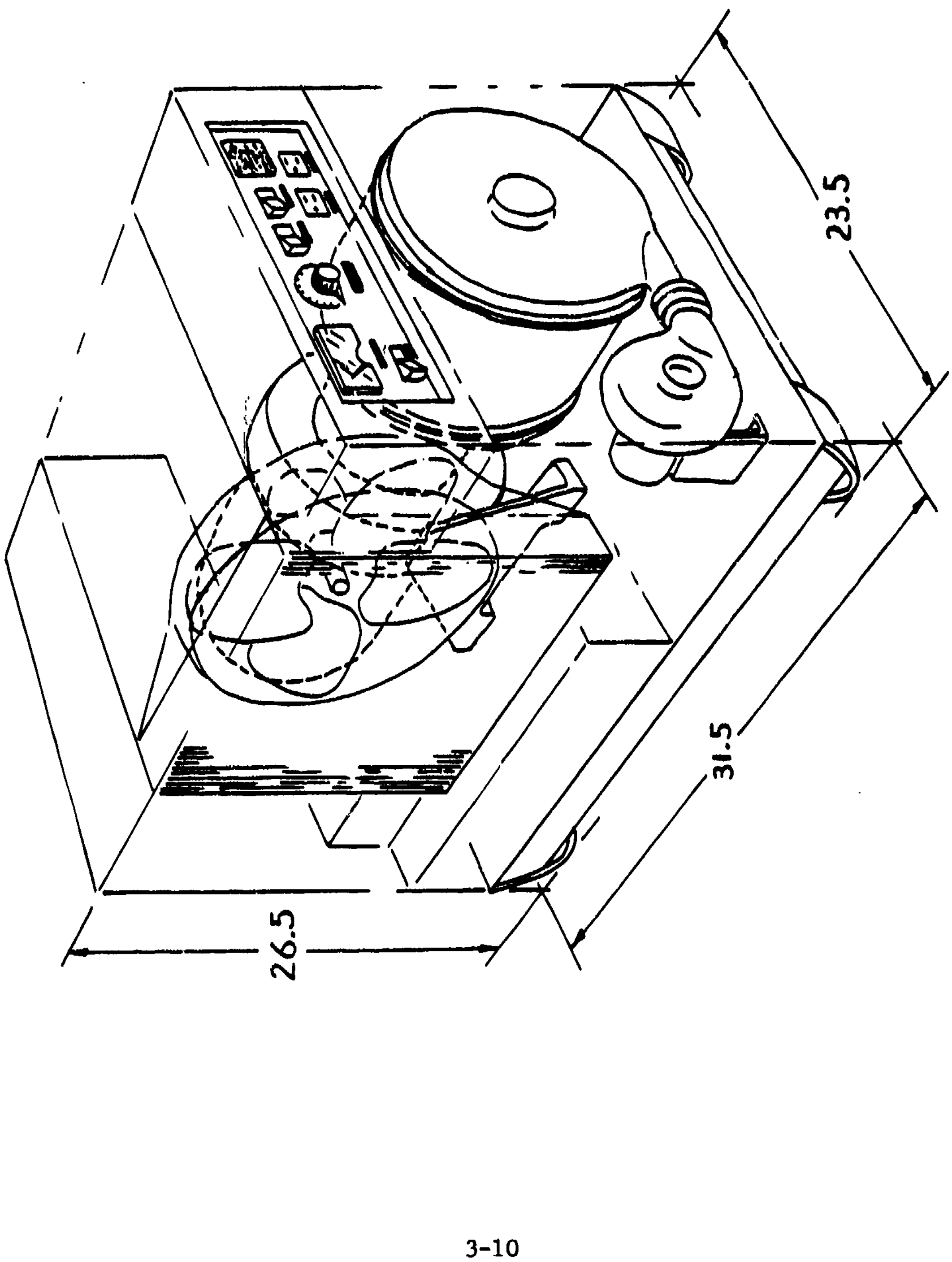


Fig. 3-5 ADP Configuration

Design Data

The Engineering Model System has a total design weight of 485 lb, and is comprised of the subsystem weights listed in Table 3-2.

The EM unit and controls account for over 88% of the total weight. The EM unit, however, was originally designed as a stationary engine for residential application without being overly concerned for engine/alternator weight. (Figure 3-6 shows the weight breakdown accounting for the EM unit.) It should be noted that the control system and auxiliaries consist of laboratory-class hardware that has not yet been value-engineered for a production unit.

Projected Design

The EM system was designed as a laboratory demonstrator of a commercial stationary power generator for which low weight was not a major criterion. Nevertheless, low weight is an important criterion for military power plants. Therefore, the projected ADP design concentrated on achieving the 300 lb military specification.

As indicated in Table 3-2, two major subsystems account for two-thirds of the total EM system weight - the linear alternator and the control system.

In keeping with the need for improvement in linear alternator specific power, a detailed investigation of the FPSE generator system was made and an advanced lightweight linear alternator was designed under the MTI product development program. This advanced alternator, based on proven motor technology, will result in an overall system weight reduction of 111 lb. Figure 3-7 depicts the envisioned lightweight ADP engine-generator configuration. The figure indicates the volume (and mass) reduction provided by the lightweight alternator concept.

The control system is the second major subsystem that was examined for potential weight reduction. Because the EM control system has not yet been fabricated, nor completely detailed, it is difficult to project the ultimate control system design. Nonetheless, there is some basis to speculate that the final configuration could weigh substantially less than the present EM

TABLE 3-2

ENGINEERING MODEL, SYSTEM WEIGHT BREAKDOWN

Subsystem	Dry Weight (lb)	
Combustor		42
Engine		61
Alternator Components		
Plunger	6.5	
Stator	118.5	
Press. Vessel	60	
Adaptor Plate	26	
Total Alternator System		211
Cooling System		13
Fuel System		12
Controls & Auxiliaries		116
Frame		30
Total EM System		485

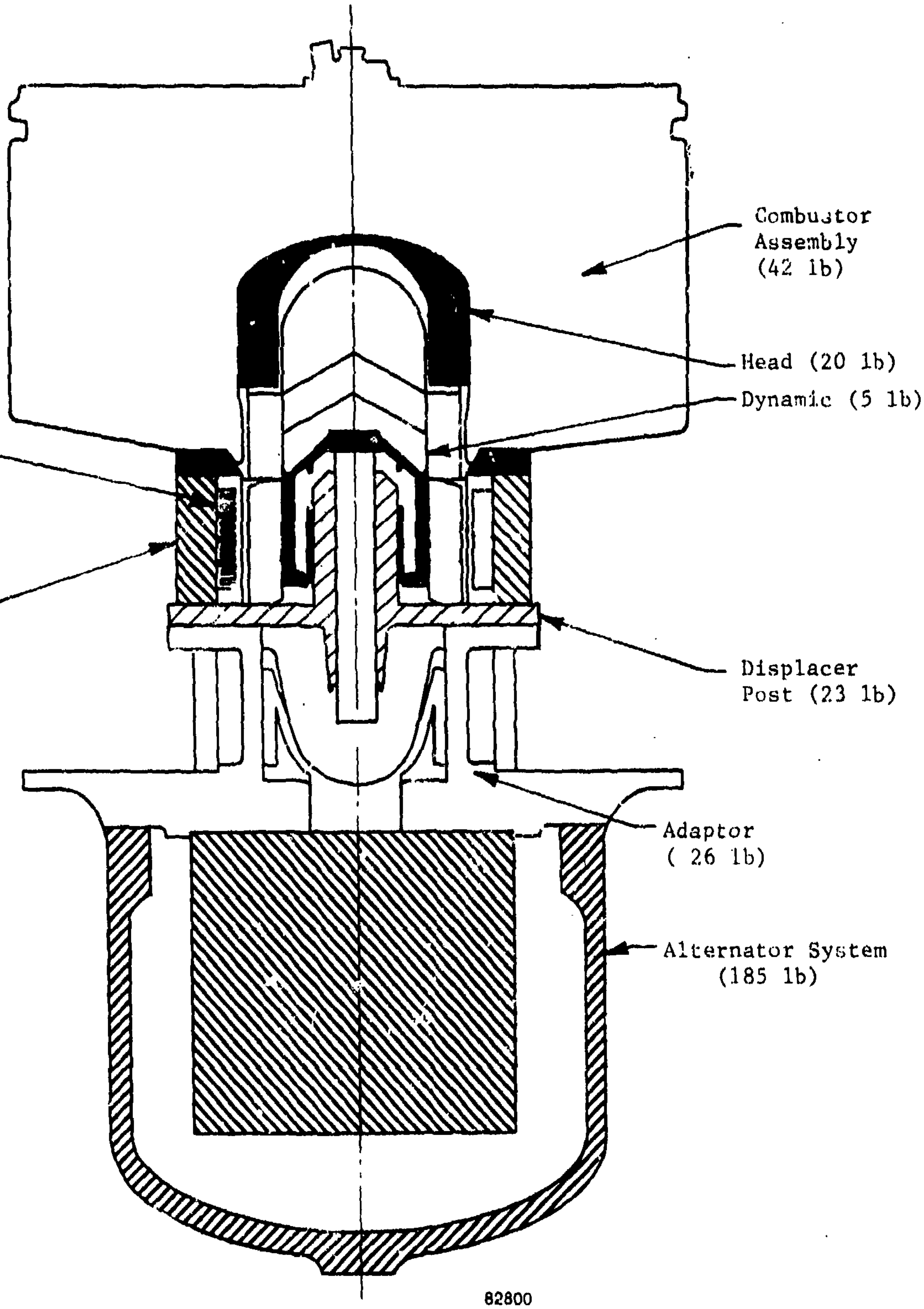


Fig. 3-6 EM Unit Weight Distribution

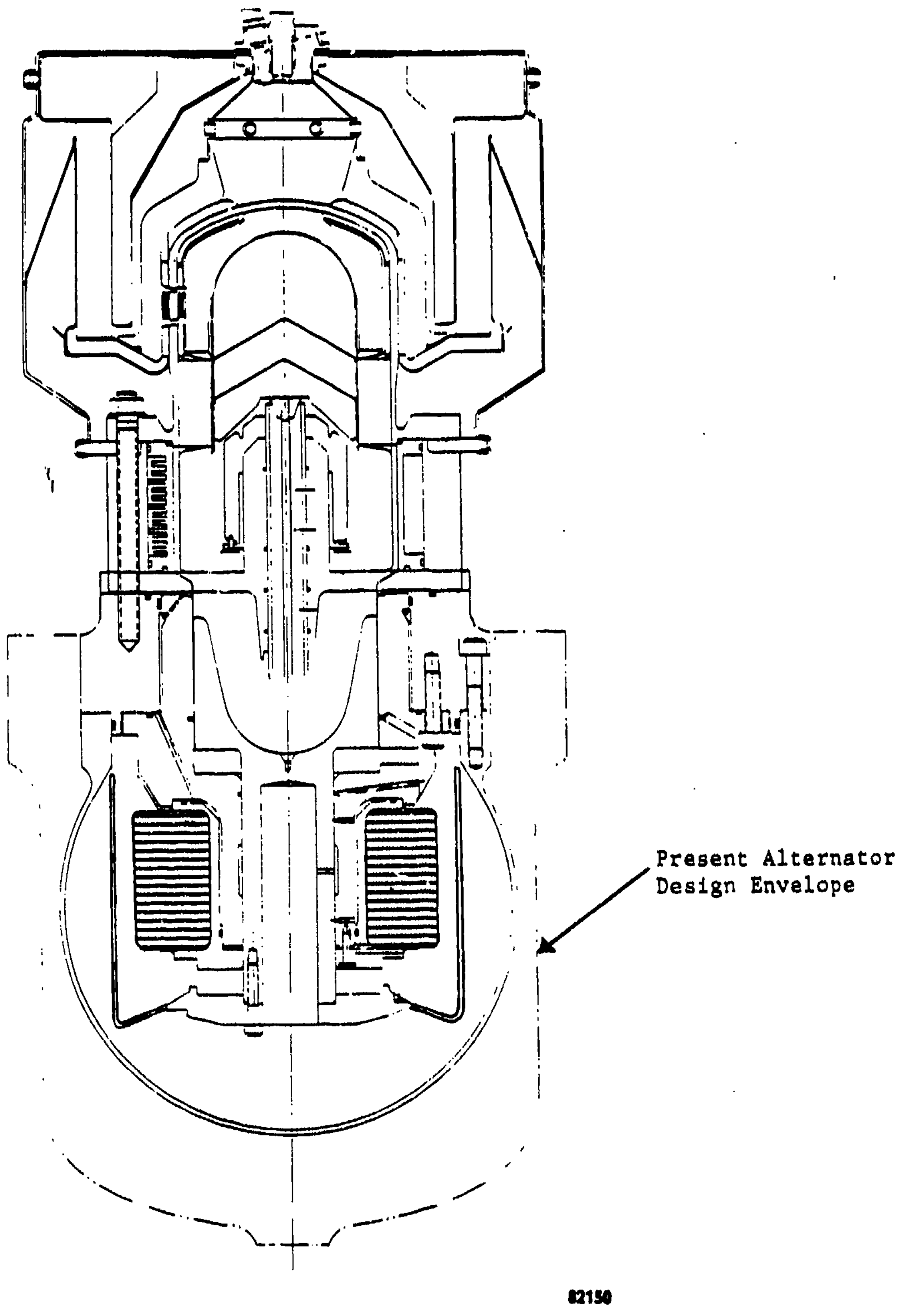


Fig. 3-7 Lightweight 3-kW_e FPSE/Alternator

control system components. Specifically, three items could result in substantially lower control system weight. Table 3-3 lists the control system elements as specified for the EM and compares these with projected requirements for the ADP. As indicated, the three components of specific interest for weight reduction are the starter battery, the power supply, and the capacitor.

The FPSE starts quite easily requiring only small amplitude displacer oscillation and a warm heater head to produce positive power output. Therefore, it is possible that a lower power energy supply would be used for start-up.

Commercially available power amplifiers utilize heavy magnetic components to provide the proper signal filtering characteristics. Due to the high magnetic quality that is inherently designed into linear motors, it is possible that much of the power supply magnetics could be eliminated, thereby reducing system weight by nearly 25 lb.

A capacitor is required for the EM control system to compensate for the inductive reactance associated with linear alternator field coils. The ADP, however, would employ a permanent magnet type of linear alternator that might not require capacitive compensation in the control system. Elimination of the capacitor would save an additional 25 lb in total system weight.

Other design areas that show potential for weight reduction simply involve a conscious effort to eliminate unnecessary mass. The following FPSE design elements, shown in Table 3-4, have been identified for possible weight reduction in the ADP.

In total, the ADP system can be designed to meet the military specification for maximum weight. Table 3-5 indicates the design changes required from the EM to the ADP to achieve the overall weight goal of 300 lb.

TABLE 3-3

CONTROL SYSTEM ELEMENTS AND PROJECTED ADP REQUIREMENTS

	Weight for EM Design (lb)	Weight for ADP Design (lb)
Electronic Control	4	4
Current Sensor	1	1
Parasitic Load Switch	5	4
Power Supply	35	10
Auxiliaries	20	15
Battery	10	5
Electronic Power Supply	5	5
Converter	15	12
Transformer-Rectifier-Filter	6	5
Capacitor	15	-
Total	116	61

TABLE 3-4

FPSE DESIGN ELEMENTS AND POSSIBLE WEIGHT REDUCTION

FPSE Design Element	Weight Reduction (lb)
Combustor	- 7
Displacer Drive	- 5
Heater Head	- 1
Displacer Post	- 1
Total	-14

TABLE 3-5

DESIGN CHANGES REQUIRED TO ACHIEVE WEIGHT GOAL

Subsystem	EM Subsystem Weight	Component Weight Reduction	ADP Subsystem Weight
Combustor	42	-7	35
Engine	61	-7	54
Alternator	211	-111	100
Cooling System	13		13
Fuel System	12		12
Control System	116	-55	61
Frame	30	-5	25
Total	485	-185	300

3.1.3 Orientation

Requirements

The 3 kW Stirling Engine Purchase Description requires that the system configuration and the center of gravity shall be such that tipping will not occur when the unit is tilted 31°.

Test Data

The TDE and "Prototype Engine" have not been configured as total systems. However, the "Prototype Engine" was operated in both the combustor-up and the combustor-down positions with no discernible difference in operating characteristics. Furthermore, the gas bearing stiffness is such that the effects of gravity are small in comparison to the thermodynamic forces. It is, therefore, anticipated that orientation will have no effect on the engine/alternator performance.

Design Data

The centroid was calculated for the EM system as illustrated in Figure 3-8. A 31° tilt from the horizontal position was considered for the least stable configuration. Even under the conditions illustrated, a calculated restoring moment of 1697 in.-lb resulted. Hence, the EM would operate without tilting in such an orientation.

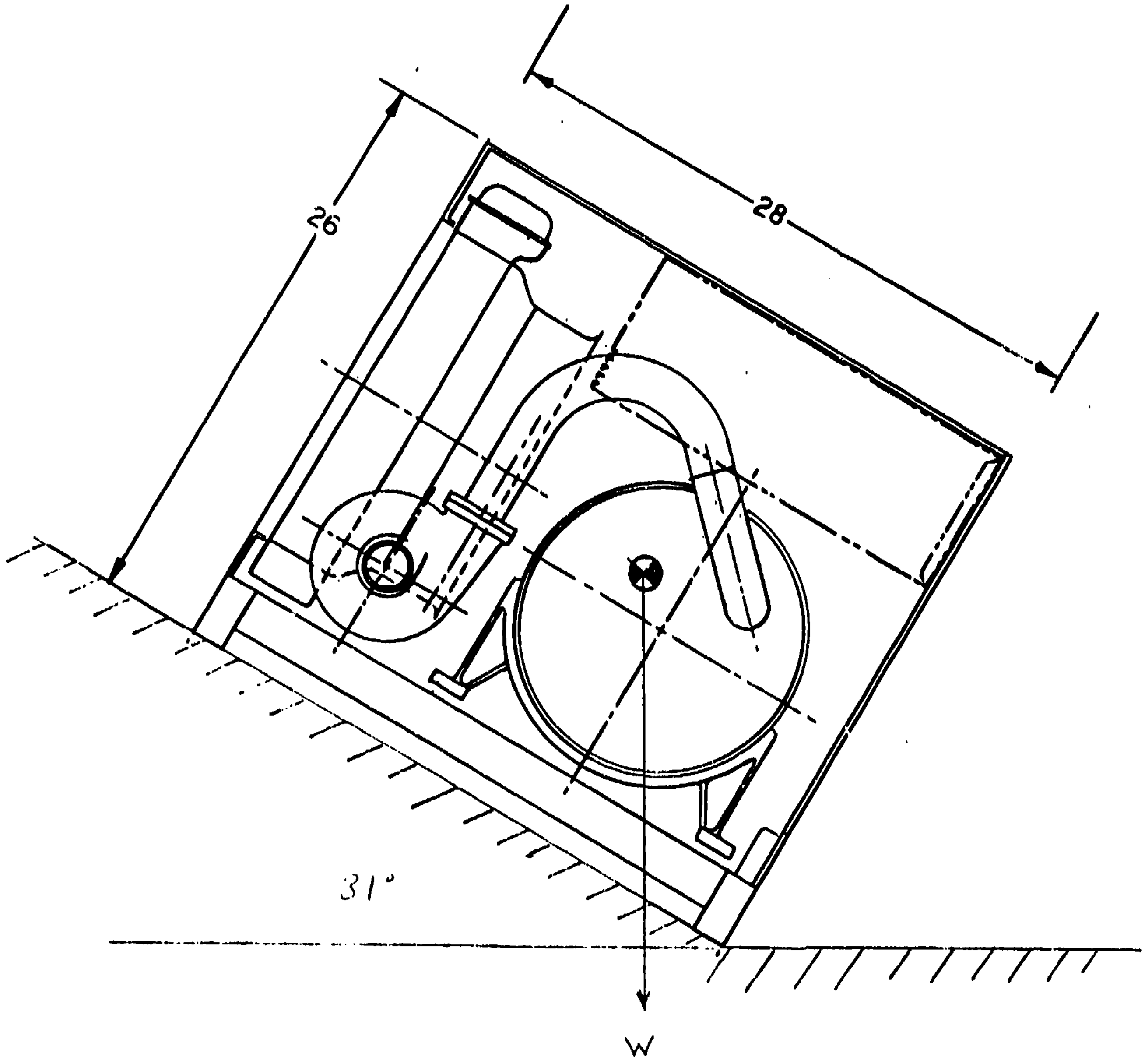
Projected Design

The centroid for the ADP is shown in Figure 3-9. With a 31° tilt, the ADP would be stable, having a restoring moment of 780 in.-lb.

3.1.4 Mechanical

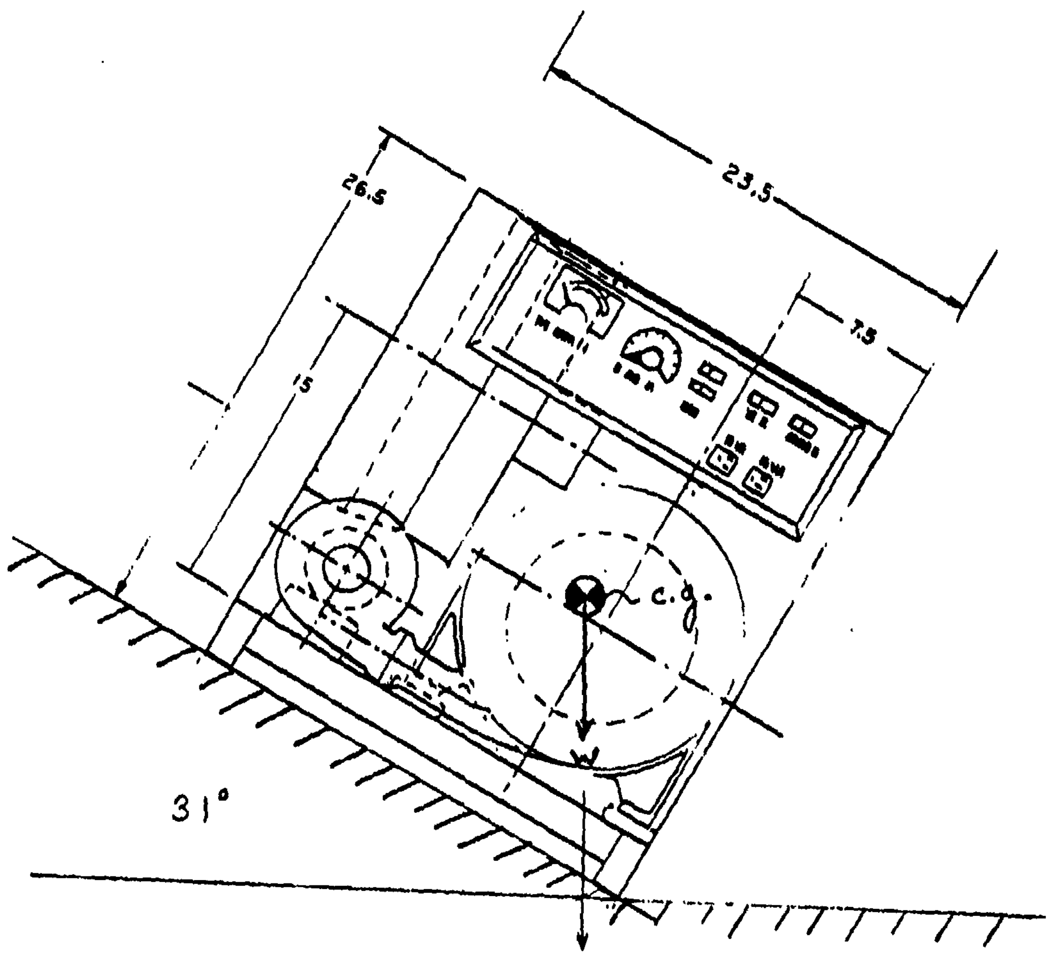
The mechanical requirements for military generator sets involve design capability to withstand:

- Drop Test (free fall)
- Vibration Test
- Drop Test Ends
- Railroad Impact Test
- Humidity Test.



(Maximum Tilt Angle = 41°)

Fig. 3-8 Orientation Capability of the EM System



(Maximum Tilt Angle = 38°)

Fig. 3-9 Orientation Capability for the ADP

The tests required are specified in MIL-STD-810B and MIL-STD-705. Pertinent excerpts from these documents are listed in Appendix B.

Test Data

The available hardware systems are nonsystem prototypes to which the standards do not apply. However, MTI has developed several free-piston resonant compressors that were subjected to U.S. Navy drop hammer tests and continued to operate successfully. Since the FPSE dynamic components are of a construction and operation that are similar to the earlier resonant compressors, and since they use the same chrome oxide surface protective coatings, FPSEs are anticipated to withstand U.S. Army shock and vibration tests equally well.

Design and Projected Data

Both the EM and the ADP frames and mounts were sized to survive the specified military drop tests.

SUBSECTION 3.2

THERMODYNAMIC PARAMETERS

3.2 Thermodynamic Parameters

Thermodynamic parameters are considered to be all those operational parameters involving heat transfer, heat flow, energy conversion and the operation of associated systems. Table 3-6 lists a summary of the thermodynamic parameter comparison. As indicated, the projection is for the FPSE to significantly exceed the requirement for maximum fuel consumption and to meet the requirements in all other aspects.

3.2.1 Specific Fuel Consumption

Requirement

The 3 kW Stirling Engine Purchase Description requires that the rated load fuel consumption of the engine including all accessories necessary to sustain operation in the generator set not exceed 0.6 lb of fuel per brake horsepower hour on any of the fuels listed (combat gasoline, JP-4, JP-5, DF-1, and DF-2).

Because the FPSE has the linear alternator integrated with the engine in a hermetic encasement, a more accurate measure of fuel consumption would include the alternator efficiency and would be expressed in terms of pounds of fuel per net kilowatt-hour. Assuming that a rotary alternator has typical rated efficiency of 85%, then the military requirement as specified in the purchase description would be 0.95 lb of fuel per net kilowatt-hour.

Test Data

The TDE consists of three major subsystems: combustor, engine, and alternator. The TDE is a research system, and, as such, its component subsystems have not been matched to operate simultaneously at their optimum conditions. As an example, the alternator was designed to operate at 60 Hz, whereas the engine was designed for 45 Hz. Therefore, taken as a system, the measured TDE performance does not accurately represent the performance capability of FPSE technology. For this reason, two separate sets of measurements are being considered here to calculate specific fuel consumption (SFC): one based on independently measured component efficiencies and the other based on measured system performance.

TABLE 3-6

COMPARISON OF THERMODYNAMIC PARAMETERS

Parameter	Test Data	Design	Projection	Requirement
Specific Fuel Consumption lb/kWh	0.85[1] 1.31[2]	0.75	0.625	<0.95[3]
IR Signature	N/A	$\Delta T = 18°C$	$\Delta T = 7°C$	As Low As Possible
Exposed Metal Temperature	120°C Max.	Insulated/ Enclosed	Insulated/ Enclosed	Enclosed
Fuel Capacity	Natural Gas	Natural Gas (Diesel)	Combat Gas JP-4, JP-5 DF-1, DF-2	Combat Gas JP-4, JP-5 DF-1, DF-2
Emissions	Low NO_x, CO, HC	Low	Low	N/A
Fuel System Safety	Manual Safety Controls	Automatic Safety Controls	Fail-Safe Design	Fail-Safe Design

[1]Based on measured component peak efficiency
[2]Based on measured rate system efficiency
[3]Overall SFC including generator

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Figures 3-10, 3-11 and 3-12 show the measured peak efficiencies for the engine, alternator, and combustor system respectively. The engine/alternator drive (or transmission) system taken as a whole includes the gas springs and gas bearings. This is estimated to be about 90% efficient. Finally, the TDE operates with total auxiliary support from the laboratory test cell. It is estimated, however, that a well-designed auxiliary system for the TDE would consume about 11% of the gross power generated.

The measured component efficiencies provide a total of 0.22 for the whole optimized TDE; see Table 3-7. Based on the above measurements and estimates, the following calculation can be made for the SFC of an optimized TDE.

$$SFC = \frac{3413 \text{ Btu}}{\text{kWh}} \times \frac{1}{18,300 \text{ Btu/lb (DF-2)}} \times \frac{1}{0.22}$$

$$SFC = 0.85 \text{ lb/kWh}$$

Taken as a total system consisting of unmatched components, the best measured overall system efficiency is 14% and consists of the measurements listed in Table 3-8. The efficiency calculation is as follows:

$$SFC = \frac{3413 \text{ Btu}}{\text{kWh}} \times \frac{1}{18,300 \text{ Btu/lb (DF-2)}} \times \frac{1}{0.14}$$

$$SFC = 1.31 \text{ lb/kWh.}$$

Design Data

The EM has been designed and is being developed as a well-matched system to provide good overall performance. Additionally the EM will operate as a stand alone system providing all of the auxiliary power necessary for self-sustained operation. In addition to the cooling system parasitic power of 165 W (detailed in Section 3.1.1), auxiliary power is required for the combustor system's air blower (75 W) and atomizer (60 W). A description of these two components is provided in Table 3-9.

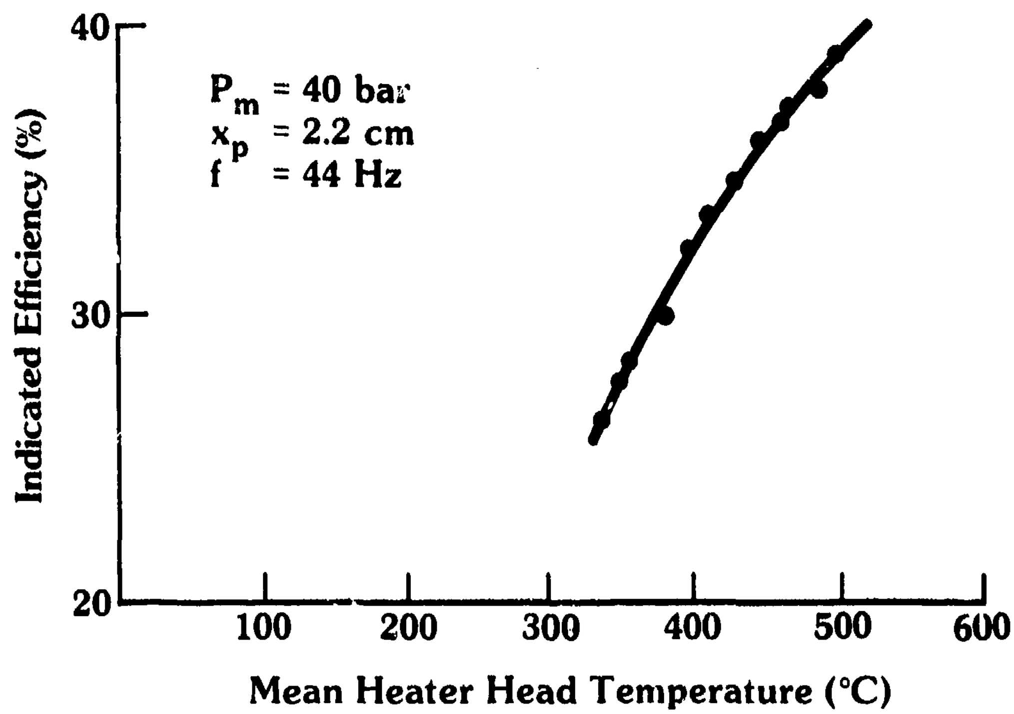

Fig. 3-10 Total Cycle Efficiency

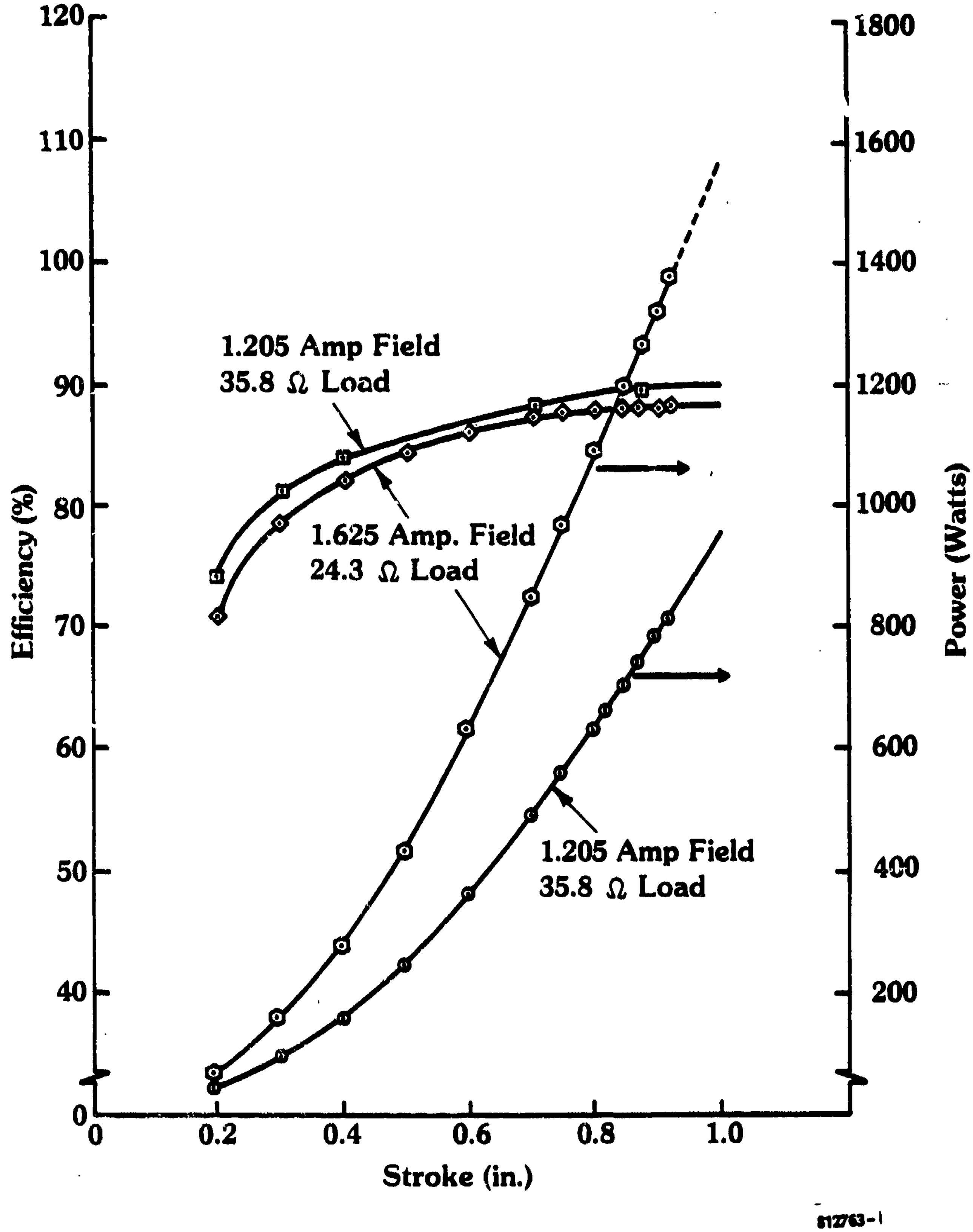

Fig. 3-11 Alternator Peak Efficiencies

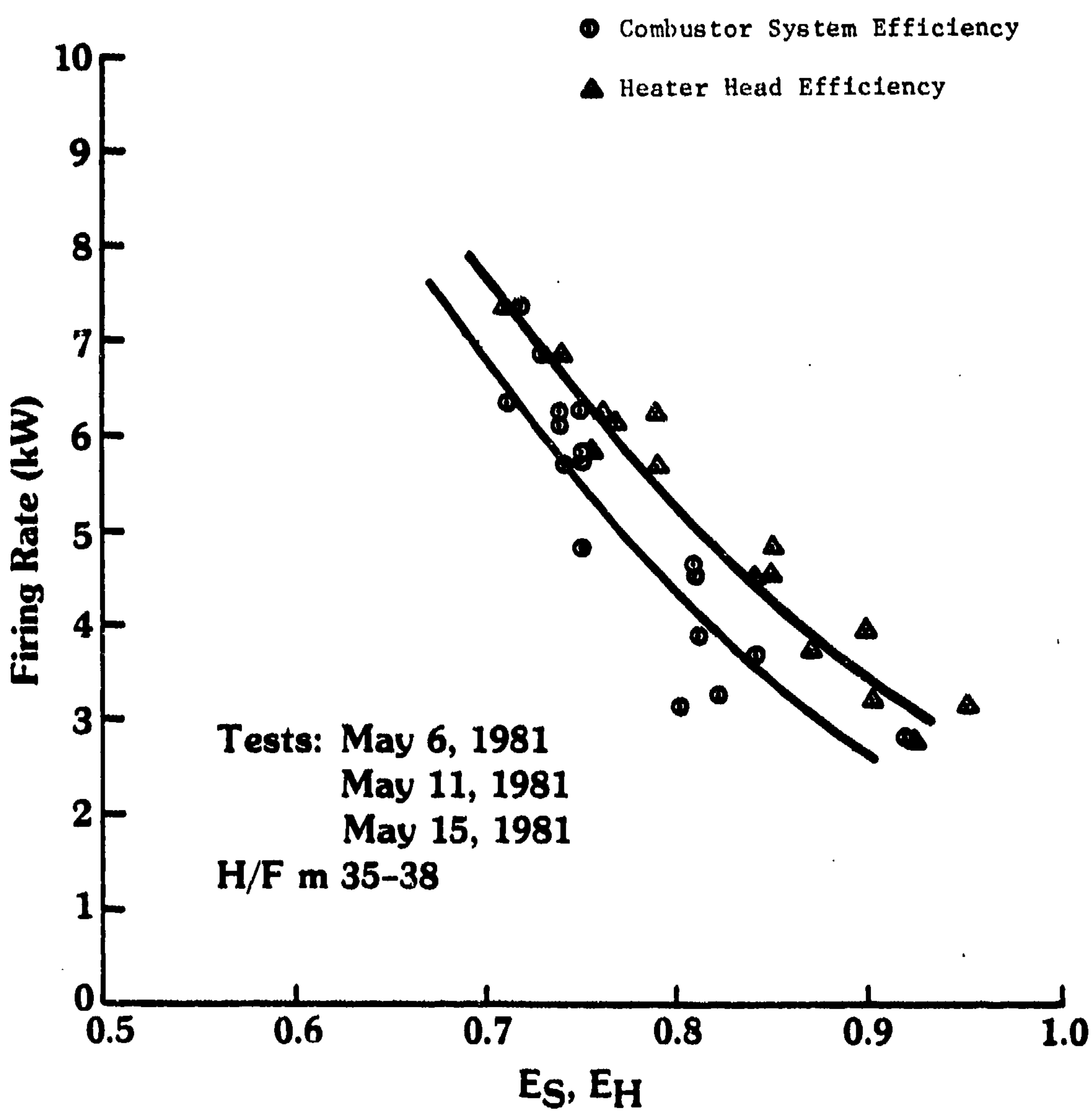

Fig. 3-12 Combustor Peak Efficiencies

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TABLE 3-7

TDE MEASURED COMPONENT EFFICIENCIES

Subsystem	Maximum Efficiency
Combustor	0.85
Engine	0.36
Alternator	0.90
Drive	0.90
Auxiliary	0.89
Total	0.22

TABLE 3-8

TDE MEASURED SYSTEM EFFICIENCIES

Subsystem	Measured Efficiency (%)
Combustor	0.8
Engine	0.29
Alternator/Drive	0.67
Auxiliaries	0.89 (est.)
Total	0.14

TABLE 3-9

PARAMETERS FOR THE COMBUSTOR AIR BLOWER AND ATOMIZER

Air Blower

Propeller Diameter	4.2 in.
Housing Motor Diameter	6.88 in.
Operating Speed	16,000 rpm
Pressure Head	15.7 in. H_2O
Flow	9.86 cfm
Power Consumption	75 W

Atomizer Air Compressor

Type	4 vanes swastika
Rotor Diameter	2.17 in.
Length	1.50 in.
Housing I.D.	2.32 in.
Operating Speed	1725 rpm
Pressure Drop	10 psia
Power Consumption	60 W

The total auxiliary power requirements for the EM total 480 W and consist of the following:

Cooling System Fan	75
Cooling System Pump	90
Combustor Blower	75
Combustor Atomizer	60
Controls	180
Total	480 W

Now, considering both the parasitic power requirements and the subsystem design goals, the total EM system efficiency design target is 0.25, as seen in Table 3-10. The following total system performance is calculated for the EM system:

$$SFC = \frac{3413 \text{ Btu}}{\text{kWh}} \times \frac{1}{18{,}300 \text{ Btu/lb}} \times \frac{1}{0.25}$$

$$SFC = 0.75 \text{ lb/kWh.}$$

Projected Design

One of the design objectives of the advanced development prototype is to improve upon the EM component efficiencies so that an overall system efficiency of 30% results. The major sources of improvement are expected to be realized in the engine and alternator subsystems. It has been determined that by reducing the alternator flux gap from 0.045 in. to 0.010 in., the alternator efficiency will increase from 85 to 90%. On the engine side, an efficiency improvement is expected to be realized by decreasing the displacer drive losses. The overall projected system efficiency and SFC for the ADP is given in Table 3-11. The calculation for system efficiency follows:

$$SFC = \frac{3413 \text{ Btu}}{\text{kWh}} \times \frac{1}{18{,}300 \text{ Btu/lb}} \times \frac{1}{0.30}$$

$$SFC = 0.625 \text{ lb/kWh.}$$

TABLE 3-10

3 kW EM SYSTEM EFFICIENCY DESIGN TARGETS

Subsystem	Efficiency
Combustor	0.90
Engine	0.40
Alternator	0.85
*Drive	0.97
Auxiliaries & Controls	0.84
Total	0.25

*It should be noted that the high drive efficiency for the EM results from the elimination a major source of efficiency loss - the power piston aft-gas spring.

TABLE 3-11

ADP PROJECTED EFFICIENCY

Subsystems	Efficiency
Combustor	0.90
Engine	0.45
Alternator	0.90
Drive	0.97
Auxiliaries & Controls	0.84
Total	0.30

3.2.2 IR Signature

Requirements

Although no military standard currently exists for power plant infrared (IR) radiation signature, the intent is to limit the system exhaust plume to a minimum practical level.

Test Data

Both the TDEs and "Prototype Engines" have a nonsystem research configuration, which do not accurately reflect IR signature for total systems. Therefore, no IR signature test data is available.

Design Data

A calculation was made to determine the temperature of the exhaust plume of the EM system. This calculation is depicted schematically in Figure 3-13. The EM frame is designed as an enclosure to ensure adequate mixing of the combustor exhaust gas with the warm coolant air. As indicated in the figure, the calculated exhaust plume temperature is 124°F on a 90°F ambient day. To be detailed in Section 3.5.4, the EM is designed to have a nearly constant performance independent of ambient temperature. The net exhaust plume for the EM system, then, will be 18°C above ambient.

Projected Design

The ADP will have a significantly lower net temperature rise than the EM for two reasons:

1. The ADP is more efficient than the EM, thereby requiring less heat rejected.
2. The ADP employs a smaller coolant radiator that produces nearly twice as much flow as does the EM radiator.

The calculated IR signature for the ADP is shown in Figure 3-14. As shown, the ADP will have a net temperature rise above ambient of 7°C.

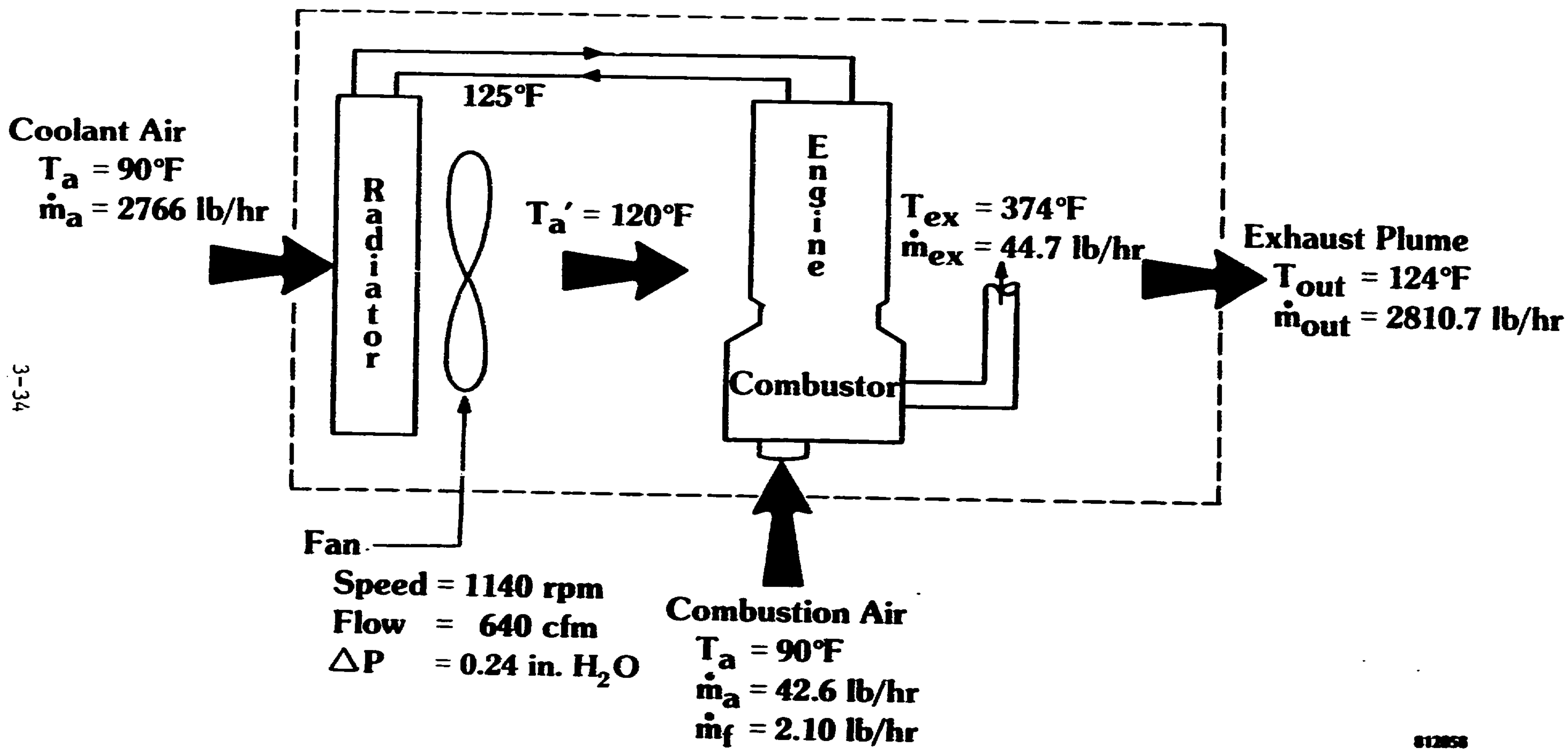

Fig. 3-13 Exhaust Plume Temperature Calculation

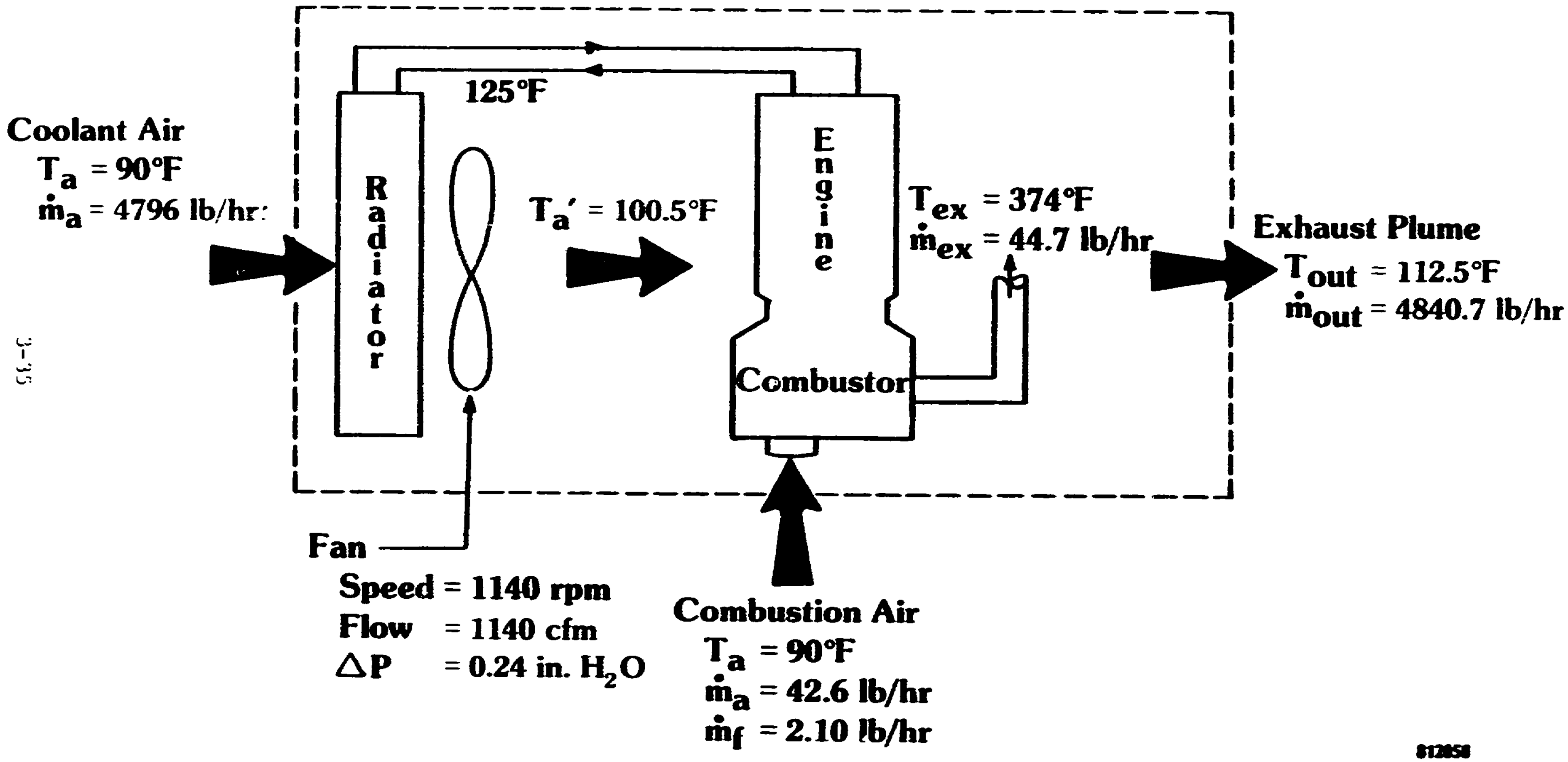

Fig. 3-14 IR Signature for the ADP

3.2.3 Exposed Metal Temperature

Requirement

According to the 3.0 kW Stirling Engine Purchase Description, all parts that are of such a nature or so located as to become a hazard to operating personnel shall be fully enclosed or so located as to minimize such hazards.

Test Data

In order to verify the low exposed metal temperatures of FPSEs, temperature measurements were taken by placing thermocouples at various locations on the TDE during operation. The TDE was operating at 60% rated power, and a stable operating condition was established for 10 minutes prior to recording the temperature measurements. Figure 3-15 shows the results of those measurements. Only the combustor exhaust pipe has a temperature of sufficient degree to be a concern to operating personnel.

Design and Projected Data

Both the EM and ADP systems will be configured so that the combustor exhaust pipe is internal to the overall system package and totally removed from possible contact with operating personnel.

3.2.4 Multifuel Capability

Requirements

The 3.0 kW Stirling Engine Purchase Description states that the engine, burner, fuel supply system, and fuel control system shall be designed to operate on the following light petroleum distillates:

- Combat gasoline per Specification MIL-G-3056
- Jet fuels JP-4 and JP-5 per Specification MIL-T-5624
- Diesel fuels DF-1, DF-2, and DF-A per Specification VV-F-800.

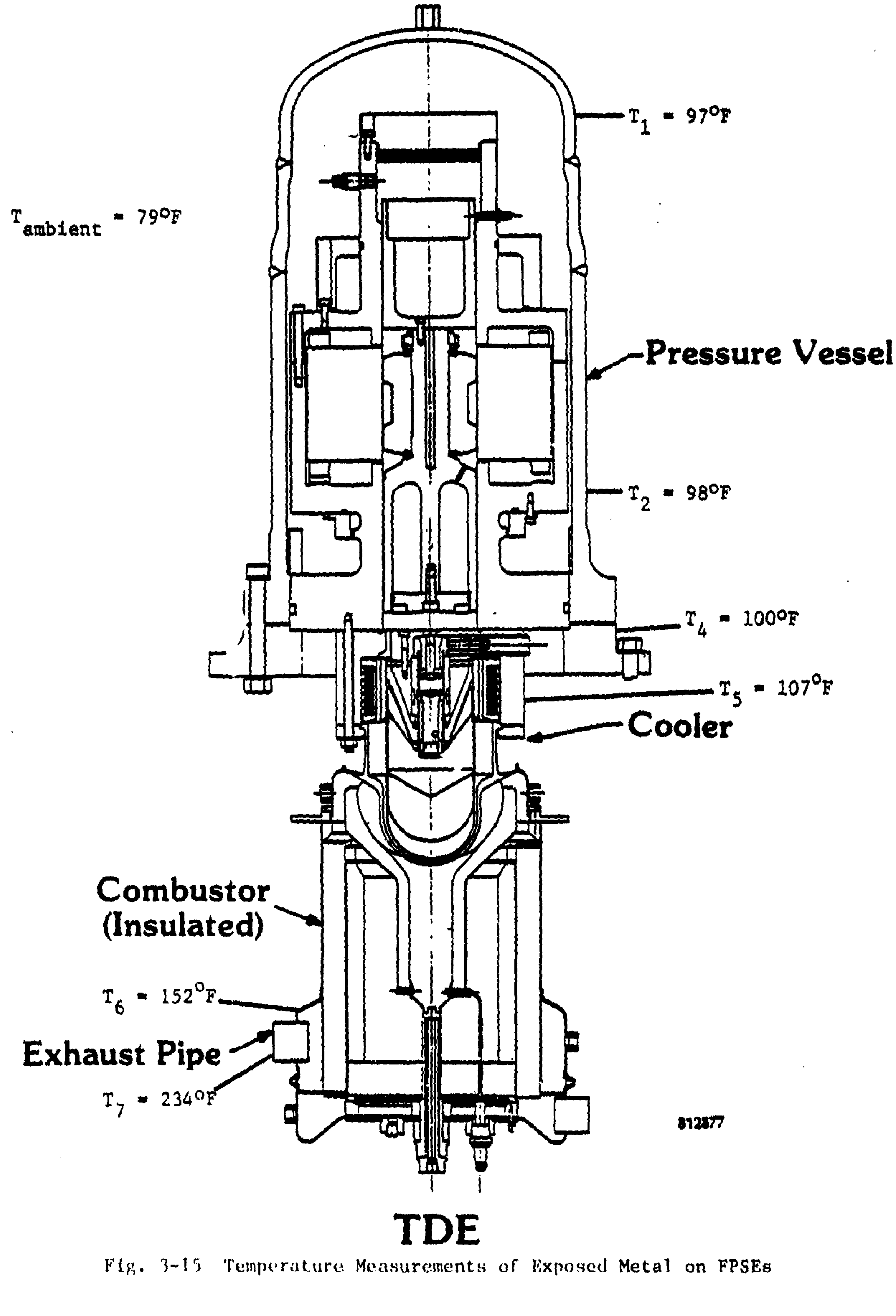

Fig. 3-15 Temperature Measurements of Exposed Metal on FPSEs

Test Data

MTI's experience with fossil-fired free-piston Stirling engines includes the TDE and "Prototype Engines" burning natural gas and methane fuels.

Extensive rig testing of the TDE combustion system was conducted using methane. The results of these tests, described in MTI Report No. 81FPSE2, indicated:

1. Good ignition and blowout limits, e.g., lean air/fuel ratio limits of approximately 50 and 300 respectively.
2. Combustor, although designed for 3 kW heat input, is capable of running up to 10 kW.
3. Sufficient combustor volume and acceptable wall temperatures (<1700°F).
4. A very flat combustor exit-gas temperature profile.

Subsequent running on natural gas (90-95%) methane) in the engine has also indicated satisfactory operation.

The current TDE and Prototype combustion systems have utilized methane or predominantly methane (natural gas) fuels. With adjustments to the gas nozzle orifice size, other gases such as ethane, propane and butane could easily be accommodated. In considering only combustion principles, olefin series gases such as ethylene, propylene or butylene could also be burned. However, the tendency of these compounds to form gum could be detrimental to the heater or preheater. As a general rule, gases of a lower heating value of 800 Btu/SCF could probably be utilized on the current TDE engine with no modifications other than nozzle orifice size. Other fuels, such as hydrogen (274 Btu/SCF), carbon monoxide (321), oxygen (200-300) or air-blown coal-derived low-Btu gases (90-150), coke oven gas (∿500), and process gases (consisting of CO, methane and inerts), would require extensive redesign of the combustor, fuel injector and preheater as well as a rig development program.

Design Data and Projected Design

The Engineering Model is being designed to operate on natural gas and on diesel fuel. The EM fuel capability will be continually improved so that the ADP will have total fuel flexibility over the range of military logistics fuels. The following discussion addresses the design considerations to achieve this capability. For the Stirling engine continuous combustion system, the relevant physical, chemical and thermodynamic properties of light petroleum distillate fuels are similar. The key word here is relevant. Fuel properties such as distillation range, vapor pressure, lead content, octane number and cetane number are not of particular concern. For example, the latter two indicate auto ignition temperature requirements for spark ignition (high auto ignition temperature to prevent knock) and diesel engines (low auto ignition temperature), which are irrelevant to a continuous combustion process at atmospheric pressure. For the liquid fuels being considered, the applicable properties include specific gravity, freezing point or pour point, flame temperature, lower heating value, viscosity and sulfur content. A comparison shown in Table 3-12 of some of these properties reveals the approximate range of variation.

The fact that the hydrogen/carbon mole ratio of gasoline, jet fuel and diesel fuel is approximately constant ($\sim$1.8) means that the mass ratio of air/fuel to achieve a given temperature rise is also roughly the same. Thus, a control system which provides a constant air/fuel to achieve a predetermined temperature rise (desirable from a cycle efficiency viewpoint) would be relatively insensitive to fuel type if fuel flow control is on a mass basis. If volumetric fuel flow control is used, the large specific gravity variation must be factored in, perhaps with a simple manual adjustment. Another alternative would be to use an exhaust gas oxygen sensor to provide feedback to the air/fuel control. Once again, the small variation in hydrogen/carbon ratio among these fuels results in a fixed relationship between oxygen (or carbon dioxide) in the exhaust and air/fuel mass ratio. In summary, it appears feasible to use a single control system for the range of fuels listed in the purchase description.

TABLE 3-12

RANGE OF LIQUID FUEL PROPERTIES

Property	Maximum	Minimum	% Difference
Specific gravity (60°F)	0.83	0.72	15
Lower heating value (Btu/lb)	18,500	18,000	3
Adiabatic stoichiometric flame (°F) temperature	∿4100		∿0
Kinematic viscosity @ 100°F (c.s.)	6	0.5	-
Stoichiometric A/F	14.7	14.5	1
Sulfur (weight %)	1.0	0	-

Fuel supply can also be provided by a single system if the pump is designed to handle both low lubricity gasoline and high viscosity diesel fuel. Most diesel fuels will have viscosities of 2-3 centistokes at 100°F; fuel viscosity will have a major effect on fuel nozzle atomization. For low ambient temperature operation it may be necessary to heat the fuel to insure adequate pumpability and atomization, e.g., 6-10 centistokes maximum. Fuel storage could be in the same tank since all of the army fuels are compatible. It may be desirable, however, to provide separate tanks if long-term storage areas are characterized by ambient temperature extremes.

The combustor itself would also be capable of multifuel operation. The changes in burner wall temperature, which result from increased flame luminosity, i.e., aromatic content, could be handled by designing the cooling for the most luminous or radiant flame DF-2 fuel. Likewise, the fuel nozzle spray characteristics would be based on the most difficult fuel to atomize and ignite; once again, DF-2. There should be no significant difference in combustion efficiency from fuel to fuel, i.e., fuel consumption.

Thus, insofar as the engine, combustor, fuel nozzle, air/fuel control and fuel supply system are concerned, it is feasible to utilize gasoline, jet fuel and diesel fuel in a single EM design. The possible exception is the preheater. As sulfur content of the fuel increases (gasoline to jet fuel to diesel fuel) the amount of sulfuric acid in the exhaust products increases proportionately. As long as the acid remains in a gaseous state there is no problem. If, however, the exhaust is cooled below the dew point (∿300°F), a corrosive condensate is introduced. If either the average exhaust gas temperature in the preheater or the local gas temperature in contact with a cool preheater wall is below 300°F, condensation occurs. United Stirling of Sweden experience with the P-40 stainless steel preheater has indicated corrosion using diesel fuel but none with unleaded gasoline. It seems reasonable to expect similar results in the EM burning jet fuel or diesel fuel if a stainless steel preheater is used. To prevent this would require reducing the preheater effectiveness or using a material impervious to sulfuric acid (possibly ceramics).

To develop an EM Stirling engine system to operate on the military fuels detailed in the purchase description will require:

- A fuel nozzle and combustor optimized for DF-2 fuel but capable of satisfactory operation (efficiency, temperature profile, ignition and blowout) on gasoline and jet fuel.
- A liquid fuel control system capable of adjusting to changes in viscosity, density and heating value.
- A preheater which is either tolerant of or avoids condensation of sulfuric acid in the quantities contained in diesel fuel combustion products.
- A fuel supply system which can handle variations in lubricity, viscosity and density.

3.2.5 Emissions

Requirements

The purchase description requires that the Stirling engine power plant have a "low air pollution characteristic".

Test Data

Gaseous emissions (NO_x, CO and HC) of the TDE were measured. A total of nine data points were taken using a matrix of air/fuel ratios (35, 30 and 20 by volume) and maximum heater head temperatures (400, 450 and 500 °C) burning natural gas fuel. The results are presented in Figures 3-16 and 3-17, on a volumetric and mass (emissions index) basis respectively, as a function of lambda (λ) - λ was calculated from the gas analyzer CO_2 and fuel composition. The latter is defined as air/fuel divided by the stoichiometric (theoretical for complete combustion without excess air) air/fuel.

The following conclusions can be made:

- Small variations in preheat temperature, heater load, and mean head temperature did not affect the emissions levels.
- As combustion becomes leaner (increasing λ) NO_x decreases and CO increases as expected.

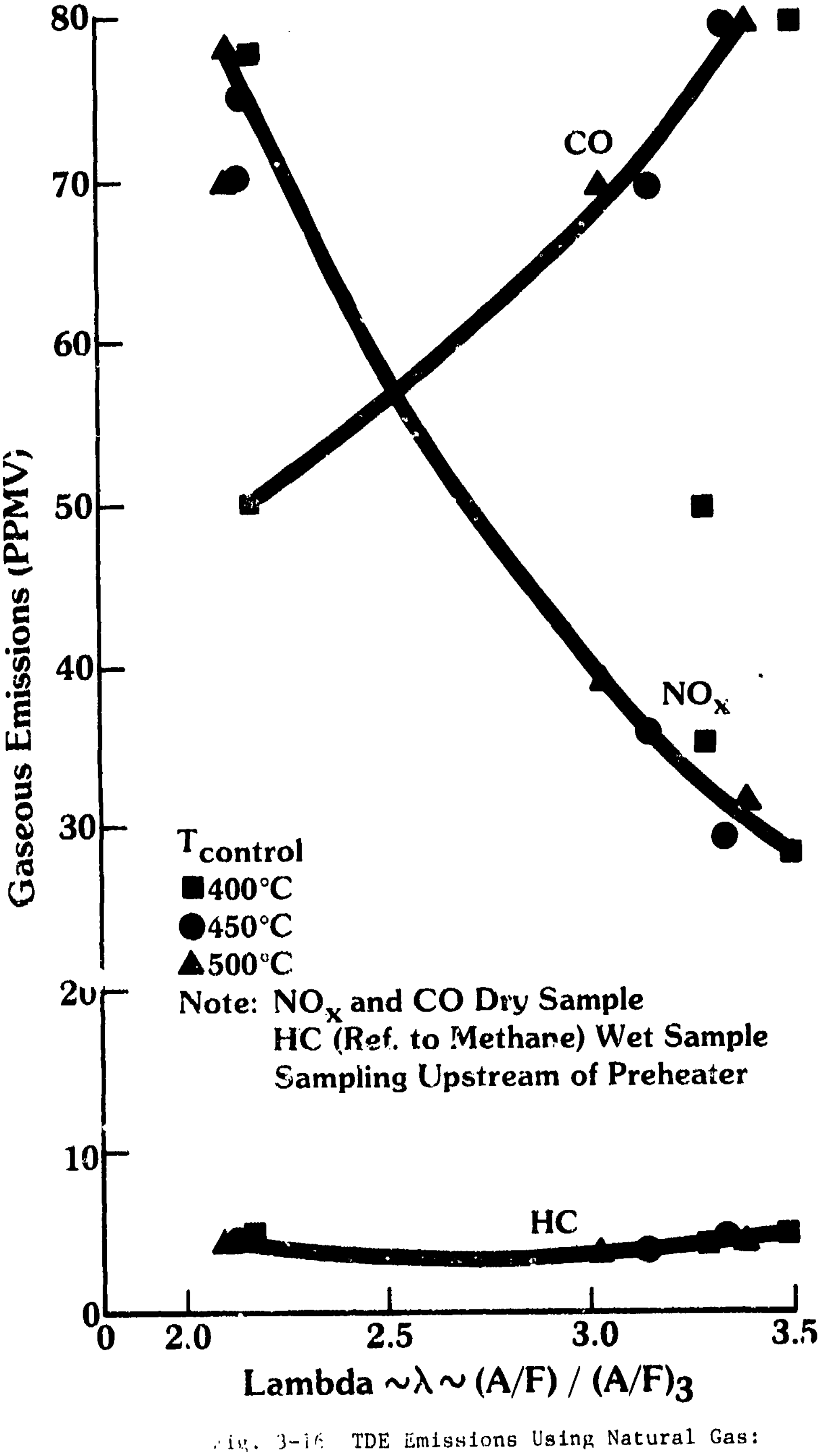

Fig. 3-16 TDE Emissions Using Natural Gas: Volumetric Parameters

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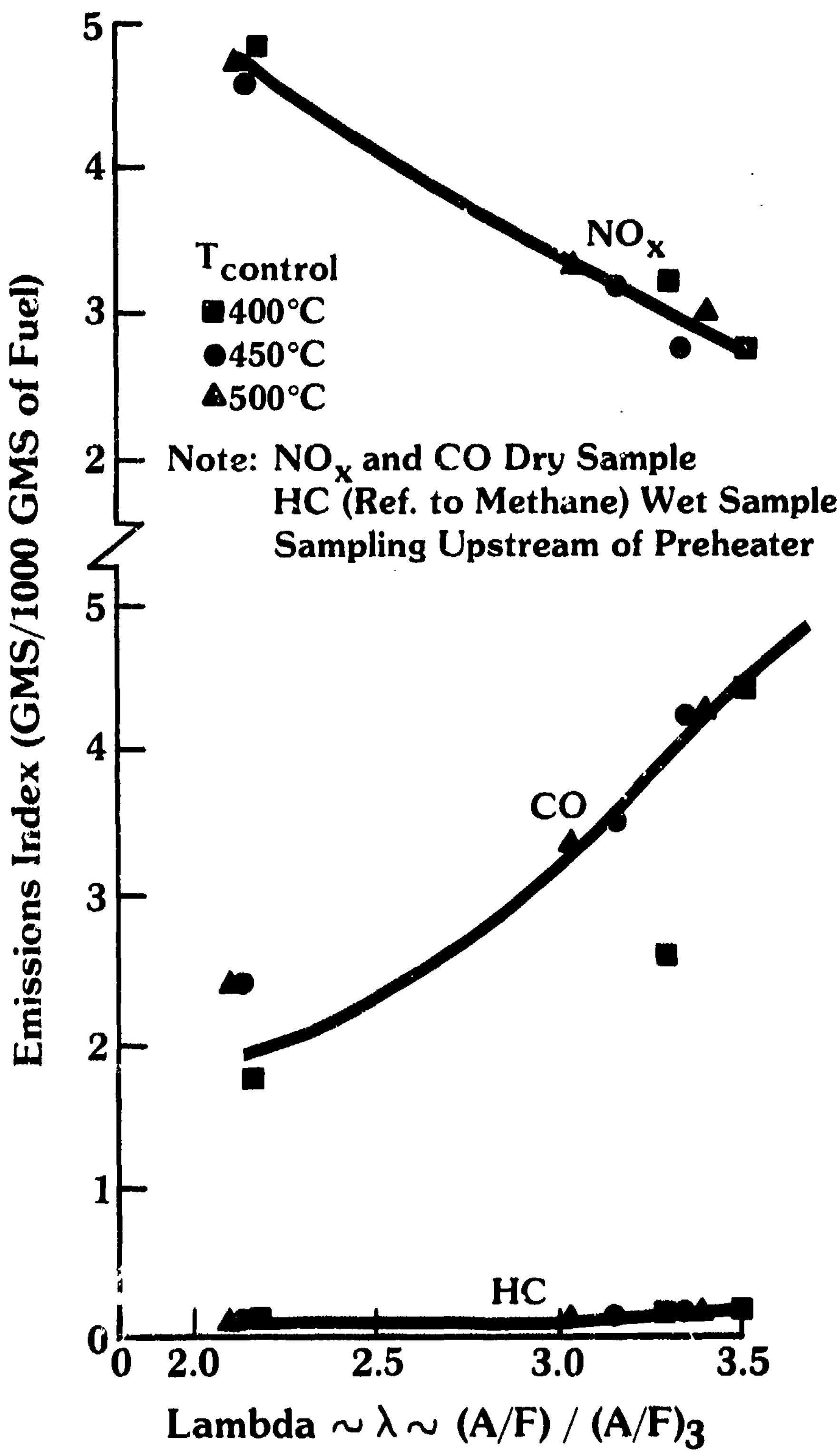

Fig. 3-17 TDE Emissions Using Natural Gas: Mass Parameters

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- Emissions levels are extremely low. That is, NO_x was less than 100 ppm and CO and HC indicate a high combustion efficiency.
- The TDE data compares favorably to published emissions of the GPU-3 burning diesel fuel.

Design Data and Projected Design

Both the EM and the ADP are being designed to achieve low chemical emmissions from liquid fuel sources. Much of the appropriate technology to accomplish this is being developed under the DOE Automotive Stirling Engine Program.

3.2.6 Fuel System Safety

Requirements

Paragraph 4.5 of MIL-STD-1472A requires that a fail-safe design be provided in those areas where failure can disable the system or cause catastrophe through damage to equipment, injury to personnel, or inadvertent operation of critical equipment.

Test Data

The Stirling engine combustion system, operating at essentially atmospheric pressure, is no more dangerous than a residential gas- or oil-fired furnace/ boiler or vehicle internal combustion engine. The potential hazards of the Stirling engine or any other fossil fuel combustion system are:

- Fuel leakage, i.e., harmful vapor, explosion or fire.
- Combining the combustion process to the system designed for that purpose.
- Leakage of combustion products containing carbon monoxide.

For "Prototype Engine" fuel system, a number of safety features are provided. Starting at the natural gas supply, a pressure switch indicates pressures that are either too high or too low. If either condition occurs, provisions exist to shut the engine down. For positive control there is an on/off solenoid switch to stop the flow of natural gas when the engine is not in use.

In order to open the solenoid, it is necessary for the test cell exhaust fan to be on, thus ensuring adequate ventilation if there should be leaks in either the gas or engine exhaust systems. After the solenoid, there is a control valve to adjust heat input to the engine. In the event of failure, the valve will automatically close. If a loss of air supply occurs, provisions exist to automatically shut off fuel. Finally, once the engine is shut down, the blower is left on to cool the hot parts and to purge the combustion system of unburned fuel and products of combustion.

For the P-40 Automotive Stirling Engine (ASE) to burn unleaded gasoline, an on/off fuel solenoid valve is also used. Should loss of air occur, the Bosch K-Jetronic air/fuel controller will sense the loss of air and stop fuel flow. After shutdown, the atomizing air is left on to purge the nozzle of fuel so that it does not drop on the hot parts and ignite.

Both FPSE and ASE combustors are designed to aerodynamically stabilize the combustion process in a predetermined volume through the use of swirling air. By suitably locating the ignitor and fuel injector and by providing a swirl induced recirculating region, a flame is prevented from occurring upstream of the combustor. By providing a larger than necessary combustor volume, combustion is complete before the heater head. As a further safeguard, the ignitor of the P-40 engine is always on.

In summary, the potential for natural gas, liquid fuel and exhaust system leakage or combustion external to the burner is no greater than current residential, commercial, military or vehicle systems burning fossil fuels.

Design Data and Projected Design

Both the EM and the ADP will be designed to incorporate safety controls that will provide for complete fail-safe operation of the liquid fuel combustor.

SUBSECTION 3.3

AUDIO COMPARISON

3.3 Audio Comparison

Requirements

The purchase description requirement for noise states:

"The power source shall be inaudible to the unaided ear of an observer located in a quiet jungle background 100 meters from the power source. Compliance with this requirement will be considered to be demonstrated when the audio noise sound pressure levels emanating from the set during operation from no load to full rated load meet the following criteria when the microphone is located 1.2 meters above the ground on a 6 meter radius circle measured in any direction from the geometrical center of the set.

Octave Band Center Frequency, Hz	Maximum Noise Level in Decibels re/ .0002 Microbar
63	60
125	46
250	44
500	45
1000	45
2000	46
4000	47
8000	48

During acoustical measurements, the ambient background noise levels, including wind noise, shall be at least 10 db below that of the set noise in each octave band."

Test Data

Stirling engines are inherently quiet due to the continuous atmospheric combustion means of inputting energy to the working cycle. Free-piston Stirling engines have even a greater capacity for quiet operation due to the utilization of only two moving parts on gas bearings.

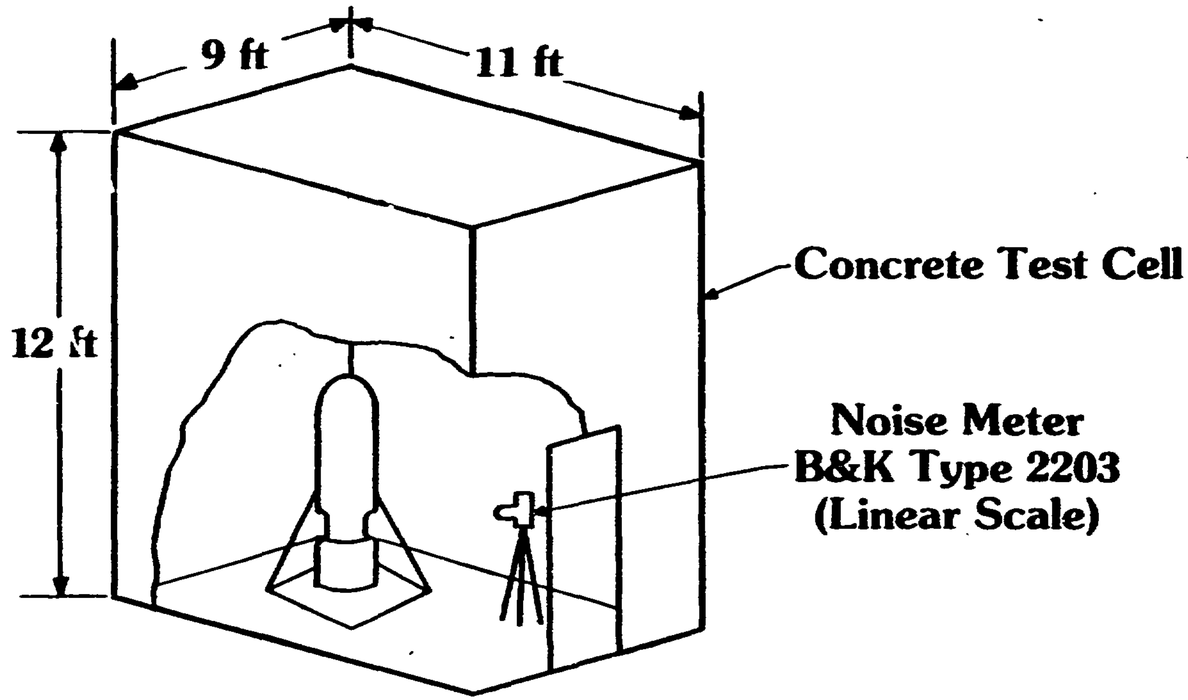
Noise measurements were taken of the TDE in operation in its test cell in order to establish a frame of reference for estimating initial FPSE system operational noise. Figure 3-18 illustrates the test environment in which the noise measurement was made. As illustrated, the test cell environment provided for a high degree of reverberation as indicated by the dramatic difference between the measurements taken with the cell door open and the cell door closed. The measurements were taken at one point with a B&K type 2203 noise meter over the full frequency range. The noise sources were determined to be the engine/alternator and combustor subsystem, as well as the experimental mounting frame and an external gas bearing pump. No attempt was made to simulate noise that would be generated by the coolant system exhaust fan.

Although the test set-up was admittedly crude, the test results, shown in Figure 3-18, are indicative of the potential of the FPSE to meet the military requirements for silent power systems.

Design Data and Projected Design

It is probable that, in a completely packaged FPSE generator system, the major noise source contribution would be from the coolant system radiator fan and motor. Therefore, care was taken in the EM and ADP radiator system design to minimize the audio emission potential. The following elements were considered to minimize noise emissions:

- Torin radiator fans were selected so that the required air flow matched the maximum fan efficiency. This should produce the lowest sound pressure level (SPL).
- Relatively low speed (1140 rpm) was selected for a low SPL.
- The fan and pump motor mounts will be vibration-isolated from the system frame.
- The EM frame includes an enclosure that contains sound insulating materials to baffle any high-frequency emissions. Figure 3-19 illustrates the frame enclosure envisioned for the EM.



Measurements at 5 Feet	
• Normal Speech	= 72 db
• Engine* (Door Open)	= 78 db
• Engine* (Door Closed)	= 82 db

*Engine/alternator/combustor, mechanical mounts, and external bearing pump

Fig. 3-18 TDE Noise Measurement

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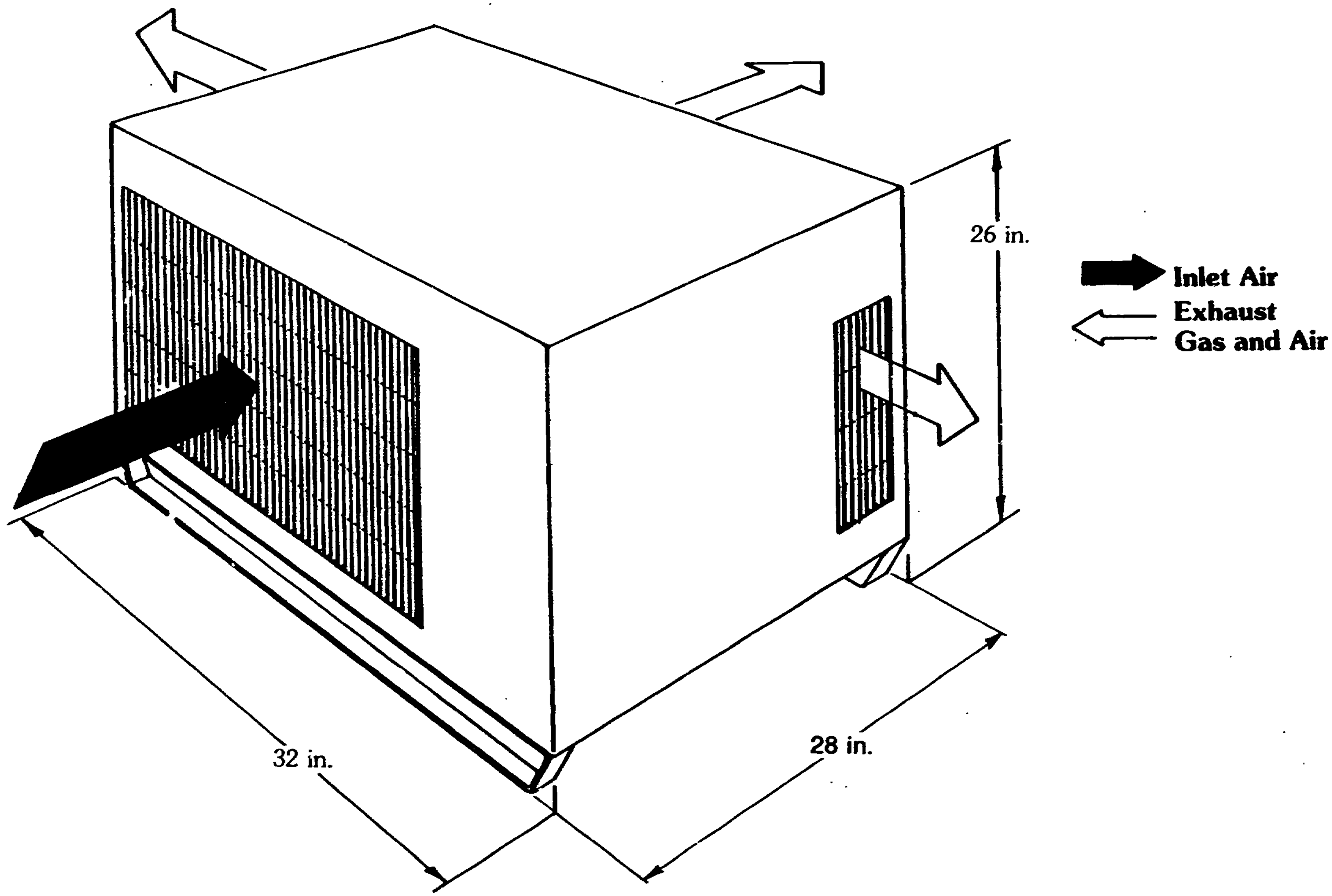

Fig. 3-19 MTI 3-kW Engineering Model Package

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SUBSECTION 3.4

MATERIAL COMPARISON

3.4 Materials Comparison

Requirements

The purchase description material guideline states

> "Material used shall be of good commercial quality for the purpose intended. Materials which are latest state-of-the-art may be considered in order to achieve design objectives. In all cases materials used should be consistent with strength required for performance, safety and reliability."

Test Data

The materials used to construct the TDE and "Prototype Engine" are listed in Tables 3-13 and Table 3-14 respectively. The materials listed are consistent with the materials requirements.

Design Data

Table 3-15 indicates the compliance with requirements of the materials selected for fabrication of the EM system.

Projected Design

The ADP will incorporate commonly available engineering materials in its design as does the EM system. One item is, however, worth noting: The dramatic weight reduction that will be accomplished in the ADP alternator system requires the use of 2 lb of samarium cobalt permanent magnets. The decrease in system weight, however, will compensate for the use of the increased cost permanent magnet material. It should be noted, however, that alternative permanent magnet designs, incorporating either Barium Ferrite or ceramic magnets, are being considered for their impact on system weight.

TABLE 3-13

TDE MATERIALS LIST

Combustor:	
Fuel nozzle	Brass
Recuperator	316 SS
Combustor cup	316 SS or 310 SS or Inco 625
Combustor liner	Kaowool
	B&W Kaowool (Alumina Oxide Fiber)
Engine:	
Displacer	316 SS
Heater head	Inconel 617
Regenerator	304 SS
Cooler	Aluminum
Pressure vessel	304 SS
Alternator:	
Stator & Plunger	Hypereo 50/Copper
Bearings/Piston/Cylinder	Chrome Oxide/Aluminum
Gas Spring	Aluminum

TABLE 3-14

PROTOTYPE ENGINE MATERIALS LIST

Combustor:	
Fuel nozzle assembly	Brass
Recuperator	316 SS
Combustor cups	310 SS
Engine:	
Displacer assembly	316 SS
Diaphragm packs	301 SS
Heater head	316 SS
Heater tubes	316 SS
Regenerator	304 SS
Cooler	Aluminum
Alternator:	
Stator	Iron/Copper
Plunger	Iron
Bearings/Pistons/Cylinders	CrO_2 Coated Aluminum
Gas springs	Aluminum

TABLE 3-15

EM MATERIALS LIST

Combustor:	
Fuel Nozzle	Brass
Recuperator	316-SS
Combustor Cup	316-SS or 310-SS or Inco-625
Combustor Liner	Kaowool B&W Kaowool (Aluminum Oxide Fiber)
Engine:	
Displacer	316-SS
Heater Head	Inconel, 718
Regenerator	304-SS
Cooler	Aluminum
Pressure Vessel	Low Alloy Steel
Alternator:	
Stator & Plunger	Hyperco-50/Copper
Bearings/Piston/Cylinder	Chrome Oxide/Aluminum

SUBSECTION 3.5

OPERATIONAL PARAMETERS

3.5 Operational Parameters

Operational parameters are considered as those items that characterize system operation. Table 3-16 summarizes the comparison of operational parameters with military requirements. As indicated, the FPSE is expected to meet or exceed each of the requirements.

3.5.1 Power

Requirement

The purchase description requires the generator set to be capable of producing continuous power of 3 kW.

Test Data

The TDE was designed for 1 kW electrical power output at 720 °C. Although mechanical constraints presently preclude operation at the maximum temperature point, the design power output level was exceeded. Figure 3-20 illustrates the thermodynamic power output that was achieved by the TDE as a function of heater head temperature.

Design Data

The EM is designed to have a gross electric power output of 3800 W. The parasitic load required to operate the auxiliaries and the control system, however, will require 480 W and the new available power output will be 3.3 kW.

Projected Design

The EM is designed to have a certain degree of design margin to ensure that at least 3 kW electric is available to the user. Based on performance testing of the EM, the ADP will be scaled accordingly to provide precisely 3 kW rated power output.

3.5.2 Frequency

Requirements

MIL-STD-1332B requires that the generator maintain an operating frequency of 60 Hz.

TABLE 3–16

COMPARISON OF OPERATIONAL PARAMETERS

Parameter	Test Data	Design Data	Projection	Requirement
Power	1.0 kW_e	3.3 kW_e	3.0 kW_e	3.0 kW_e
Frequency	60 Hz	60 Hz	60 Hz	60 Hz
Lubrication	Gas Bearings	Gas Bearings	Gas Bearings	N/A
Climatic Conditions	Engine Starts at Cold or Hot Temperature	95°F Design Point — O.K. Over Range	95°F Design Point — O.K. Over Range	-25 to +125°F
Altitude Condition	N/A	Much Easier to Maintain Power Than with IC Engine	Much Easier to Maintain Power Than with IC Engine	Rated Power at 5000 ft, 107°F
Reliability	200-hr Endurance Run	— 10,000-hr MTBO	750-hr MTBF 10,000-hr MTBO	460-hr MTBF 3000-hr MTBO
Maintenance	Developmental Repair	Developmental Repair	Limited Maintenance on Engine/Alternator	Easy Repair
Control	Manual	Automatic	Automatic	Automatic

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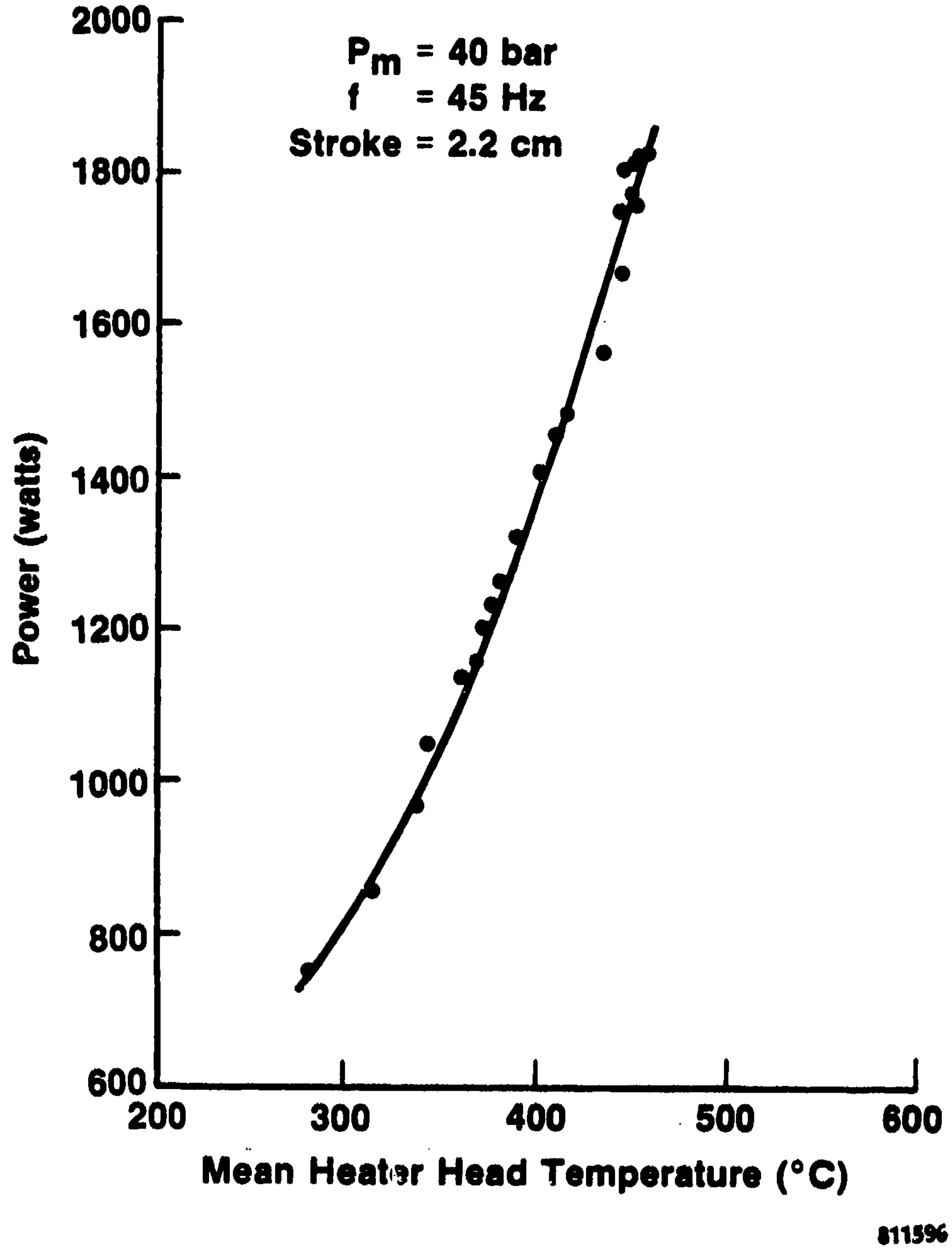

Fig. 3-20 TDE Thermodynamic Power Output

Test Data

FPSEs perform as thermal oscillators and operate at the resonant frequency as determined by the system dynamic design parameters (charge pressure, area, and piston mass). The TDE has been operated up to its resonant frequency of 45 Hz.

The "Prototype Engine" was designed to operate at higher frequency levels and, in fact, achieved regular operation at 60 Hz.

Design Data and Design Projection

The EM has been designed to operate at 60 Hz. The ADP will also be designed to operate at 60 Hz.

3.5.3 Climatic Conditions

Requirements

The purchase description states:

> "The engine shall be capable of starting and carrying rated load within 10 minutes in any ambient temperature between minus 25°F and plus 125°F without external starting aids. From minus 25°F to minus 50°F, external heat may be applied for starting and the engine shall be capable of carrying load within 30 minutes."

Test Data

The method for starting the TDE is to apply heat to the heater head while motoring the alternator piston until positive power output is developed. This technique has worked well with cold starts (heater head at ambient temperature) and with warm starts (heater head at elevated temperature).

Design Data

There are two issues involved here: ability to maintain rated load and start-up time for a range of ambient temperatures. These two issues are addressed in the following discussion.

Design calculations were performed for the EM to determine the change in performance expected between operation at the design point condition of 90°F and operation at an ambient temperature of -25°F. The calculations were performed assuming two separate methods of combustor control:

Case 1: Variable speed air blower with fixed fuel/air mass control

Case 2: Variable speed air blower with fixed fuel/air (F/A) volume control.

The 90°F day formulated the baseline for both control schemes analyzed. The calculated specific fuel consumption was 0.75 lb/kWh. Calculations were then made to model the steady-state performance of the system considering each of the control cases on a -25°F day. The major effects that low ambient temperature has on system performance arise because of the increased combustion air density and the lower temperature at which the radiator rejects engine waste heat.

For Case 1 (fixed F/A mass ratio), the effect on the combustion air was a reduction in its volumetric flow rate and a subsequent reduction in heater head pressure drop. The overall change, however, was so slight that it had no significant impact on the system parasitic power requirements.

The effect of low ambient temperature on the coolant system radiator was also examined. A constant heat exchanger effectiveness was assumed for both the 90°F ambient condition and the -25°F ambient condition. This assumption implies that the temperature difference between the ambient air and the coolant fluid is the same for both ambient conditions. The 90°F baseline included a coolant temperature out of the radiator of 125°F. Therefore, the coolant temperature for the -25°F day was calculated to be +10°F. A computer simulation of engine performance was made with the lower temperature and, as expected, an increase in calculated engine efficiency resulted. This increase totaled nearly 15% and yielded a calculated specific fuel consumption (SFC) of 0.68.

For Case 2 (fixed F/A volume ratio), the effect on the combustion air was an increase in mass flow rate resulting in a subsequent reduction in combustion gas temperature and heater head temperature. The reduction in heater head temperature would cause the F/A controller to supply more fuel until the head temperature attains its set point level. This process results in an overall 6% decrease in combustor efficiency. This efficiency loss, however, is compensated by the reduced radiator coolant temperature as discussed above. The overall effect is a net performance be efit, and the SFC was calculated as 0.72.

Performance at 125°F (Ambient) Operation

System operation was evaluated for performance capability with 125°F ambient conditions. Since the primary concern was to evaluate whether the generator could, in fact, achieve 3 kW output with elevated coolant temperature, only the fixed fuel/air control was considered in the analysis. The major impact of elevated ambient temperature was determined to be a substantial reduction in both operating efficiency and power output capability. If no modifications were made, the specific fuel consumption would rise from the 90°F (ambient) operation of 0.75 to 0.84, and the power capability would fall from 3 kW to 2.4 kW.

Two engine modifications were analyzed as approaches for achieving full rated power with 125°F ambient conditions. The first involved overdriving the combustor to produce a mean heater head temperature of 1500°F. (The nominal heater head design temperature of the EM is 1400°F). The analysis confirmed that the 100°F increase in heater temperature would allow the engine to produce a net output of 2.992 kW. In addition, the engine efficiency would increase to its original level resulting in an overall SFC of 0.62 lb/kWh. The penalty paid for operating at elevated heater head temperature is a significant decrease in life. The design point heater life at 1400°F is 10,000 hrs, whereby the heater life at 1500°F would be 600 hrs.

Because of the severe life penalty involved in operating at an elevated heater temperature, an alternate approach for achieving 3 kW at 125°F ambient was investigated; namely, increasing the area of the power piston while holding all other dimensions constant. The analysis indicated that by increasing the power piston diameter by 10%, a net power output of 3.04 kW could be maintained on a 125°F day with a heater head temperature of 1400°F. The swept volume rate through the heat exchangers would increase, resulting in additional pressure drop losses and a consequential increase in SFC to 0.84 lb/kWh.

The analysis confirmed the capability of achieving 3 kW output with 125°F ambient conditions. The ultimate approach was not identified. However, two approaches exist for achieving the full rated power. The next generation design will need to take into account design compromises that include trade-offs between elevated heater head temperature and increased piston area to ensure the full 3 kW capability at high ambient temperature conditions.

Table 3-17 lists the calculated fuel consumption values for different climatic and altitude conditions and for the fully rated power output of 3 kW. As indicated, the specific fuel consumption never rises above the maximum military requirement of 0.95 lb_m/kWh. The overall conclusion is that the EM, with only slight modifications to the piston diameter, will be capable of operating at 3 kW rated power output over the range of ambient temperatures from -25°F to 125°F.

Start-up Time

The effect of ambient temperature upon start-up time involves the additional time that would be required to bring the heater head up to design temperature. This time can be calculated from the expression:

$$Q = mc_p \int_{T_1}^{T_2} \frac{dT}{dt}$$

where: m is the heater head mass

c_p is the specific heat of the heater head

T_2 = operating temperature = 1350°F

T_1 = ambient temperature.

The above expression was used to calculate the ratio of time needed to reach full operation between ambient starting temperatures of -25°F and 90°F. The result is that it would take 9% longer to reach full operating temperature

TABLE 3-17

CALCULATED FUEL CONSUMPTION* IN VARYING CLIMATIC AND ALTITUDE CONDITIONS FOR THE EM SYSTEM

Control Scheme	Sea Level/90°F	5000 ft/107°F	Sea Level/-25°F	Sea Level/125°F
Fixed F/A Mass	0.75	0.76	0.68	0.84
Fixed F/A Volume	0.75	0.78	0.72	N/A

*SFC in lb_m/kWh

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on a -25°F day than on a 90°F day. Since the design start-up time for the EM is less than 2 minutes, it would require up to 2 minutes and 11 seconds to reach operating temperature from a cold start at -25°F ambient (assuming that the liquid fuel is adequately prepared for cold weather atomization).

Projected Design

The ADP is expected to have climatic condition responses similar to the EM.

3.5.4 Altitude Conditions

Requirement

The purchase description requires that the engine be capable of developing and maintaining rated power output at elevations up to and including 5000 ft with ambient air temperature of 107°F.

Test Data

No relevant test data have been recorded for any of the MTI research FPSEs.

Design Data and Projection

As stated in the previous discussion, the EM and ADP will have the capability for maintaining rated load through manipulation of the displacer stroke. The parameter to investigate, then, is the required change in combustor firing rate as dictated by the change in engine system efficiency as a function of altitude.

Calculations were made for both control approaches addressed in the previous discussion. (The results are listed in Table 3-17). As indicated, little variation is projected between fuel consumption at sea level and altitude. Only a slight increase in combustor firing rate would be required.

3.5.5 Reliability

Requirement

The purchase description requires that:

> The generator set shall be designed to be capable of achieving a Mean Time Between Failure (MTBF) of not less than 460 operating hours under operating conditions specified. For the purpose of determining MTBF, a failure is defined as any malfunction which the organizational mechanic cannot remedy by adjustment, repair or replacement action using the controls, tools and parts (available at the organizational level) within one hour and which causes or may cause: inability to commence operation, cessation of operation, or degradation of performance capability of system below designated levels; serious damage to the system below designated levels; serious damage to the system by continued operation; serious personnel hazards. The generator set shall also be designed for a minimum of 3000 hours of operation before overhaul.

Test Data

FPSEs have an inherent capability for achieving high reliability and long life due to operation with only two moving parts and gas-lubricated bearings. The TDE engine currently has logged over 500 hours of cumulative test time. Most of this time involved performance testing, however, an endurance test was performed during the periods of October 1978 to January 1979. The objective was to accumulate 200 operating hours and identity those components which were limiting engine endurance.

The endurance test was conducted by running the engine continuously (24 hr/day) to a component failure. Failures that prevented engine operation were repaired and the affected components replaced, after which testing continued.

The initial engine configuration for this test included the:

- Electric heated finned heater head;
- Displacer with insulation; and,
- Gas bearing-supported displacer.

The engine was run at relatively low power (0.7 kW) due to the limitations of the external heat system. The heat source during this period was a copper block heated with electric cartridge heaters. This was interfaced to an internally finned head via a gap filled with powdered metal. The test stoppages experienced during the endurance testing are shown in Figure 3-21 and discussed in the following paragraphs. It should be noted that the only internal engine failures experienced during the endurance test were the result of fatigue failure of the displacer dome Ceri Blanket insulation.

Discussion of Engine Stoppages

The first 46 hours of operation were primarily for performance evaluation. During this period, the engine was disassembled for inspection of various parts and for repair of minor instrumentation problems.

The displacer insulation was the first major failure, occurring after 49.5 hours of operation. The insulation in the displacer shell was subject to a 30-40 Hz vibration, at acceleration loads of 50-100 g, and, as a result, failed in high-cycle fatigue. Post failure investigation revealed that the material used (Ceri Blanket) contains microscopic "stones" generated by the fiber-forming process. The acceleration of these "stones" during operation apparently pounds the brittle fibers to a dust-like consistency. The powdered insulation was fine enough to penetrate a barrier screen designed to keep insulation fiber inside the displacer shell and out of the close clearances of the displacer rod bearing. The resulting debris jammed the displacer rod, stopping the engine. A second displacer assembly was installed. This displacer also contained insulation.

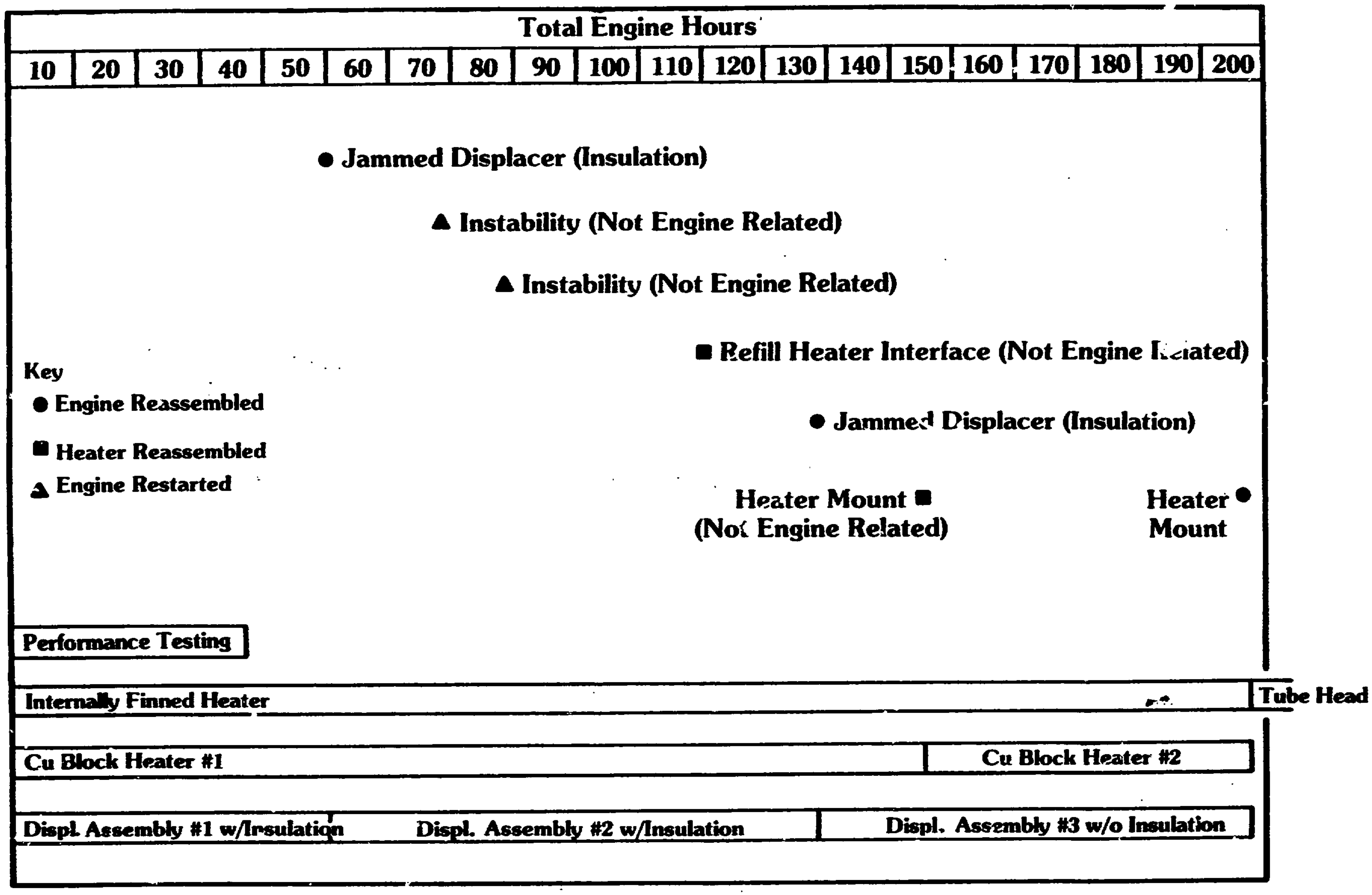

Figure 3-21 Endurance Test Results - TDE

The next two stoppages (74.7 and 88.0 hours) were due to unstable engine operation, and were not related to engine performance. Just prior to each stoppage, the heater temperature had been slowly increased in an attempt to increase the engine output. At about 350 °C, a 1 Hz oscillation of the engine amplitude started. As the temperature was further increased, the oscillation grew out of control, and the engine had to be stopped and cooled down before being restarted. These stoppages did not require disassembly of either the engine or heater head, and testing was continued after cooldown. The instability is the result of changes in the interface gap dimension due to differences in the thermal conductivity of the copper block and the Inconel 617 heater head.

The next engine stoppage (110 hours) was to correct a deterioration of engine performance due to loss of conductance of the metal powder in the interface gap between the copper heater and head. The copper block was removed from the head, the powdered metal interface removed, and the system reassembled with new powder. The engine was not disassembled.

The next engine stoppage (128.5 hours) was the result of a jammed displacer. Upon inspection, this was again found to be due to displacer insulation powdering similar to that experienced at 49.5 hours. The insulation was removed from the displacer, and the affected parts were cleaned. The engine was reassembled, and the test continued.

The last engine stoppage (198 hours) in this period was the result of a fatigue failure of the copper block/engine mount. At this point, the endurance test was terminated, since the endurance goal had been substantially achieved. The head was replaced with the electric-tubed heater, and performance testing resumed.

It should be noted that the Ceri Blanket insulation is not currently being used in FPSE hardware.

Design Data

The EM is the first FPSE generator being built into a total system configuration. The MTBF is difficult to project at this point, since many of the control system and auxiliary components will be evaluated on an experimental basis. The engine alternator unit is, however, being designed for a 10,000-hour operational life as determined by a 1% creep life on the heater head.

Projected Design

The ADP system will include auxiliary and main components of such a quality as to provide an MTBF of 750 hours. The engine/alternator design life will be 10,000 hours or greater. A reliability study was performed by MTI in evaluation of a solar-fired 15 kW FPSE. The results of that study are listed in Table 3-18 as an indication of the types of failures and low failure rates that could be expected for advanced FPSE systems.

3.5.6 Maintenance

The purchase description emphasizes that the system design should consider ease of maintenance and repair. Organizational level and direct support level maintenance and repair shall be able to be performed with field mechanics' tools.

Test Data

The TDE and Prototype Engines are designed for experimental research, and require periodic repair of a developmental nature. Nevertheless, entire combustor/engine/alternator systems can and have been disassembled and reassembled by two technicians within 4 hours.

Design Data

The EM system is designed to accommodate developmental repairs in a laboratory environment.

TABLE 3-18

SOLAR-FIRED 15-kW FPSE RELIABILITY STUDY

Item	Failure Rate (failures per 10^6 hours)
Displacer Orifice Bleed	1.00
Clamping Ring	.20
Cooler Assy	.20
Cooler Tubes	.12
Displacer Spider & Post	.10
Displacer Post Inner	.10
Displacer Post "O" Ring (6 ea)	.375
Engine Cylinder	.10
Cylinder Flange "O" Ring	.375
Port Seal "O" Ring	.375
Cylinder OD "O" Ring	.375
Alternator Stator Coils	.137
Spring Washer	.200
Tie Bolt	.02
Plenum Cap	.27
Locknut	.10
CUMULATIVE TOTAL	4.047

Projected Design

The ADP will be capable of being repaired in the field with mechanics' tools. Periodic, but limited maintenance may be required for the engine/alternator system. Such maintenance could include checking engine charge pressure and gas bearing flow rates at 6- to 12-month intervals.

3.5.7 Control

The purchase description requires that the control system be automatic to the extent that normal operation after start-up can be unattended except for scheduled maintenance.

Test Data

The TDE is controlled by a combustor control system and an independent alternator field control system. The combustor system utilizes an automatic fuel/air controller that senses heater head fin temperature and that adjusts the firing rate to maintain a constant preset temperature. The alternator system utilizes a manual control system to adjust the stator magnetic field coil voltage to control engine stroke. Additionally, engine charge pressure can be controlled manually.

All start and stop sequences are accomplished in the test cell manually by the test cell operator.

Design Data and Projected Design

The power control system for the EM system is an innovative and proprietary MTI design which promises to be a significant step in moving the free-piston engine/alternator from the laboratory to the marketplace. This control system implies a significant change in the approach to free-piston operation and control. By implementing the control, the generator system output voltage and frequency are directly dependent on a predetermined voltage and frequency input function. Since the system is electrically activated, the response can be made very fast (as discussed in the next subsection).

SUBSECTION 3.6

ELECTRICAL PARAMETERS

3.6 Electrical Parameters

The electrical parameters are considered to be those parameters that characterize the power signal output from the generator system. A comparison between FPSE electrical parameters and requirements is shown in Table 3-19. As indicated, the measured and design data meet all of the requirements except for percent of frequency undershoot and percent of voltage dip during a transient load change. The FPSE recovery time is so fast, as compared to the required response time, that this might mitigate the degree of undershoot and dip. In any case, the ADP is expected to meet the ultimate military requirements.

Requirements

The requirements for electrical performance characteristics of AC generator sets are listed in MIL-STD-1332B and are shown in Table 3-20. The generator class of interest is Utility Class 2A.

Test Data

Neither the TDE nor the "Prototype Engine" was designed to handle quick transient load changes. Therefore, no transient response tests were conducted. However, steady-state electrical tests were run on the TDE to determine its voltage, wave form, and frequency characteristics. Both the short-term (30 seconds) and long-term (40 hours) tests were run. A summary of the results of these tests is given in Table 3-21, along with a comparison to the required MIL-STD. The backup material for Table 3-21 is included in Figures 3-22 through 3-25.

Figure 3-22 gives the long-term variation of the frequency with time. The short- and long-term variation of the voltage across a resistive load is shown in Figure 3-23 and a tabulation of the long-term voltage data is given in Table 3-22. Figure 3-24 was used to calculate the maximum deviation factor for the voltage wave form. The figure, Table 3-23 and the equations that follow present the tabulated data and calculations that were performed to find the maximum deviation factor.

TABLE 3-19

FPSE ELECTRICAL PARAMETERS VERSUS REQUIREMENTS

Parameter	Test Data	Design Projection	Projection	Requirement Tactical, Utility 2C
Voltage				
• Steady State Stability (Variation) (Bandwidth) %				
– Short Term (30 sec)	<1	<1	<1	1
– Long Term (4 hr)	2.54	<2	<2	2
• Transient				
– Dip/Recovery	N/A	43/0.17	<43/ >0.17	20/3
– Rise/Recovery	N/A	30/1	30/1	30/3
Wave Form				
• Max. Deviation Factor %	1.5	<1.5	<1	5
• Individual Harmonic %	<2	<2	<2	2
Frequency				
• Steady State Stability (Variation) (Bandwidth) %				
– Short Term (30 sec)	<1	<1	<1	1
– Long Term (4 hr)	<2	<2	<2	3
• Transient				
– Undershoot/Recovery	N/A	7/0.17	<7/ >0.17	4/4
– Overshoot/Recovery	N/A	3/2	3/2	4/4

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TABLE 3-20

ELECTRICAL PERFORMANCE CHARACTERISTICS OF AC GENERATOR SETS

Characteristic parameter	Precise Class 1	Utility Class 2A	Utility Class 2B	Utility Class 2C	Test Method MIL-STD-705
a. Voltage characteristics					
1. Regulation (%)	1	2	3	4	608.1
2. Steady-state-stability (variation) (bandwidth%)					
(a) Short term (30 seconds)	1	1	2	2	608.1
(b) Long term (4 hours)	2	2	4	4	608.2
3. Transient performance					
(a) Application of rated load					
(1) Dip	15	20	20	30	619.2
(2) Recovery (seconds)	0.5	3	3	3	619.2
(b) Rejection of rated load					
(1) Rise (%)	15	30	30	30	619.2
(2) Recovery (seconds)	0.5	3	3	3	619.2
(c) Application of simulated motor load (twice rated current)					
(1) Dip (%)	30	N/A	40	N/A	619.1
(2) Recovery to 95% of rated voltage (seconds) (Note 1)	0.7	N/A	5	N/A	619.1
4. Waveform (Note 2)					
(a) Maximum deviation factor (%)	5	5	5	6	601.1
(b) Maximum individual harmonic (%)	2	2	2	3	601.4
5. Voltage unbalance with unbalanced load (%) (Note 3)	5	5	5	5	620.2
6. Phase balance voltage (%)	1	1	1	1	508.1
7. Voltage adjustment range (%) (min) (Note 4)	-5 +1[illegible]	±10	-5 +17 (Note 5)	-5 +5	511.1
b. Frequency characteristics					
1. Regulation (%)	0-3 Adj'able	0-5 Adj'able	3	3	608.1
2. Steady-state-stability (variation) (bandwidth %)					
(a) Short term (30 seconds)	0.5	0.5	2	4	608.1
(b) Long term (4 hours)	1	1	3	4	608.2
3. Transient performance					
(a) Application of rated load					
(1) Undershoot (%)	4	4	4	4	608.1
(2) Recovery (seconds)	2	4	4	4	608.1
(b) Rejection of rated load					
(1) Overshoot (%)	4	4	4	5	608.1
(2) Recovery (seconds)	2	4	4	6	608.1
4. Frequency adjustment range (%) (min) (Where required)	±3	±4	±3	±3	511.2

NOTES:

1. The voltage shall stabilize at or above this voltage (not applicable to all sets rated 5 kw or smaller, or 500 kw and larger).
2. Specified values are for three phase output; for single phase, add additional 1%.
3. With generator set connected for three phase output and supplying a single line-to-line, unity power factor, load of 25% of rated current and with no other load on the set. (Not applicable for single phase connections of sets.)
4. For Mode II sets, upper voltage adjustment is +10% of rated voltage. For Mode I sets operating at 50 Hz, upper voltage adjustment may be limited to the nominal voltages shown in table IV, Note 4.
5. Values shown are for sets rated at 15 kw and above.

TABLE 3-21

ENGINE-GENERATOR SPECIFICATIONS

Specifications	Military Requirements	TDE Value
1) Voltage		
Steady State Stability (variation)(bandwidth) %		
• short term (30 seconds)	1	<1
• long term (4 hours)	2	2.54
2) Wave Form		
• maximum deviation factor %	5	1.5
• individual harmonic %	2	<2
3) Frequency		
Steady State Stability (variation)(bandwidth) %		
• short term (30 seconds)	1	<1
• long term (4 hours)	3	<2
4) Engine Time Constant (min.)	---	<5

Test Point

Voltage - 68 volts

Current - 7.0 amps

Power Factor - 1.0

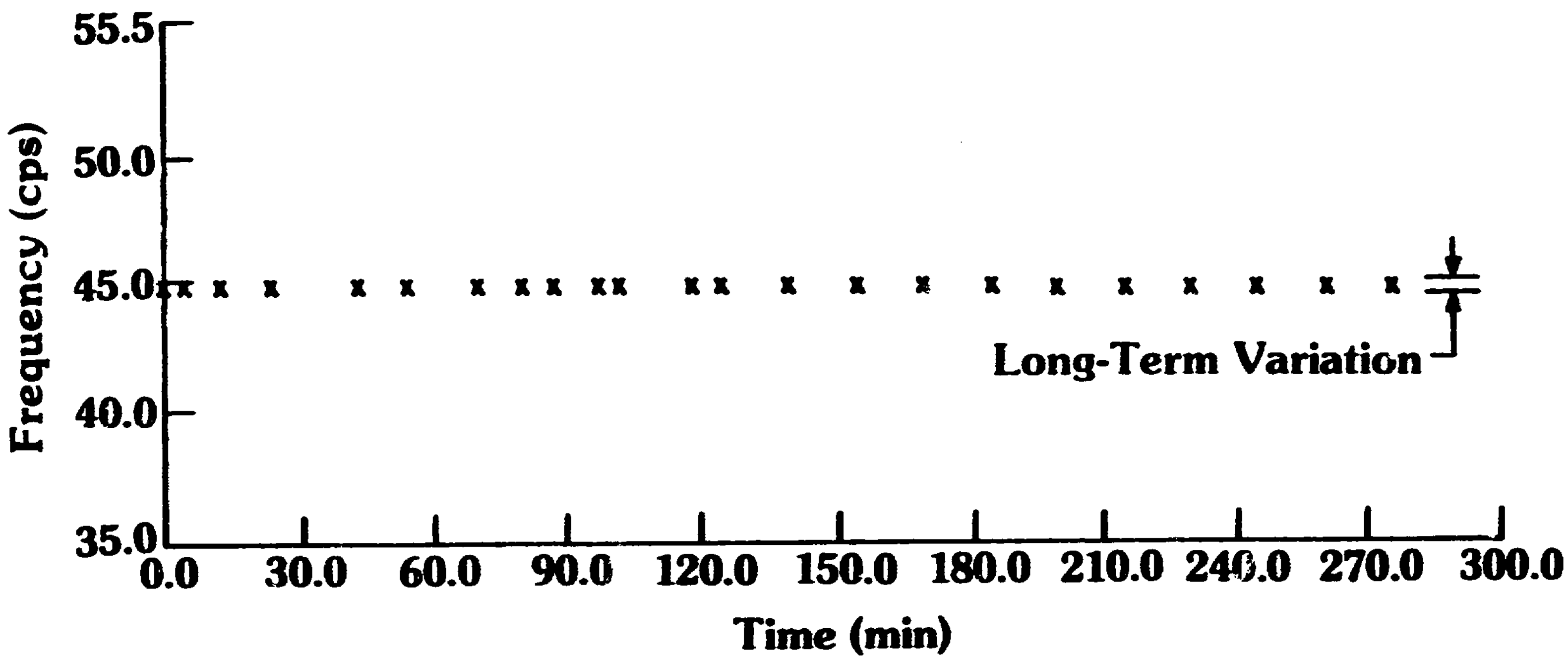

Fig. 3-22 Frequency Versus Time

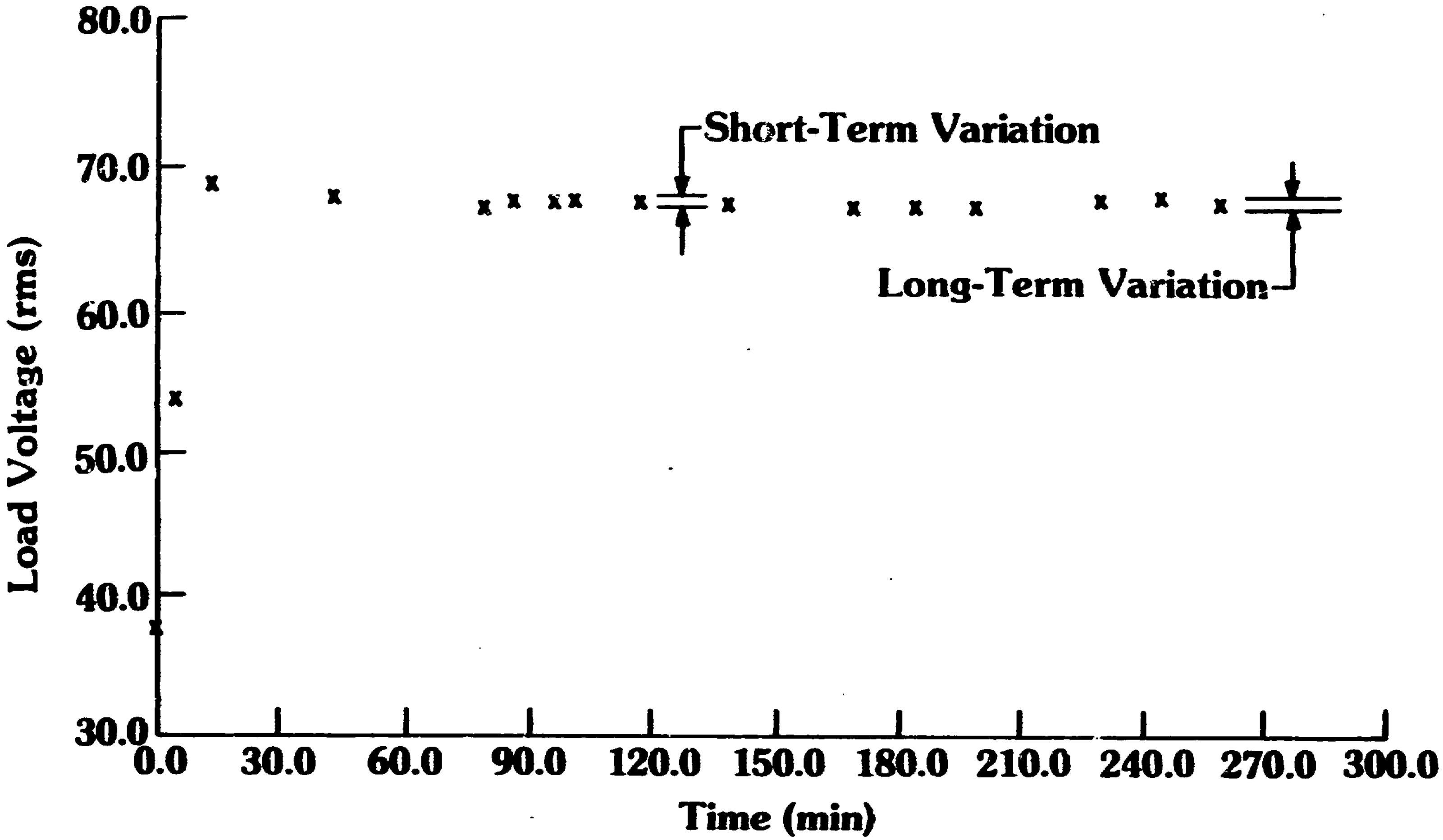

Fig. 3-23 Load Voltage rms Versus Time

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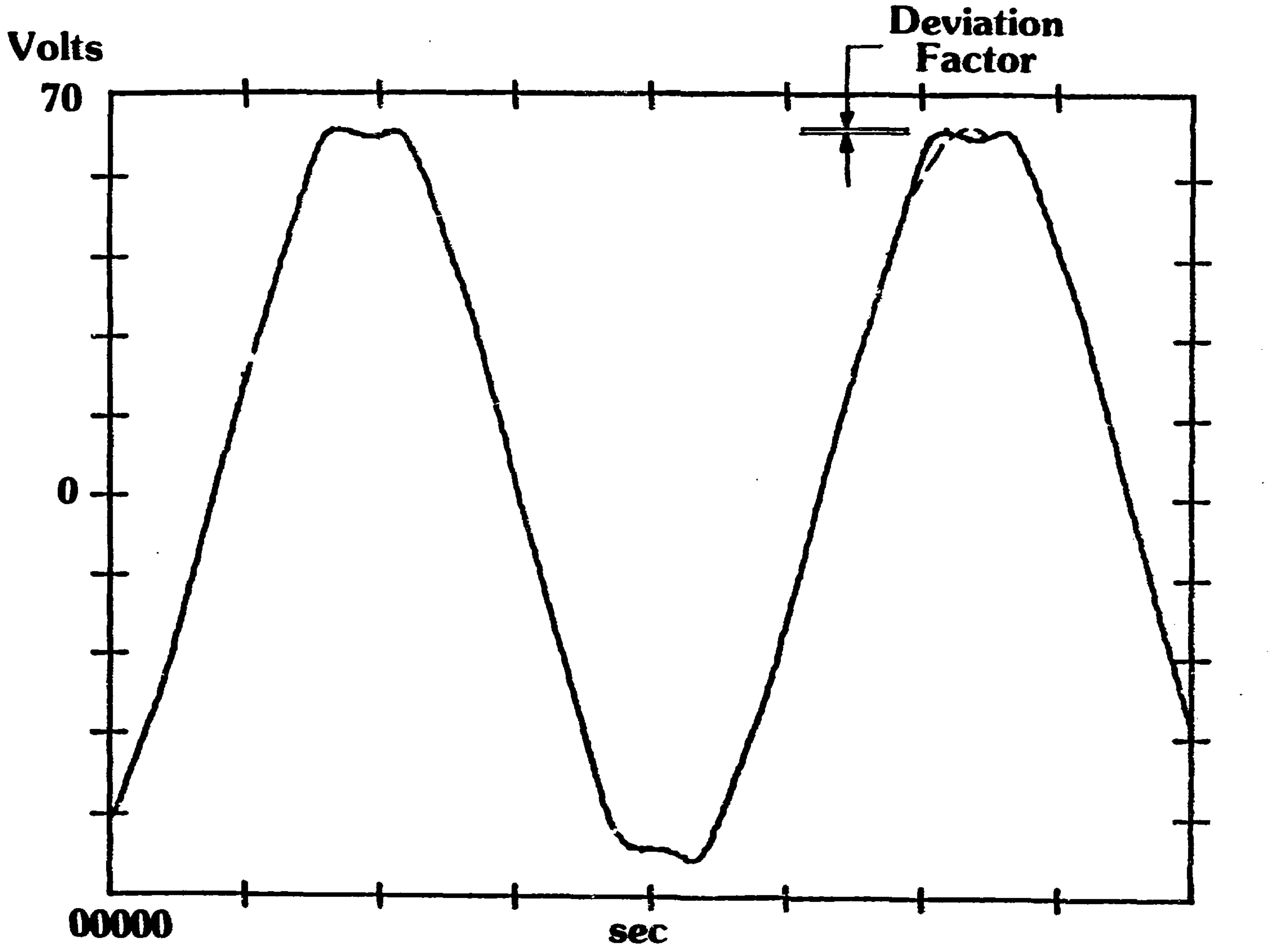

Fig. 3-24 Alternator Voltage Wave Form

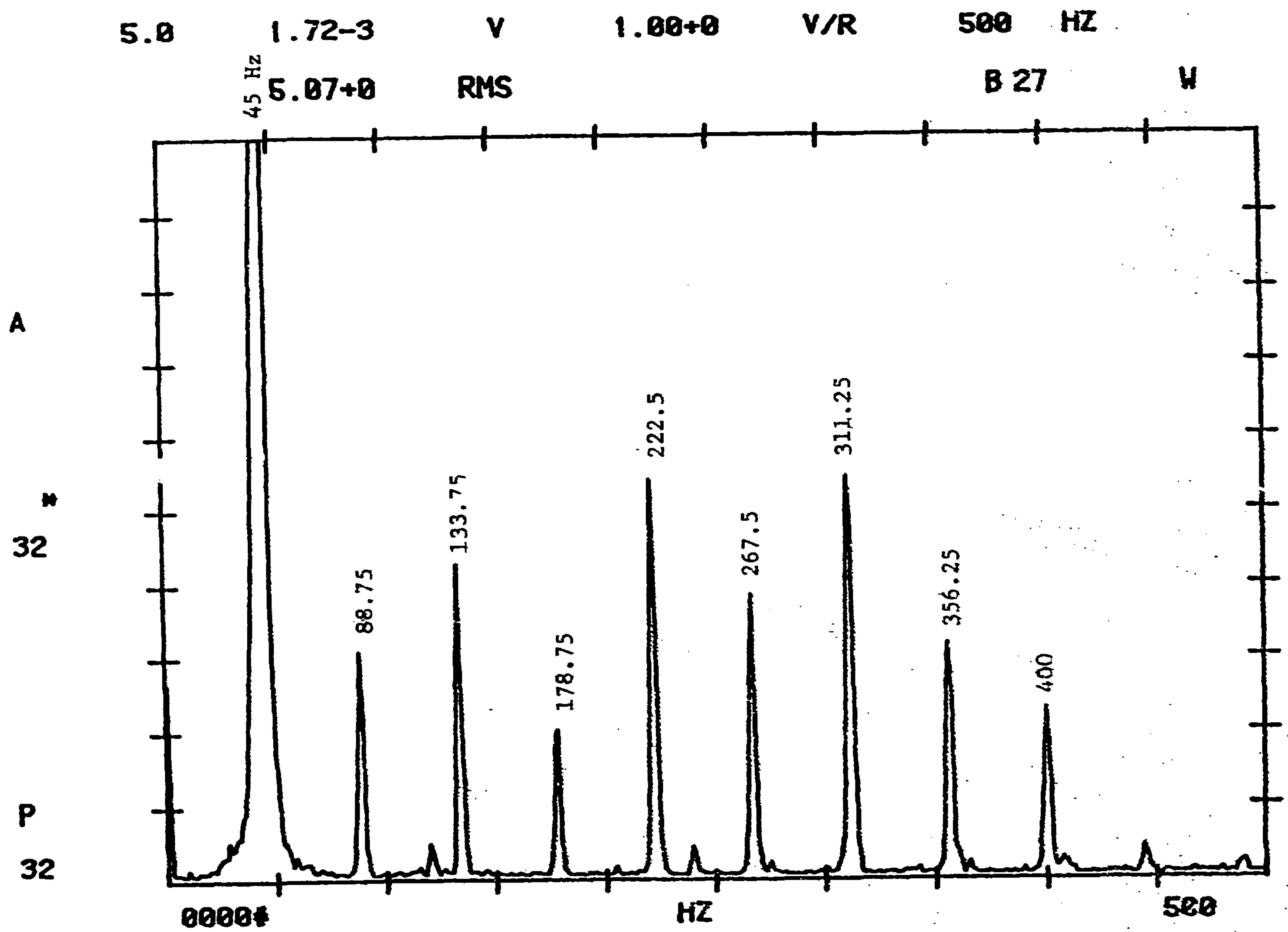

Fig. 3-25 Alternator Voltage Harmonic Content

TABLE 3-22

STEADY-STATE VOLTAGE VARIATION DATA

TIME (MIN)	LOAD VOLTAGE RMS VOLTS PEAK	FREQ HZ	VOLTS AVG	FREQ HZ	LOAD CURRENT RMS AMPS PEAK	FREQ HZ	AMPS AVG	FREQ HZ
0(10:00 A.M.)	5.68 x 10^1	44.75			.0649 x 10^2	44.5		
10								
20	6.43	44.75	5.69 x 10^1	44.75				
30					.0668	44.75	.0659 x 10^2	44.75
40								
50	6.24	44.75	6.31	44.75				
60	6.21	44.75			.0708	44.75	.0668	44.75
70			6.28	44.75				
80	6.34	44.75	6.37	44.75	.0668	44.75	.0688	44.75
90					.0688	44.75		
100	6.37	44.75					.0698	44.75
110			6.34	44.75	.0644	44.75		
120(2 Hrs.)	6.37	44.75	6.34	44.75	.0693	44.75	.0703	44.75
130							.0693	44.75
140	6.31	44.75	6.28	44.75	.0688	44.75		
150	6.37	44.75	6.28	44.75			.0693	44.75
160					.0683	44.75	.0683	44.75
170	6.34	44.75	6.31	44.75	.0688	44.75		
180	6.34	44.75	6.37	44.75			.0688	44.75
190					.0578	44.75	.0664	45.00
200	6.34	44.75	6.34	44.75	.0703	44.75		
210	6.37	44.75	6.24	44.75			.0693	44.75
220					.0703	44.75	.0698	44.75
230	6.37	44.75	6.28	44.75				
240(4 Hrs.)					.0703	44.75	.0693	44.75
250								
260								
270								
280								
290								
300								

TABLE 3-23

VALUES FOR MAXIMUM DEVIATION FACTOR

ORDINATE NO.	ORDINATE LENGTH (mm)	ORDINATE SQUARED $(mm)^2$	ANGLE ELECTRICAL DEGREES	SINE OF ANGLE	ORDINATE LENGTH EQUIVALENT SINE WAVE (in.)
0	0	0	0	0	0
1	4.8	23.04	10.59	.184	.38
2	13.7	187.69	21.18	.361	.74
3	22.1	488.41	31.76	.526	1.08
4	29.0	841.00	41.35	.674	1.38
5	37.1	1376.41	52.94	.798	1.64
6	46.0	2116.00	63.53	.895	1.84
7	50.8	2580.64	74.11	.962	1.97
8	51.8	2683.24	84.71	.996	2.04
9	50.8	2580.64	95.29	.996	2.04
10	51.0	2601.00	105.88	.962	1.97
11	51.8	2683.24	116.47	.895	1.84
12	48.8	2381.44	127.06	.798	1.64
13	41.9	1755.61	137.65	.674	1.38
14	35.3	1246.09	148.24	.526	1.08
15	27.2	739.84	158.82	.361	.74
16	18.8	353.44	169.41	.184	.38
17	9.1	82.81	180.00	0	0
18	0	0	190.59	-.184	-.38
19	-9.1	82.81	201.18	-.361	-.74
20	-18.3	334.89	211.76	-.526	-1.08
21	-27.7	767.29	222.35	-.674	-1.38
22	-37.3	1391.29	232.94	-.798	-1.64
23	-44.9	2016.01	243.53	-.895	-1.84
24	-48.5	2352.25	254.12	-.962	-1.97
25	-49.5	2450.25	264.71	-.996	-2.04
26	-50.0	2500.00	275.29	-.996	-2.04
27	-51.3	2631.69	285.88	-.962	-1.97
28	-48.3	2332.89	296.47	-.895	-1.84
29	-42.2	1780.84	307.06	-.798	-1.64
30	-35.1	1232.01	317.65	-.674	-1.38
31	-29.5	870.25	328.24	-.526	-1.08
32	-22.1	488.41	338.82	-.361	-.74
33	-12.7	161.29	349.41	-.184	-.38
34	0	0	360.00	0	0

- Sum of the ordinate value squared:

$$(\text{mm})^2 = 46{,}112.71$$

$$\text{Amplitude} = \sqrt{\frac{46{,}112.71}{34}} * \sqrt{2}$$

$$\text{Amplitude} = 52.08 \text{ mm}$$

- Maximum Deviation Factor, Figure 3-24:

$$\text{MDF} = \frac{.03}{2.07} \times 100 = 1.45\%$$

Figure 3-25 provides the measured harmonics in the voltage wave form. The fifth and seventh are the largest harmonics. Table 3-24 gives a tabulation of the harmonic content after three hours of running.

Design Data

As delineated in Section 3.5.7, the EM employs a unique control mechanism to accommodate quick transient load changes. The concept has been tested to verify the mechanical performance, and excellent results have been achieved. The control system has not yet been tested in a full engine configuration. However, an analysis has been completed in which the generator transient system response characteristics were mathematically modeled.

Figures 3-26 and 3-27 show the transient response predicted for the electrical and dynamic parameters of interest. Table 3-25 lists the anticipated transient responses for the EM system. As indicated, the only deviation from the specifications is expected in the frequency undershoot and the voltage dip that will occur when the load is instantaneously switched from 20% to full load. A 7% frequency undershoot is anticipated relative to a 4% requirement, and a 43% voltage dip is anticipated relative to a 20% requirement; however, the recovery time will be 0.17 seconds for both the voltage and frequency relative to a 3.0 and 4.0 second requirement, respectively.

TABLE 3-24

STEADY-STATE VOLTAGE HARMONIC CONTENT TEST DATA

MAJOR FREQUENCIES	RMS LOAD VOLTAGE 1:51 P.M. VOLTS PEAK	FREQ HZ	% OF FUND	RMS CURRENT 1:57 P.M. AMPS PEAK	FREQ HZ	% OF FUNDAMENTAL
Fundamental	6.28	44.75	----	.0693	44.75	------
2nd	.0225	90	.358	251×10^{-6}	90	.362
3rd	.0932	133.75	1.484	991×10^{-6}	135	1.430
4th	.0654	178.75	1.041	709×10^{-6}	180	1.023
5th	.104	223.75	1.656	.001	223.75	1.443
6th	.110	268.75	1.751	.00119	268.75	1.717
7th	.0634	313.75	1.009	717×10^{-6}	313.75	1.034
8th	.041	358.75	.652	499×10^{-6}	358.75	.720
9th	.019	402.5	.302	175×10^{-6}	403.75	.252
10th	.012	447.5	.191	130×10^{-6}	448.75	.187

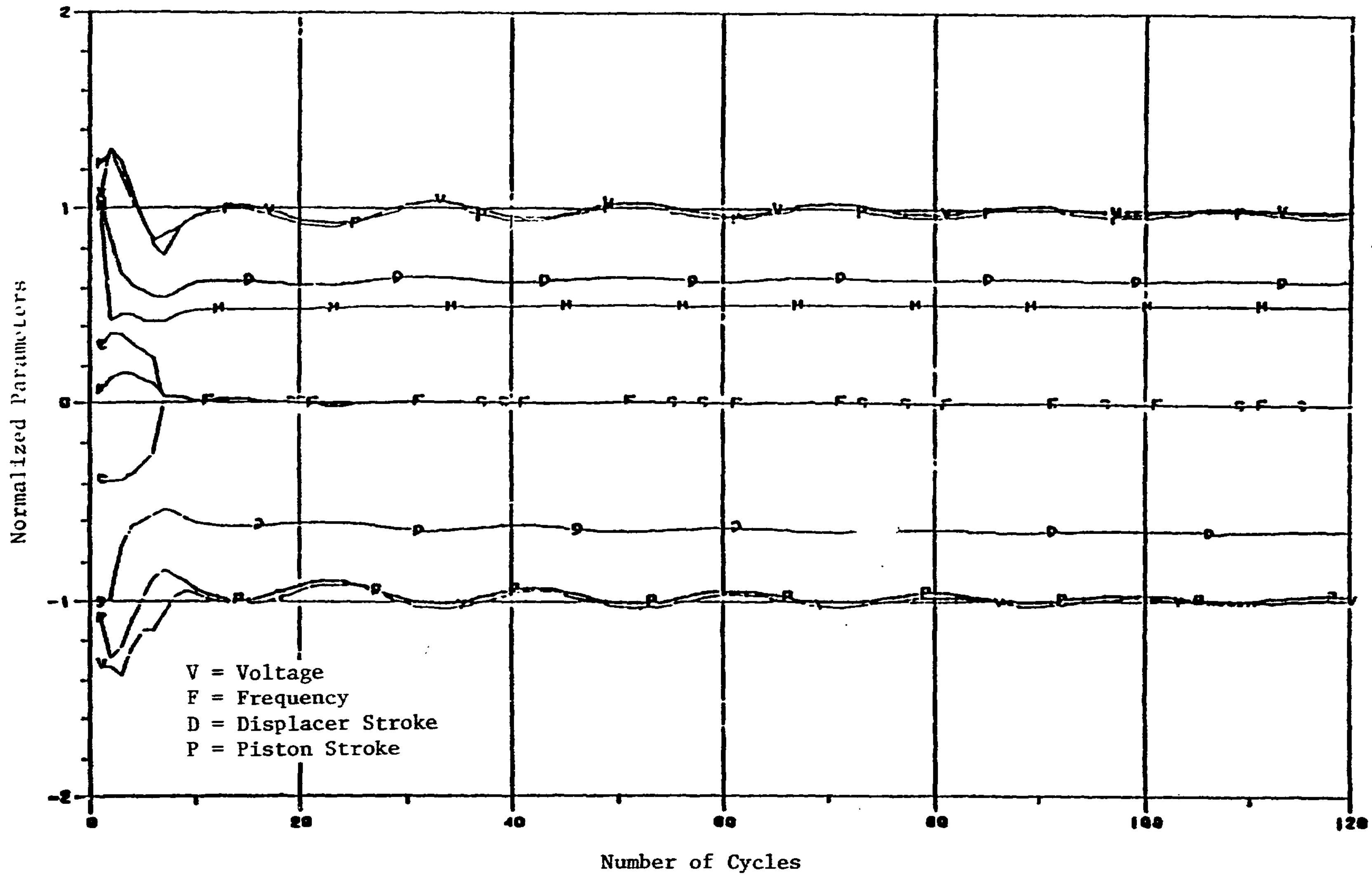

Fig. 3-26 *Transient Response Predicted for Engine System Parameters for Step Load Change From Full Load to 20% Load*

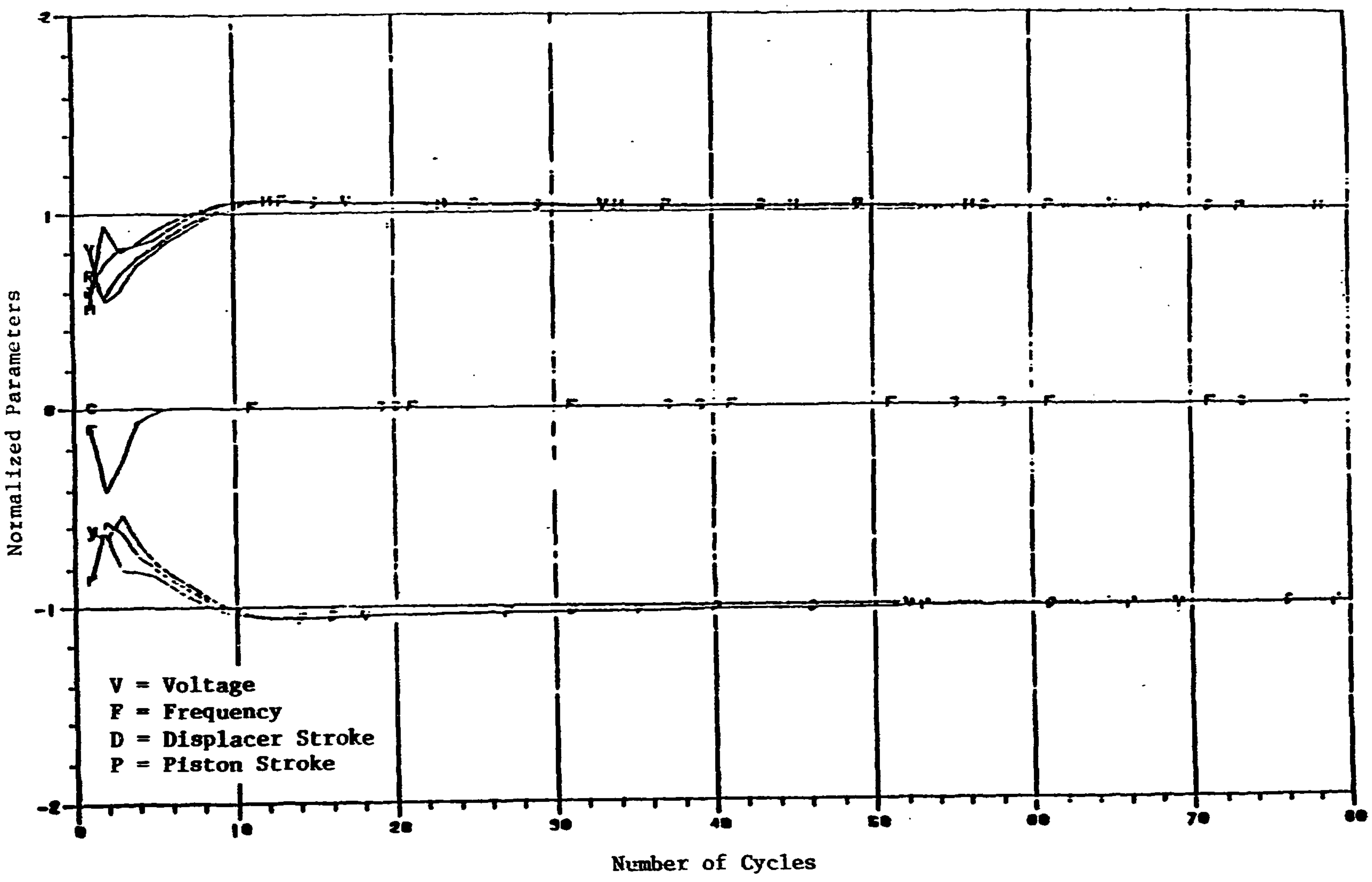

Fig. 3-27 Transient Response Predicted for Engine System Parameters for Step Load Change from 20% Load to Full Load

TABLE 3-25

TRANSIENT RESPONSES FOR THE EM SYSTEM

Transient Response	EM Predicted Performance	Military Requirement
• Voltage		
- Dip (%)/Recovery (sec)	43/0.17	20/3
- Rise (%)/Recovery (sec)	30/1	30/3
• Frequency		
- Undershoot/Recovery	7/0.17	4/4
- Overshoot/Recovery	3/2	4/4

Projected Design

The ADP will be designed to have response characteristics that will meet the current military requirements, if those requirements are the most desirable for actual operation. It is recommended, however, that the current requirements be reevaluated to determine whether or not it would be advantageous to have a very fast response at the sacrifice of some bandwidth deviation. If this is the case, the EM control system, as designed, would also be suitable for the ADP.

SECTION 4.0

CONCLUSIONS

4.0 CONCLUSIONS

4.1 Parameter Comparison Summary

The general conclusions can be summarized as follows:

- The state of the art of the FPSE allows for current commercial hardware designs to achieve a significant portion of the military requirements and standards.
- Engineering projections show that the FPSE can, in the near term, be developed to comply with all military requirements for ground power.

A complilation of the parameters investigated in this study is given in Table 4-1. Specific conclusions regarding the technology readiness of FPSE can be drawn from this information. These conclusions can be expressed in terms of three categories: (1) demonstrated capabilities of established technology (as evidenced by available "test data"), (2) state of the art (as evidenced by ongoing commercial design and development activities), and (3) future development (as evidenced by design projections and engineering calculations). The following discussion delineates these conclusions.

4.1.1 Summary of Physical Parameters

Established Technology

Experience to date has primarily been related to nonsystem experimental development. These units do not meet military requirements for physical attributes of generator sets.

State of the Art

The current EM design will meet requirements for orientation and mechanical design. However, the EM was designed as a laboratory prototype system and will not be capable of meeting size or weight requirements.

Future Development

The ADP will be packaged for a more compact configuration to meet

TABLE 4-1

MERADCOM STUDY, COMPARATIVE RESULTS

Parameter	Test Data (1)	Design (2)	Projection (2)	Requirement (2)
Physical:				
Size	40 in. x 12 in. dia	14.5 ft^3	11.5 ft^3	12 ft^3
Weight	466 lb_m	485 lb_m	438 383 (3) 298 (4)	300 lb_m
Orientation	Tested Flame Up and Flame Down	Operational to 41° from Horizontal	Operational to 38° from Horizontal	31° from Horizontal
Shock and Vibration	N/A	Mounts and Frame Designed to Meet Specifications	Mounts and Frame Designed to Meet Specifications	18-in. Drop
Thermodynamics:				
Specific Fuel Consumption (lb/kW_e)	0.78 (5) 1.21 (6)	0.75	0.62	<0.95 (7)
IR Signature	N/A	ΔT = 18°C	ΔT < 7°C	As Low as Possible
Exposed Metal Temperature	120°C max	Insulated/Enclosed	Insulated/Enclosed	Enclosed
Fuel Capacity	Natural Gas	Natural Gas (Diesel)	Combat Gas JP-4, JP-5, DF-1, DF-2	Combat Gas JP-4, JP-5, DF-1, DF-2
Fuel System Safety	Manual Safety Controls	Automatic Safety Controls	Fail-Safe Design	Fail-Safe Design
Audio:				
Noise	78 db @ 5 ft	Low Noise	Inaudible at 100 m	Inaudible at 100 m
Materials:				
Material	Commercial Quality Cobalt Alloy	Commercial Quality Cobalt Alloy	Commercial Quality	Commercial Quality

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TABLE 4-1 (Cont'd)

Parameter	Test Data (1)	Design (2)	Projection (2)	Requirement (2)
Operational:				
Power	1.0 kW_e	3.3 kW_e	3.0 kW_e	3.0 kW_e
Frequency	46 Hz	60 Hz	60 Hz	60 Hz
Lubrication	Gas Bearings	Gas Bearings	Gas Bearings	N/A
Climatic Conditions	Engine Starts at Cold or Hot Temperature	95°F Design Point - O.K. Over Range	95°F Design Point - O.K. Over Range	-25 to +125°F
Altitude Condtions	N/A	Much Easier to Maintain Power than ICE	Much Easier to Maintain Power than ICE	Rated Power at 5000 ft, 107°F
Reliability	200-hr Endurance Run	— 10,000-hr MTBO	750-hr MTBF 10,000-hr MTBO	460-hr MTBF 3000-hr MTBO
Maintenance	Developmental Repair	Developmental Repair	Limited Maintenance on Engine/Alternator	Easy Repai
Control	Manual	Automatic	Automatic	Automatic
Electrical:				(8)
Voltage				
- Steady-State Stability: Variation; Bandwidth (%)				
Short-Term (30 sec)	<1.0	<1.0	<1.0	1.0
Long-Term (4 hr)	2.54	<2.0	<2.0	2.0
- Transient:				
Dip/Recovery	N/A	43/0.17	<43/>0.17	20/3
Rise/Recovery	N/A	30/1.00	30/1	30/1
Wave Form				
- Max Deviation Factor (%)	1.5	<1.5	<1.5	5
- Individual Harmonic (%)	<2.0	<2.0	<2.0	2

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TABLE 4-1 (Cont'd)

Parameter	Test Data (1)	Design (2)	Projection (2)	Requirement (2)
Electrical (Cont'd)				(8)
Frequency				
- Steady-State Stability: Variation; Bandwidth (%)				
Short-Term (30 sec)	<1	<1	<1	1
Long-Term (4 hr)	<2	<2	<2	3
- Transient				
Undershoot/Recovery	N/A	7/0.17	<7/>0.17	4/4
Overshoot/Recovery	N/A	3/2.00	3/2	4/4

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(1) 3-kW Engine/Alternator Component (PE)

(2) Total System

(3) With Lightweight Control System

(4) With Lightweight Alternator

(5) Based on Measured Component Peak Efficiency

(6) Based on Measured Rate System Efficiency

(7) Overall SFC Including Generator

(8) Tactical, Utility 2C

military requirements for size. However, some technology development of lightweight alternator systems will be required to achieve the overall system weight requirement. If this is accomplished, the ADP would then meet all requirements for physical parameters.

4.1.2 Summary of Thermodynamic Parameters

Established Technology

If properly matched in a system configuration, available components could achieve desired levels of specific fuel consumption. Additionally, testing of available hardware provides sufficient evidence to anticipate that the other military requirements for thermodynamic parameters can be demonstrated in the near term with continued development.

State of the Art

The EM system meets nearly all of the thermodynamic requirements. Additional development of the combustion system would be required, however, to achieve a total multifuel capability.

Future Development

The ADP is projected to achieve all of the military thermodynamic performance parameters.

4.1.3 Summary of Audio Parameters

Established Technology

Preliminary tests confirm the potential for "silent" operation of FPSE systems.

State of the Art

Design attention will need to be given toward minimizing noise emissions from auxiliary components.

Future Development

The ADP is expected to comply with the noise specification for Silent Lightweight Electric Energy Power Systems (SLEEPS).

4.1.4 Summary of Materials Parameters

Established Technology

Current hardware systems incorporate readily available engineering materials.

State of the Art

A manufacturing cost study was made for the EM. This study concluded that, with the materials and fabrication technique required in the design, the unit could be manufactured at a competitive cost with equivalent diesel engine generator systems.

Future Development

The ADP will utilize commonly available engineering materials in its design. No ceramic material will be required to achieve the predicted performance levels. The linear alternator, however, might contain a small quantity of samarium cobalt permanent magnets to provide for an overall high specific power system.

4.1.5 Summary of Operational Parameters

Established Technology

Test data from available hardware confirms the potential for the FPSE to meet the military operational requirements.

State of the Art

The EM will help to establish the required reliability and maintainability levels on a total system basis.

Future Development

The ADP is expected to meet all requirements for operational parameters.

4.1.6 Summary of Electrical Parameters

Established Technology

Although currently available FPSE generators operate without transient control capability, they have demonstrated excellent capability for achieving steady-state requirements for voltage, wave form, and frequency.

State of the Art

The EM embodies a unique electromechanical controller to accommodate quick transient load changes. The EM will have stand-alone capability with utility class signal characteristics.

Future Development

The ADP will have full system control capability for achieving all military requirements for electrical characteristics of AC generators.

4.2 Comparison with Alternative Military Generators

The general conclusions are summarized as follows:

- Current FPSE hardware designs compare most favorably with alternative generator sets now in the standard family.
- Advanced FPSEs will surpass the operational characteristics of alternative standard family generator sets in all respects.

The EM and ADP were evaluated relative to present generator sets in the military standard family. These standard family units include gasoline-engine-driven generators, diesel-engine-driven generators, and a gas-turbine-driven generator. The specifications for these units are presented in Appendix C. Two parameters were selected for graphic comparison with FPSEs. These parameters are system weight and system fuel consumption. The results of these comparisons are presented in Figure 4-1. As indicated, the FPSE (both near term and advanced versions) exceed available capabilities for fuel consumption, even as compared with diesel engine generators.

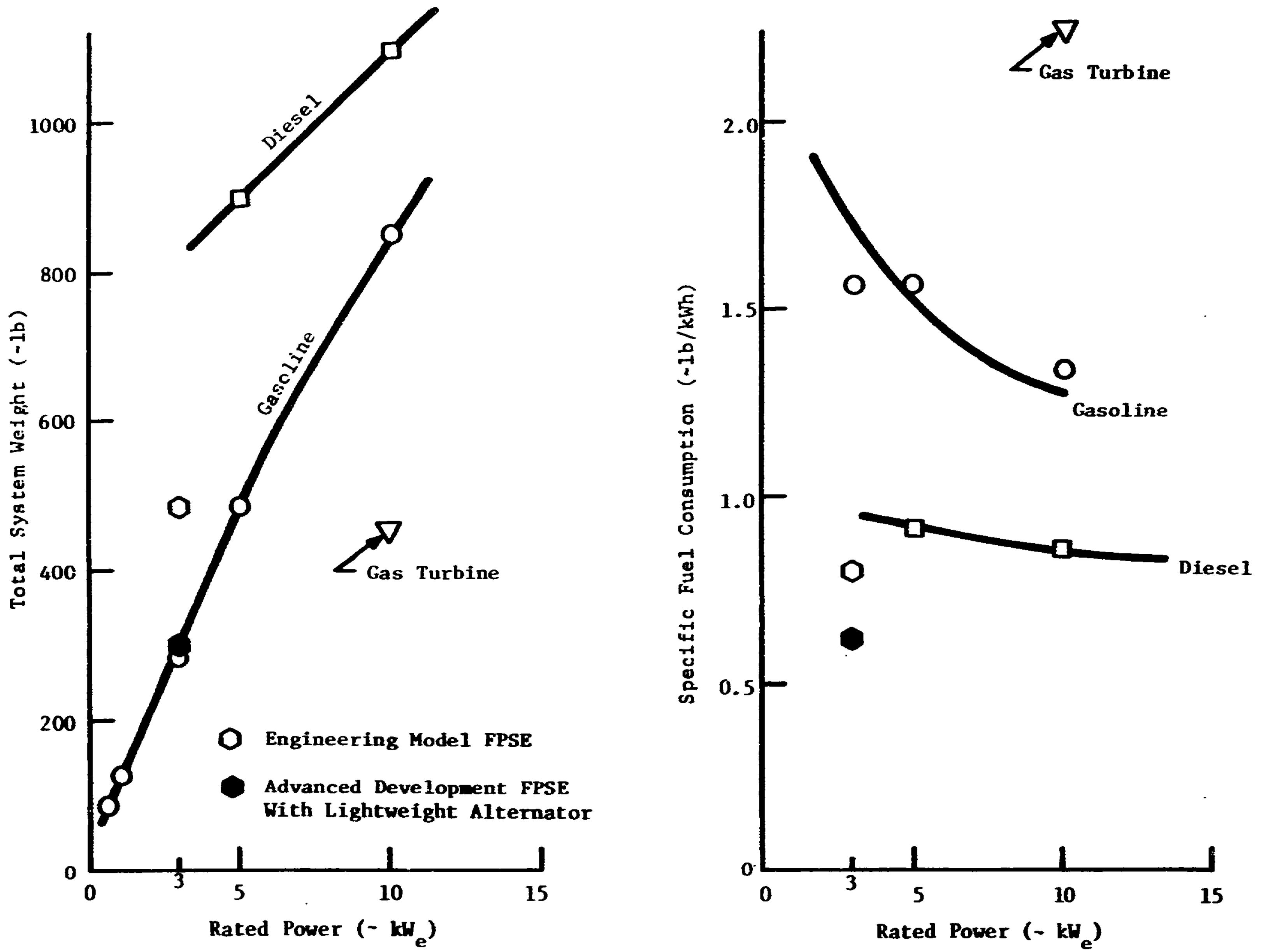

Fig. 4-1 Comparison of FPSE Characteristics With Other Military Generators

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In terms of system weight, the commercial-type FPSE (as typified by the EM) compares favorably with diesel sets. The lightweight militarized version (as typified by the ADP) could provide an overall system weight that is equal to the weight of equivalent-size gasoline engine generators.

These competitive attributes, coupled with the FPSE's unique capability for multifuel operation with long life, high reliability, and low maintenance, provide significant incentive for the Army to pursue development of the FPSE for advanced military power sources.

4.3 Development Status

The general conclusions are given as follows:

- The operational and developmental testing of a FPSE generator operating with full military logistics fuel capability could be established by 1984.
- A systems development program needs to be implemented in order to adapt commercially oriented FPSE technology for military application.

The TDE and "Prototype Engine" are experimental prototypes that have been used to conduct exploratory research in the field of free-piston engines and generators. These machines continue to provide significant contributions towards advancing the technological capabilities of linear machinery.

The Engineering Model is presently being assembled as a complete standalone system in the development class of 6.3A hardware. The EM was designed for stationary commercial applications, however. Presently, the engine and alternator subsystems are undergoing extensive performance testing prior to system integration.

The ADP is projected as an extension of the commercially oriented EM system design. The ADP embodies engineering modifications necessary to enable free-piston Stirling engine generators to meet all military requirements for ground power. However, significant system development is required to accomplish this militarization. Figure 4-2 shows the time frame in which the ADP could, with continued development, be available for qualification testing. As indicated, the demonstration of a FPSE generator system that meets all military requirements for ground power could be established by the end of 1984.

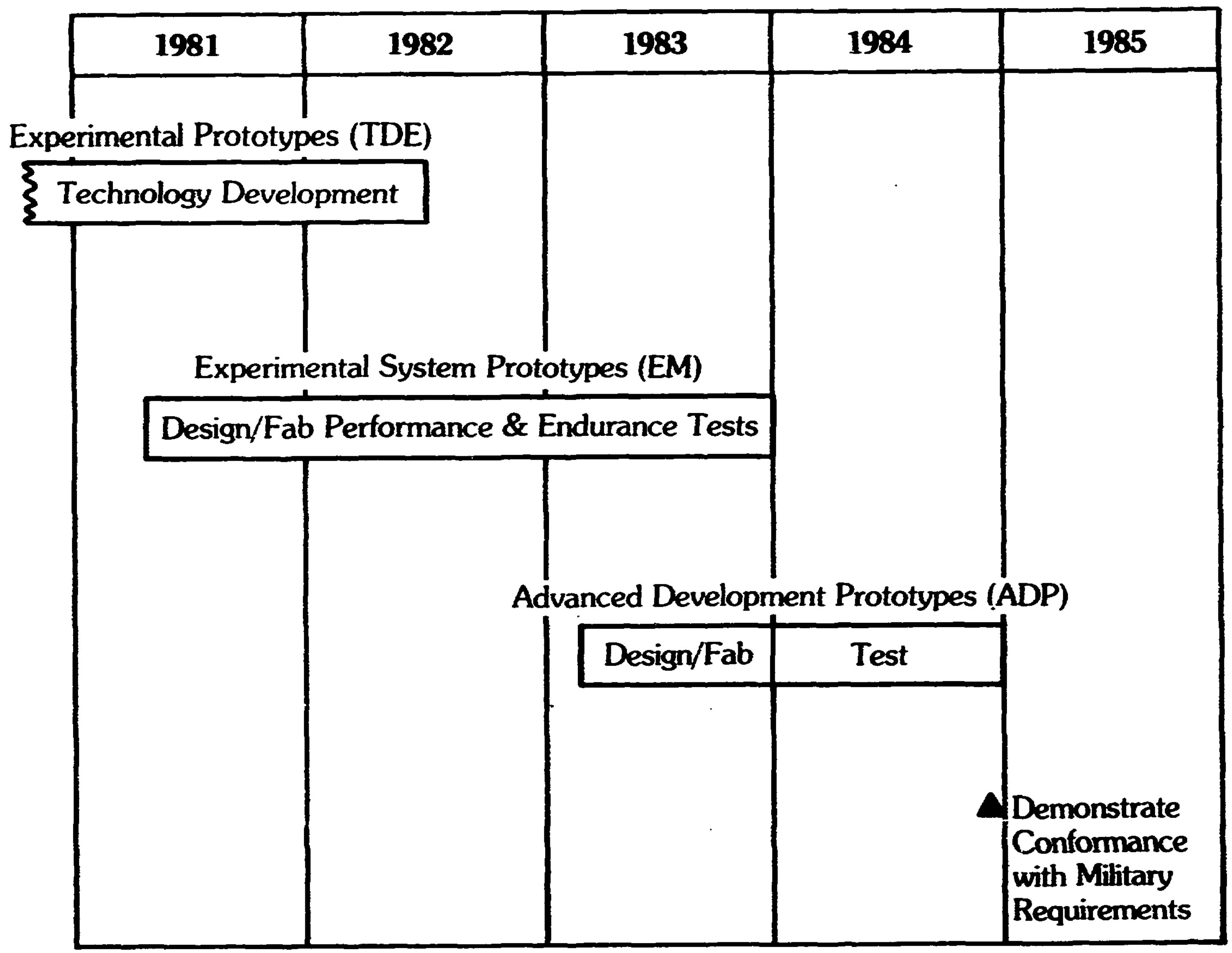

Fig. 4-2 FPSE Development Status Timetable

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SECTION 5.0

RECOMMENDATIONS

5.0 RECOMMENDATIONS

The previous section justifies the militarization of free-piston Stirling engine generators, based on their potential to provide superiority in military field power. However, several development issues exist that need to be addressed to enable militarization. Furthermore, these issues strictly involve development for military application. The issues involve the following:

- Reduce overall weight to enhance system portability in a combat environment.
- Establish multifuel operation to provide full capability to operate with military logistics fuels.
- Establish system durability to survive operation and use by nontechnical personnel in a combat situation.

The FPSE is currently being developed for stationary commercial applications that do not have the stringent requirements for weight, fuel flexibility, and ruggedness as do military applications. Because of this situation, the issues listed above are not likely to be resolved without military support. Therefore, it is recommended that an appropriate development program be established within the Department of the Army to provide the required development. Recommended development program plans are detailed in the following section.

5.1 Recommended Development of a Lightweight Linear Alternator

A lightweight alternator design was identified in Section 2.1.1 as having the potential to reduce the overall system weight by more than 110 lb. A program is recommended to develop and integrate the alternator with an existing engine within six months. The overall program, including system test and evaluation, could be completed within 11 months. The proposed design is based upon proven linear machinery principles, and the program is categorized as low risk. The overall objective of this program is the development of an alternator which will significantly reduce the weight and size of the present Engineering Model free-piston Stirling engine-generator system. The specific technical objectives are that the alternator selected must integrate with the existing Engineering Model configuration, maintain efficiency levels of 85% or greater and have the potential to reduce the weight of the system by more than 100 lb. The selected design has the potential to meet or exceed all of the technical objectives. The development schedule for implementing this program is shown in Figure 5-1.

5.2 Recommended Multifuel Combustor Development

In Section 2.2.6, evidence was presented to confirm that a single external heat system for a FPSE could be developed to burn the full range of military logistics fuels including DF-1, DF-2, DF-A, JP-4, JP-5, and combat gasoline. It is recommended that existing hardware be used to verify the feasibility of multiple liquid-fuel combustors for FPSEs for military applications.

The program objective would be to characterize existing combustor operation with a range of liquid fuels and to an advanced combustor design based on experimental evidence. Such a program could result in the total development of an advanced experimental combustor and integration with an experiemental engine within 10 months.

5.3 Recommended Development Program for a Militarized FPSE Generator Advanced Development Prototype System

The objective of this program is to achieve full demonstration of a 3-kW free-postion Stirling engine-generator system operating on military logistic fuels to provide electrical-power output characteristics, as specified in MIL-STD-1332B, for Type-I Class-2 generators. The program result will be the delivery of (TBD)* operational prototype systems to the Army's Mobility Equipment Research and Development Command (MERADCOM) for operational testing.

The development plan is to evolve an ADP system from the technology established with the EM. The availability of EM hardware and test

*To be determined

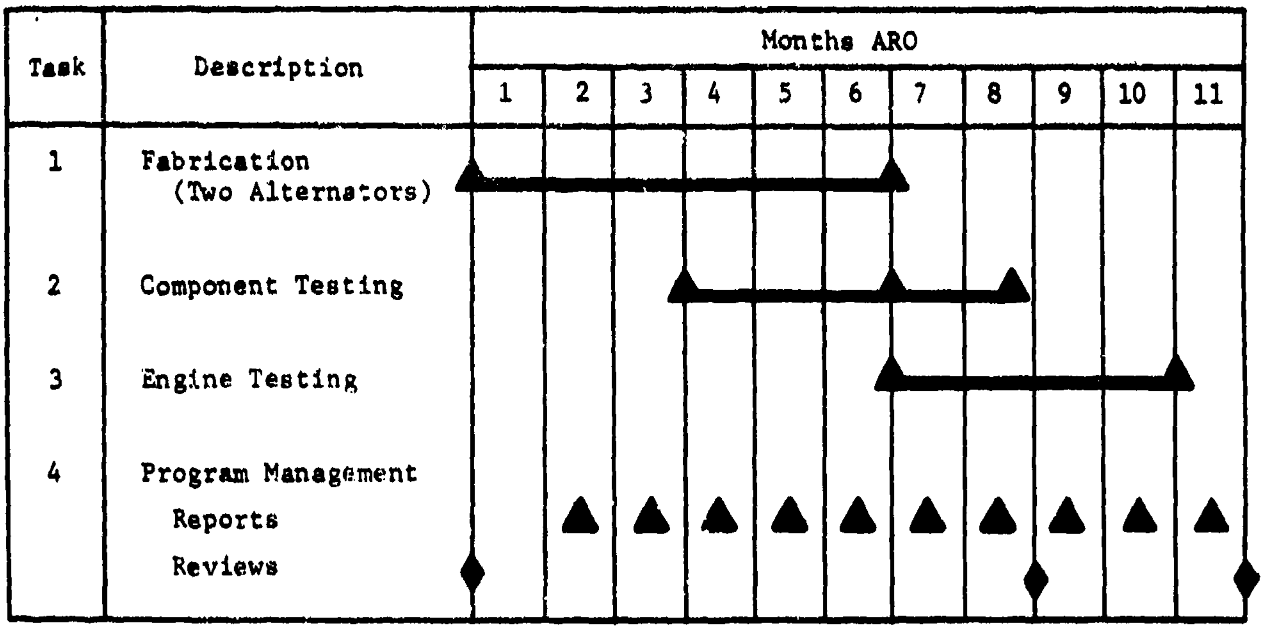

Figure 5-1 Lightweight Alternator Development Schedule

facilities is essential to the development of an ADP and will provide a technology baseline for verification of performance and endurance capability. Additionally, the EM hardware will provide workhorse engines to enable component and subsystem development early in the program.

During the initial program effort, the ADP design will be formulated through two complementary efforts:

1. A Reference Engine System Design (RESD), consisting of a computer model of the ADP, will be established to enable parametric evaluation of alternative component designs and operating conditions. The RESD will be updated and modified as new component data becomes available.

2. The ADP design will require supportive component development to reduce risks. These development efforts will be directed at a multifuel combustion system, lightweight alternator subsystem, controllable displacer drive, system controls, and auxiliary components. Component performance will be evaluated on both rig tests and in engine tests, utilizing the EM on a test-bed engine.

Following the RESD analysis, a detailed design of the ADP system will be completed and seven units will be fabricated. These ADP engine systems will be utilized to conduct engine performance testing, endurance testing, control development testing, durability and cost reduction development, system performance evaluation, and system environmental testing.

Finally, (TBD) additional ADP systems will be fabricated and assembled in a pre-engineering configuration. These units will have full capability for operating on military logistics fuels to provide electrical-power output that meets military specification for tactical-type, utility-class generators. Two units will remain at the development laboratory for field testing, while the remaining units will be shipped to MERADCOM for operational testing. The overall schedule for the development program, as shown in Figure 5-2, spans four years. During that time, over 25,000 hours of engine operating experience will be accumulated.

The development program will require the following tasks:

- Task 1.0 System Design and Analysis
- Task 2.0 Component and Subsystem Development
- Task 3.0 Laboratory System Development and Test
- Task 4.0 Advanced Development Prototype System Test and Delivery
- Task 5.0 Advanced Component Development
- Task 6.0 Program Management.

The objectives, technical approach, and schedule for each of these tasks are detailed in a separate report to MERADCOM.

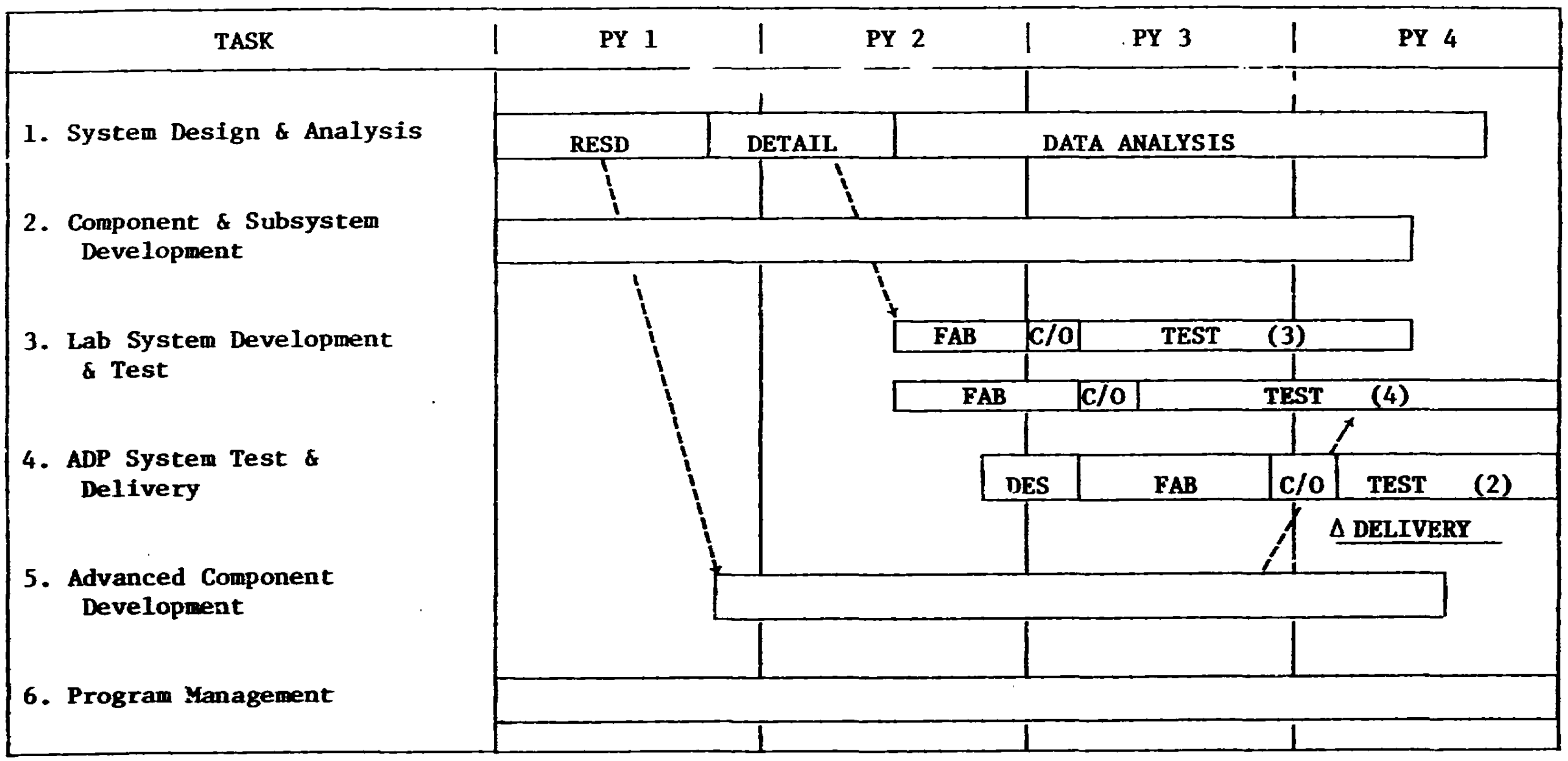

Figure 5-2 FPSE Advanced Development Prototype System Development Program Schedule

APPENDIX A

REPLICATION OF REFERENCE DOCUMENTS

/MAY 1975

Required Operational Capability (ROC) for a Family of Silent Lightweight Electric Energy Plans (SLEEP), TRADOC ACN 13215

1. Statement of the Need.

a. Title: A Family of Silent Lightweight Electric Energy Plants (SLEEP).

b. Statement of the Requirement. A family of lightweight, compact, reliable, easily transported, multifuel electric energy plants that will be difficult to detect by visual, aural and IR means is required to furnish electrical energy to operate communications equipment, command posts, visual and IR illumination devices, maintenance equipment, ground surveillance radar, to charge batteries, to permit combat vehicles to maintain a combat ready posture (to include large IR lamps) with the main engine(s) shut down for prolonged periods. The SLEEP family is not intended to replace batteries, but will replace present DOD standard generators of the same power ratings, if proven cost effective. SLEEP includes that degree of silencing obtainable on existing generators by use of thermal and acoustical kits where required.

c. CARDS reference number: 0652.

2. Time Frame. The SLEEP family is required by the field Army for missions throughout the world in the 1978-1985 time frame.

3. Threat/Operational Deficiency. Current electric power generating sources are extremely susceptible to aural and IR detection, endangering personnel and equipment in their vicinity in addition to hampering the using units' ability to listen for enemy activity. A generator set that is difficult to detect by visual and aural means will enhance the combat capability of friendly tactical units, allowing weapons and surveillance systems along with other support equipment having electric power requirements to be deployed in forward areas. Operation of a vehicle engine to drive its generator and maintain battery charge in stationary use creates poor fuel efficiency, rapid and undue wear of the vehicle engine, and makes the vehicle susceptible to enemy detection because of its sound and high IR heat source. Existing generator sets are designed for one fuel. Some combat vehicle engines require automotive gasoline and others use diesel fuel. For generator sets to be logistically and tactically compatible with their transport vehicles, multifuel design is required (provided the energy process is other than a piston engine driven electrical power generator).

4. Operational/Organizational Concepts.

a. Mission Capability. The SLEEP family of generator sets will be used as the principal source of silent tactical utility power at 60 or

400 Hertz for missions ranging up to 100 hours as described in section 1b above. Ratings are to be 0.5 KW, 1.5 KW, 3KW, 5 KW and 10 KW. DC sets are also required. Time needed to service and check out the set for recommitment, from shutdown to resumption of power generation, will be a maximum of 30 minutes, with a maximum reaction time of 15 minutes, depending on climatic conditions. The power plants shall be designed to minimize the effects of CBR, fire, blast and similar agents or events. Nuclear hardening is not required.

b. Geographical areas of use. The SLEEP family will be capable of specified performance at rated load under climatic categories 1, 2, 3, 4, 5, 6, 7, 8 as described in AR 70-38, from sea level to 8000 feet elevation, with protective shelter varying from permanent facilities to no cover at all. Electric performance may be derated at elevations above 5000 feet.

c. Type units. SLEEP generators will be authorized only in those specified units where noise discipline is essential (e.g., brigade area and forward) to the performance of its tactical mission.

5. <u>Essential Characteristics</u>.

a. Electrical performance for AC and DC sets will conform to MIL-STD-1332.

b. Reliability, availability, and maintainability (RAM) characteristics. Because of the varied operational uses and range of new technologies being considered for this system, RAM characteristics will be deferred for inclusion in Section II of the Development Plan (DP) or before that time when sufficient information is obtained to establish and justify specific RAM values.

c. The power source shall meet the standards for aural non-detectability of steady-state noise at a nominal distance of 100 meters from the power source, as defined by Sound Pressure Levels (SPL) and respective Octave Bands prescribed in MIL STD 1474, 1 Mar 73. For hearing protection of friendly personnel working on or near the item, the power source will not emit noise levels in excess of those prescribed under Category D criteria by MIL STD 1474.

d. Meet the radio interference limits for engine generators as specified in notice 4 to MIL STD 461.

e. Power plants shall use lubricants available in the Army inventory and be compatible with transport vehicles used in forward areas.

f. Have a cooling means or system which permits specific performance during operation at all loads up to rated load without overheating. All plant cooling air and exhaust emission will be concentrated so that single ducts can be externally attached and appropriately routed.

g. Have a battery charging or stored energy restoration system, as appropriate, with a stored energy or electric starting system.

h. DC units shall have characteristics suitable for charging batteries as well as general purpose DC uses.

i. Specific physical characteristics shall meet the following parameters:

POWER RATING (KW)	VOLUME (CF)	WEIGHT (LB)
0.5	3-3.5	80
1.5	6.0	150
3.0	12.0	300
5.0	18.0	500
10.0	30.0	650

j. IR detectability of the SLEEP units will be reduced to the maximum extent determined to be both mission and cost effective during trade-off analyses. Specific IR requirements, based upon known and postulated enemy detection means, will be established (by specific set sizes) for inclusion in Section II of the Development Plan (DP).

6. Technical Assessment.

a. Studies conducted by Army and other agency development activities conclude that establishment of the proposed family of silent power sources is feasible and within the state-of-the art for a number of advanced energy conversion technologies. Rankine cycle engine-generators and fuel cells appear to be the most attractive for the power ratings up to approximately 5KW; and an enclosure-silenced, open Brayton cycle is appropriate for ratings above 5KW. Other development considerations include Wankel-engine generators (developments being pursued by UK and FRG); Stirling-cycle engine generators; and multi-fuel thermoelectric generators for low power ratings.

b. In general, risk for the small ratings of the family is considered low, with a medium risk assessed for the higher power ratings. This risk is primarily associated with achievement of low noise within the weight constraints.

c. There are no known components presently in the supply system or being developed through research and development that can be used in the proposed family, with the following exceptions:

(1) 10 KW gas turbine engine generators, now in EDT phase, are envisioned as the basic component of the 10 KW SLEEP's unit, in conjunction with a silencing enclosure.

(2) Universal power conditioners now under development could provide components for the SLEEP family.

A.2 Purchase Description for 3-kW Stirling Engine

U.S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER
FORT BELVOIR, VIRGINIA 22060

28 March 1974

PURCHASE DESCRIPTION
FOR
LOW NOISE 3.0 KW STIRLING ENGINE POWER PLANT

This Purchase Description was prepared by the U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia, for use in connection with the development of an experimental model Stirling cycle engine driven generator set. It is an ad interim description intended for use in the design and advanced development phase and does not include requirements for quantity procurement of this item for general use or issue.

1. SCOPE

This Purchase Description covers the general requirements for a 3.0 KW, Direct Current, electric power plant powered by a Stirling cycle engine for high overall efficiency of energy conversion and low noise level to prevent enemy detection under military field operation. Design emphasis should be placed on the engine; however, the generator and controls should be carefully considered in achieving an overall package design to meet the physical and performance requirements specified herein.

2. APPLICABLE DOCUMENTS

The following documents of the issue in effect on the date of solicitation, form a part of the Purchase Description to the extent specified herein:

SPECIFICATIONS

MILITARY

MIL-G-3056 - Gasoline, Automotive, Combat
MIL-T-5624 - Jet Fuel, Grades JP-4 and JP-5

FEDERAL

VV-F-800 - Fuel Oil, Diesel

MILITARY STANDARD

MIL-STD-705 - Generator Sets - Engine Driven, Method of Test
MIL-STD-810 - Environmental Test Methods for Aerospace and Ground Equipment, Miscellaneous
MIL-STD-1472 - Human Engineering Design Criteria for Systems, Equipment, Facilities
MIL-STD-1474 - Noise Limits for Army Materiel

3. REQUIREMENTS

3.1 General

3.1.1 Description - The electric power plant shall consist of a Stirling cycle engine, a 3.0 KW, 28 volt, DC generator, an electric starting system and necessary controls and accessories required to provide a complete self-contained operating system. The power plant shall be designed for portability and suitability for military field use under the environmental extremes of ambient temperature, low and high humidity, under varying altitude conditions and rough handling. The power plant shall be operable by troop personnel with a minimum of specialized training. Design objectives of low noise level, light weight, low fuel consumption, low maintenance requirements, high reliability, minimum complexity and low production cost shall be emphasized.

3.1.1.1 Weight and Dimensions - Maximum weight of the complete operational unit without fuel shall be not more than 275 pounds. Maximum dimensions are not specified; however, overall dimensions shall be minimized and the total unit shall be of a rectangular configuration without projection on any side. Total volume shall not exceed 12 cubic feet. Configuration and center of gravity shall be such that tipping will not occur when the unit is tilted at a 31° incline from the horizontal.

3.1.1.2 Ease of Maintenance and Repair - Ease of operation, maintenance, and repair shall be considered in the design. The control system shall be automatic to the extent that normal operation after start up can be unattended except for scheduled maintenance. Organizational and direct support level maintenance and repair shall be capable of being performed with field mechanics' tools. The design shall minimize the need for special tools at any level of maintenance.

3.1.1.3 Use Conditions - Design of the unit shall be sufficiently rugged to withstand the extremely hard usage encountered in military service, transported in tactical vehicles and trailers over rough terrain. Shock and vibration requirements are contained in MIL-STD-705 and MIL-STD-810.

3.1.1.4 Safety - All parts that are of such nature or so located as to become a hazard to operating personnel shall be fully enclosed or so located as to minimize such hazards.

3.1.1.5 Noise Level - A major objective of this development is to achieve a low noise power source. The power source shall be inaudible to the unaided ear of an observer located in a quiet jungle background 100 meters from the power source. Compliance with this requirement will be considered to be demonstrated when the audio noise sound pressure levels emanating from the set during operation from no load to full rated load meet the following criteria when the microphone is located 1.2 meters above the ground on a 6 meter radius circle measured in any direction from the geometrical center of the set.

Octave Band Center Frequency, Hz	Maximum Noise Level in Decibels re/.0002 Microbar
63	60
125	46
250	44
500	45
1000	45
2000	43
4000	47
8000	48

During acoustical measurements, the ambient background noise levels, including wind noise, shall be at least 10 db below that of the set noise in each octave band.

3.1.1.6 Mechanical Design - In the design, full consideration shall be given to use of existing technology on the Stirling cycle engine in order to take advantage of its inherent features of high thermal efficiency, low noise level and low air pollution characteristics. Major emphasis shall be placed on design improvements in the major components, including the preheater, heater, sealing arrangement, control system and main drive mechanism, with the objective of reducing their complexity and cost without sacrificing the inherent advantages of the Stirling engine.

3.1.1.7 Reliability - The generator set shall be designed to be capable of achieving a Mean Time Between Failure (MTBF) of not less than 460 operating hours under operating conditions specified. For the purpose of determining MTBF, a failure is defined as any malfunction which the organizational mechanic cannot remedy by adjustment, repair or replacement action using the controls, tools and parts (available at the organizational level) within one hour and which causes or may cause: inability to commence operation, cessation of operation, or degradation of performance capability of system below designated levels; serious damage to the system below designated levels; serious damage to the system by continued operation; serious personnel hazards. The generator set shall also be designed for a minimum of 3000 hours of operation before overhaul.

3.1.1.8 Priority of Design Characteristics - The following priority of design characteristics is assigned for the generator set. If in the design, there are conflicting requirements or if tradeoff considerations are necessary, the sequence indicated below shall be used as a guide in making decisions regarding the design.

Noise Level
Performance
Reliability, Availability
Transportability
Maintainability

3.1.1.9 Human Factors - Power plant design shall conform to Human Engineering Design Criteria as stated in paragraph 4 of MIL-STD-1472A

3.2 Material - Material used shall be of good commercial quality for the purpose intended. Materials which are latest state-of-the-art may be considered in order to achieve design objectives. In all cases materials used should be consistent with strength required for performance, safety and reliability.

3.3 Engine Working Fluid - A specific working fluid is not specified; however, the selection of the working fluid should consider factors of reliability, availability in the supply system, safety of storage and handli cycle efficiency, power density and load and speed control.

3.4 Performance and Operational Requirements

3.4.1 Power and Speed Ratings - The Generator set shall be capable of producing continuous power of 3.0 Kilowatts under the conditions of normal and extremes of environmental and use conditions specified herein. Operating speed shall be 3600 RPM. The power output shall be 28 volt, Direct Current.

3.4.2 Climatic Conditions - The engine shall be capable of starting and operating satisfactorily under the wet-warm, hot-dry, intermediate and cold climatic conditions defined in paragraphs 2-2, Section I of AR-70-38. In addition, the engine shall be capable of starting and carrying rated load within 10 minutes in any ambient temperature between minus 25°F and plus 125°F without external starting aids. From minus 25°F to minus 50°F, external heat may be applied for starting and the engine shall be capable of carrying load within 30 minutes.

3.4.3 Altitude Conditions - The engine shall be capable of developing and maintaining rated power output at elevations up to and including 5000 feet with ambient air temperature of 107°F.

3.4.4 Speed Control - For possible future application of the engine to drive an alternator, speed control shall be capable of being maintained under steady state load conditions of not greater than 1% band width deviation for any load from no load to full rated load for periods up to 30 seconds and 1.5% for periods up to two hours.

Speed regulation from no load to full rated load shall not be greater than 3% from rated speed. Speed during full load transient of load application shall not dip greater than 3% and shall recover within 4 seconds. Speed shall not rise greater than 5% on load rejection and shall recover within 6 seconds.

3.4.5 Fuel and Fuel Consumption - The engine, burner, fuel supply system and fuel control system shall be designed to operate on the petroleum distillate fuels in the military supply system, including combat gasoline (Specification MIL-G-3056), JP-4 and JP-5 jet fuels (Specification MIL-T-5624) and DF1 and DF2 Diesel fuels (Specification VV-F-800). At extreme low temperature DFA (Arctic grade) diesel fuel will be used in lieu of fuels for which the cloud point is too high. At high temperature some means shall be provided in the fuel system so that premature vaporization of fuel does not affect the operation of the set. Rated load fuel consumption of the engine including all accessories necessary to sustain operation in the generator set shall not exceed 0.6 pounds of fuel per brake horsepower hour on any of the fuels listed.

4. QUALITY ASSURANCE PROVISIONS

4.1 Tests - Tests shall be as specified in the contract or order.

4.2 Inspection - The contractor shall maintain an inspection system in accordance with Military Specification MIL-I-45208.

MIL-STD-1332B

13 March 1973

SUPERSEDING
MIL-STD-1332A
24 May 1971

MILITARY STANDARD

DEFINITIONS OF TACTICAL, PRIME, PRECISE, AND UTILITY TERMINOLOGIES FOR CLASSIFICATION OF THE DOD MOBILE ELECTRIC POWER ENGINE GENERATOR SET FAMILY

FSC 6115

THIS DOCUMENT CONTAINS [illegible] PAGES

DEPARTMENT OF DEFENSE
Washington, D.C. 20301

DEFINITIONS OF TACTICAL, PRIME, PRECISE, AND UTILITY TERMINOLOGIES FOR CLASSIFICATION OF DOD MOBILE ELECTRIC POWER ENGINE GENERATOR SET FAMILY

MIL-STD-1332B

1. This Military Standard is mandatory for use by all Departments and Agencies of the Department of Defense.

2. Recommended corrections, additions, or deletions should be addressed to: Naval Facilities Engineering Command, US Naval Construction Battalion Center, ATTN: Code 156, Port Hueneme, California 93043.

FOREWORD

This Military Standard has been prepared for use by all Departments and Agencies of the Department of Defense. Its purpose is to define the criteria used in the classification of engine generator sets of the DOD Standard Family into Tactical and Prime, and into the subclassifications of Precise and Utility. It provides users an overview of the operating characteristics of the engine generator sets comprising the DOD Standard Family and serves as a ready reference and guide for the military services in the preparation of engine generator set specifications.

The parametric values listed in this Standard (Table II and III) represent the maximum or minimum values (as applicable) acceptable to all of the military services (Army, Navy, Air Force, and Marine Corps).

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1. SCOPE

1.1 This standard provides definitions for the classification of engine generator sets comprising the DOD Standard Family by Type, according to their application, weight, mobility, reliability, and life; by Class, according to their electrical performance characteristics; and by Mode, according to the frequency of the power generated. The table of electrical performance characteristics is annotated to reference the test method within MIL-STD-705 used to determine the value of the parameter listed. Separate tables are provided giving the voltage connections and reconnections available in each of the generator sets of the DOD Standard Family and the derating of the sets with temperature and altitude.

1.2 The DOD Mobile Electric Power Engine Generator Set Family covers a range in output capacity from 0.5 kilowatt (kw) through 750 kw and includes electrical power outputs at 60 Hertz (Hz), 50/60 Hz, 400 Hz, alternating current (ac), and direct current (dc). Detailed physical and electrical characteristics for each member of the DOD Standard Family are contained in MIL-STD-633.

2. REFERENCE DOCUMENTS

2.1 The latest issues of the following documents are applicable to the extent specified herein.

STANDARDS

MILITARY

MIL-STD-633 - Mobile Electric Power Engine Generator Set Family Characteristic Data Sheets.

MIL-STD-705 - Generator Sets, Engine Driven, Methods of Tests and Instructions

(Copies of military standards required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

OTHER

US Standard Atmosphere - 1962 (Prepared by Environmental Science Service, NASA, and US Air Force).

(Available from the Superintendent of Documents, US Government Printing Office, Washington, D. C. 20402.)

3. DEFINITIONS

3.1 Classification of engine generator sets. Engine generator sets are classified by Type, Class, and Mode as follows:

3.1.1 Type.

3.1.1.1 Type I - Tactical. Generator sets designed for high mobility in direct support of military forces where output of generator sets is normally, but not exclusively, used at generated voltage without necessity of transformation or extensive distribution systems. Life characteristics are considered secondary to light weight, small size, and a high degree of mobility. Maximum weights for Tactical generator sets are listed in table I.

3.1.1.2 Type II - Prime. Generator sets designed for long term use in semi-fixed locations for extended periods of time, with size, weight, and mobility considered secondary to long life and reliability. Generator output is normally at high voltage for distribution purposes and requires transformation to utilization voltages at the load centers. Prime power generator sets may be expected to exceed the maximum weights shown in table I for Tactical sets.

3.1.2 Class.

3.1.2.1 Class 1 - Precise. Generator sets designed to provide close control of voltage and frequency performance for critical applications. See table I.

3.1.2.2 Class 2 - Utility. Generator sets designed to provide power for general purpose applications. There are three grades of ac Utility power ranging from that which is equivalent to and compatible with commercial power distribution systems (Class 2A) to that needed for utilitarian purposes (Class 2C) where requirements for voltage and frequency control are minimal. See table II for ac parametric values and table III for dc values.

3.1.3 Mode.

3.1.3.1 Mode I. Generator sets capable of operating at either 50 or 60 Hz.

3.1.3.2 Mode II. Generator sets operating at 400 Hz.

3.1.3.3 Mode III. Generator sets operating only at 60 Hz.

3.1.3.4 Mode IV. Generator sets providing dc output.

3.2 Standard voltage connections for engine generator sets. The standard voltage connections for generator sets are listed in table IV. Where more than one standard voltage connection is shown for a DOD standard kw rating, suitable means are provided to enable reconnecting the generator windings to give all specified output voltages at the load terminals of the generator sets.

3.3 Altitudes. Altitude, shown in feet above mean sea level (msl), is defined as atmospheric pressure corresponding to the specified altitude as given in the US Standard Atmosphere, 1962:

Altitude	Atmospheric Pressure inches Hg	mm Hg (metric)
0 (msl)	29.92	760.0
1500 feet	28.33	719.7
5000 feet	24.90	632.4
8000 feet	22.23	564.6

4. GENERAL REQUIREMENTS

4.1 Environmental conditions. The electrical performance characteristic parameters listed in tables II and III are applicable throughout the range of temperatures and altitudes as follows:

DOD Standard kw rating	Capacity at Environmental Conditions msl, -25°F to +125°F (-31.7°C to +51.7°C)	msl, -65°F to +125 F (-53 °C to +51.7°C)	1500 ft 90°F (32.2°C)	5000 ft 107°F (41.7°C)	8000 ft 95°F (35°C)
0.5, 1.5 kw reciprocating engine driven	Rated kw	-	Rated kw	Rated kw	90% rated kw
3 thru 200 kw reciprocating engine driven & gas turbine engine driven (GTED)	Rated kw	Rated kw	Rated kw	Rated kw	90% rated kw
Above 200 thru 750 kw reciprocating engine driven	Rated kw	-	Rated kw	80% rated kw	75% rated kw
Above 200 thru 750 kw GTED	Rated kw -25°F to +60°F (-31.7°C to +15.5°C) 70% rated kw to 125°F (51.7°C)	-	90% rated kw	75% rated kw	70% rated kw

4.2 Power rating. Engine generator sets with dual frequency capability (50/60 Hz) are permitted to have kw ratings at 50 Hz which are 5/6 of the 60 Hz kw rating. The ac generator sets 3 kw and larger are rated at 0.8 power factor (pf) lagging. Sets below 3 kw are rated at unity (1.0) power factor.

5. DETAIL REQUIREMENTS

Not applicable.

Custodians:
Army - ME
Navy - YD
AF - 11

Review Activities:
Army - CE
Navy - MC
AF - 13, 80

User Activities:
Army - EL, MU
AF - 17

Preparing Activity:
Navy - YD

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Table I. Maximum dry weights for tactical generator sets

kw rating	Maximum Dry Weight (pounds)
.5	100
1.5	150
3.0	300
5.0	1,100
10	1,400
15	3,000
30	3,500
60	5,000
100	7,000
150	9,000
200	10,500
500/750	32,000

NOTE: 1. Maximum dry weight is the weight of the generator set le[illegible] fuel, coolant, lubricant, electrolyte, and optional equip[illegible] Optional equipment weights are shown in MIL-STD-633.

Table II. Electrical performance characteristics parameters - alternating current generator sets

Characteristic parameter	Precise Class 1	Utility Class 2A	Utility Class 2B	Utility Class 2C	Test Method MIL-STD-705
a. Voltage characteristics					
1. Regulation (%)	1	2	3	4	608.1
2. Steady-state-stability (variation) (bandwidth %)					
(a) Short term (30 seconds)	1	1	2	2	608.1
(b) Long term (4 hours)	2	2	4	4	608.2
3. Transient performance					
(a) Application of rated load					
(1) Dip	15	20	20	30	619.2
(2) Recovery (seconds)	0.5	3	3	3	619.2
(b) Rejection of rated load					
(1) Rise (%)	15	30	30	30	619.2
(2) Recovery (seconds)	0.5	3	3	3	619.2
(c) Application of simulated motor load (twice rated current)					
(1) Dip (%)	30	N/A	40	N/A	619.1
(2) Recovery to 95% of rated voltage (seconds) (Note 1)	0.7	N/A	5	N/A	619.1
4. Waveform (Note 2)					
(a) Maximum deviation factor (%)	5	5	5	6	601.1
(b) Maximum individual harmonic (%)	2	2	2	3	601.4
5. Voltage unbalance with unbalanced load (%) (Note 3)	5	5	5	5	620.2
6. Phase balance voltage (%)	1	1	1	1	508.1
7. Voltage adjustment range (%) (min) (Note 4)	-5 +17	±10	-5 +17 (Note 5)	-5 +5	511.1
b. Frequency characteristics					
1. Regulation (%)	0-3 Adj'able	0-5 Adj'able	3	3	608.1
2. Steady-state-stability (variation) (bandwidth %)					
(a) Short term (30 seconds)	0.5	0.5	2	4	608.1
(b) Long term (4 hours)	1	1	3	4	608.2

Table II. (Continued)

Characteristic parameter	Precise Class 1	Utility Class 2A	Utility Class 2B	Utility Class 2C	Test Method MIL-STD-705
3. Transient performance					
(a) Application of rated load					
(1) Undershoot (%)	4	4	4	4	608.1
(2) Recovery (seconds)	2	4	4	4	608.1
(b) Rejection of rated load					
(1) Overshoot (%)	4	4	4	5	608.1
(2) Recovery (seconds)	2	4	4	6	608.1
4. Frequency adjustment range (%) (min) (Where required)	±3	±4	±3	±3	511.2

NOTES: 1. The voltage shall stabilize at or above this voltage (not applicable to all sets rated 5 kw or smaller, or 500 kw and larger).

2. Specified values are for three phase output; for single phase, add additional 1%.

3. With generator set connected for three phase output and supplying a single line-to-line, unity power factor, load of 25% of rated current and with no other load on the set. (Not applicable for single phase connections of sets.)

4. For Mode II sets, upper voltage adjustment is +10% of rated voltage. For Mode I sets operating at 50 Hz, upper voltage adjustment may be limited to the nominal voltages shown in table IV, Note 4.

5. Values shown are for sets rated at 15 kw and above.

Table III. Electrical performance characteristic parameters (maximum or minimum limits, as applicable), dc, Utility

Characteristic parameters	Value	Test method MIL-STD-705
Voltage characteristics		
a. Regulation (%)	4	608.1
b. Steady-state-stability (variation) (bandwidth %)	2	608.1
c. Transient performance		
1. Application of rated load		
(a) Dip (%)	30	619.2
(b) Recovery (seconds)	2	619.2
2. Rejection of rated load		
(a) Rise (%)	40	619.2
(b) Recovery (seconds)	2	619.2
d. Ripple voltage (%)	5.5	650.1
e. Voltage adjusting range	(Note 1)	511.1

NOTE: 1. The voltage adjustment range is 23 to 35 volts at normal ambient temperatures and ±5 percent of nominal (28 volts) at extreme temperatures.

Table IV. Standard voltage connections for 60 Hz, 50/60 Hz, and 400 Hz engine generator sets

DOD Standard kw rating	Voltage Connections (ac): Single phase: 120 volt, 2 wire	Single phase: 240 volt, 2 wire	Single phase: 120/240 volt, 3 wire	Three phase: 120/208 volt, 4 wire	Three phase: 240/416 volt, 4 wire	Three phase: 2400/4160 volt, 4 wire	Three phase: 2400 volt, 3 wire
0.5	X						
1.5	X	X					
3, 5	X	X	X	X			
10	X		X	X			
15, 30, 60, 100, 150, 200				X	(Note 2) (Note 4) X		
500, 750						(Note 4) X	X

NOTES: 1. An "X" in voltage connection column(s) opposite a standard kw rating group indicates provision for connection and operation at all voltage connections so identified.

2. Voltage adjustment range provides for continuous operation at 277/480 volts.

3. The DOD Standard Family also includes 28 volt, dc engine generator sets rated 0.5 kw, 1.5 kw, and 3 kw.

4. Engine generator sets rated for 50/60 Hz have provision for operation at 50 Hz with 3 phase voltages as follows:

220/380 volts for the 240/416 connection for sets rated 15-200 kw and
2200/3800 volts for the 2400/4160 volt connection for sets above 200 thru 750 kw

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APPENDIX B

EXCERPTS FROM MIL-STD-810B AND MIL-STD-705

B.1 Military Requirements for Mechanical Testing of 3-kW Generator Set

Generator Sets, Gasoline Engine Driven (3KW)

Mechanical Test Requirements (Generator Set)

- Drop test (free fall)
- Vibration test
- Drop test (ends)
- Railroad impact test
- Humidity

Drop test (free fall)

The height of the drop shall be 18 inches for the mode III size 3 set.

Vibration Test

Equipment category - (h) Ground equipment, excluding category (f) (Equipment installed in ground vehicles)

for transportation test, see category g
(g) Equipment transported by common carrier, land or air
see Table 514.1-VII and Fig 514.1-7)

4.8.5 Vibration. The set shall be tested in accordance with Method 514 of MIL-STD-810 with the following exceptions:

Curve:

Frequency (Hz)	Input to Set
7 to 26.6	1.3 g
26.6 to 52	0.036-inch D.A.
52 to 500	5 g

__Resonance:__ A resonance search shall be conducted in each axis of the set with the vibration inputs as delineated above. Resonant points shall be noted visually, with the aid of a stroboscopic light, and by instrumentation with data being recorded at least every hertz from 7 to 30 hertz and at least every 5 hertz from 30 to 500 hertz to indicate the ratio of transmitted g to excitation g. Input vibration levels shall be measured by means of an accelerometer mounted as near as practicable to the center of the vibration table. Another accelerometer shall be located at the tapped hole for the generator set lifting eye, or as specified (see 3.1). The output of the two accelerometers shall be used to compute transmissibility. The resonance dwell portion of this test shall be 30 minutes per axis with the time equally divided between a maximum of three resonant frequencies. The frequency at which the resonance was originally detected shall be maintained throughout each resonance dwell. Additional requirements shall be specified (see 3.1). All bolts and screws shall be tightened as necessary before vibration in each axis or whenever relative vibration between parts increases as a result of their loosening.

__Cycling:__ The generator set shall be subjected to a cycling vibration test with the frequency being varied at a logarithmic rate from 7 to 500 to 7 hertz in fifteen minutes at the inputs specified above. The test shall be conducted a sufficient number of times to obtain a total of one hour of vibration (resonance search, dwell, cycling) in each axis.

__Operation:__ The generator set shall not be operated during the vibration tests. Following each axis of vibration, test method 614.1 of MIL-STD-705 shall be performed after 15 minutes stabilization at rated load, rated pf.

TABLE 514.1-VII

A. Test procedure and time schedule chart for equipment transported by common carrier, land or air – equipment category (g)

Equipment conditions	Procedure number	Procedure part number	Applicable tests (see 4 for test procedures): Resonance search (4.5.1.1)	Resonance dwell (4.5.1.2)	Sinusoidal cycling (4.5.1.3)	Bounce loose cargo (4.16.2)	Time schedule (per axis): Dwell time at each resonance (4.5.1.2) Land	Dwell time at each resonance (4.5.1.2) Air	Sinusoidal cycling time (4.5.1.3) Land	Sinusoidal cycling time (4.5.1.3) Air	Sweep time 5-500-5 cps (note 3) Land	Sweep time 5-500-5 cps (note 3) Air	Curve (notes 1 and 2)
Tied down (notes 4, 6 and 7)	X		X	X	X		2.5 mm (note 5)	10 min (note 5)	15 mm (note 5)	1 hr. (note 5)	15 min	15 min (note 2)	AV, AW, AX, AY, AA or AQ
Loose cargo (Note 7)	XI	1	X					See 4.16.1					
		2				X		See 4.16.2					

Note 1: For sinusoidal vibration resonance tests and cycling tests of items transported in airplanes and helicopters and weighing more than 100 pounds, the vibratory accelerations shall be reduced by +/-1 g for each 25-pound increment of weight over 100 pounds. Derating shall apply only to the highest test level of curve AY. However, the vibratory acceleration shall in no case be less than 1.5g.

Note 2: For equipment transported in air craft and weighing more than 100 pounds, the upper frequency limit of curve AY of figure 514.1-7 may be reduced according to the cut-off frequency vs. weight requirement of figure 514.1-9. When a transit case or crate is provided for the item, the case or crate shall be included in the test set-up for acceleration and frequency derating.

Note 3: Sweep time may be as long as 18 minutes if test frequencies go to 2 cps.

Note 4: When testing vibration isolated items, the resonant dwell time shall be broken into 5-minute test periods with 2-minute shut down intervals.

Note 5: Total test time per axis (resonant dwells plus cycling) is 15 minutes per 1000 miles for land transportation or one hour for aircraft transportation. For equipment shipped by both land and air, both tests shall be performed. (The load vehicle cycling time of 15 minutes per 1000 miles per axis is reduced 2.5 minutes per 1000 miles for resonance in that axis, and the aircraft cycling time of 1 hour per axis is reduced 10 minutes for each resonance in that axis. Land transportation times are per 1000 vehicle miles, which may be determined from table 514.1-VIC).

Note 6: Land and air curves for Procedure X shall be cycled separately in accordance with the applicable time schedules. The dwell time for each resonance of non-isolated items shall be determined from the total test time of the applicable curves. For example, if the resonance occurs where the applicable land vehicle curve represents a higher G level, the item shall be tested at each resonance (maximum of four) to the G level of the applicable land vehicle curve with a test time for each resonance equal to 1/6 of the total test time per axis for the land vehicle. Conversely, if the aircraft curve is equal to, or higher than, the land vehicle curve, the item shall be tested for each resonance (maximum of four) to the G level of the aircraft curve with a test time for each resonance equal to 1/6 of the cycling time per axis for aircraft.

Note 7: When a transit case or crafe is provided for the test item, the case or crate shall be included in the test setup.

B. Curve selection chart for category (g) equipment

Selection criteria		Curve
Equipment shipped by tracked vehicles		AV
Equipment shipped by truck, semitrailer, or railroad		AW
Equipment shipped by two wheeled trailers		AX
Equipment shipped by aircraft		AY
Mounted items with vibration isolators (Note 1)	Cycling	AA
	Resonance dwell	AQ

Note 1: For vibration isolated items, curves AA and AQ are to be used in the lower frequency range (below 13 and 20 cps, respectively) and a curve appropriate to the mode of transportation (AV, AW, AX, or AY) for higher frequencies.

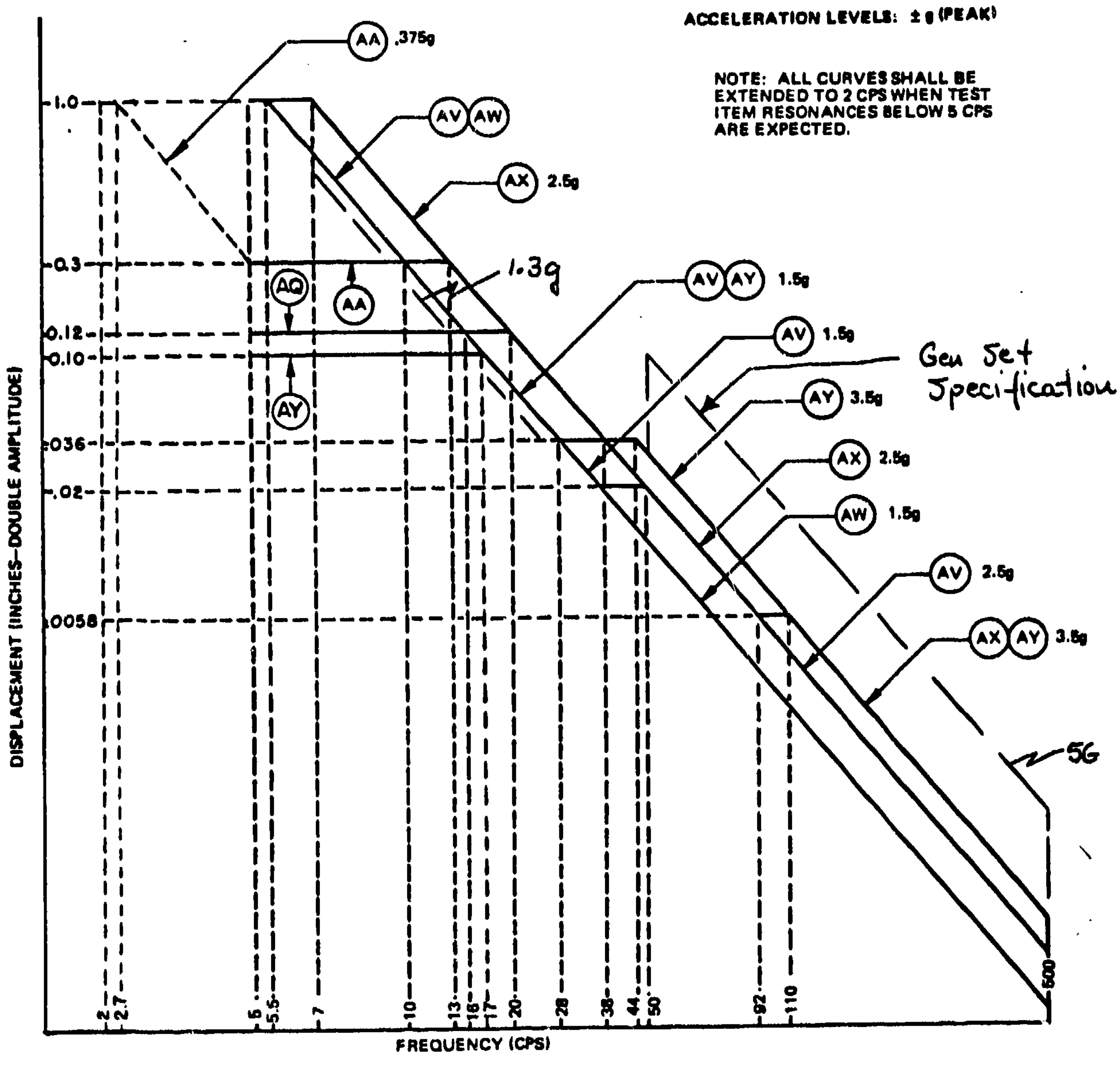


FIGURE 514.1-7. Vibration test curves for equipment transported by common carrier, land or air – equipment category (g)

4.5 Common test techniques. -

4.5.1 Sinusoidal vibration tests. - The vibration shall be applied along each of the three mutually perpendicular axes of the test item. The vibratory acceleration levels or double amplitudes of the specified test curve shall be maintained at the test item mounting points. When specified, for sinusoidal resonance search, resonance dwell, and cycling tests of items weighing more than 80 pounds mounted in airplanes, helicopters, and missiles, the vibratory accelerations shall be reduced +/-1 g for each 20 pound increment over 80 pounds. Acceleration derating shall apply only to the highest test level of the selected curve, but in no case shall the derated test level be less than 50 percent of the selected curve (see note 1 of applicable table 514.1-I through 514.1-V). For equipment weighing over 100 pounds and transported by aircraft, resonance search, resonance dwell, and cycling tests may be frequency and acceleration derated (see notes 1 and 2 of table 514.1-VII). When packaged items are always grouped together on mechanized loading platforms or pallets, acceleration and frequency derating may be based on the total load on the pallet. When the input vibration is measured at more than one control point, the control signal shall be the average of all the accelerometers unless otherwise specified. For massive test items, fixtures and large force exciters, it is recommended that the input control level be an average of at least three or more inputs.

4.5.1.1 Resonance search. - Resonant frequencies of the equipment shall be determined by varying the frequency of applied vibration slowly through the specified range at reduced test levels but with sufficient amplitude to excite the item. Sinusoidal resonance search may be preformed using the test level and cycling time specified for sinusoidal cycling test, provided the resonance search time is included in the required cycling test time of 4.5.1.3.

4.5.1.2 Resonance dwell. - The test item shall be vibrated along each axis at the most severe resonant frequencies determined in 4.5.1.1. Test levels, frequency ranges, and test times shall be in accordance with the applicable conditions from tables 514.1-I through 514.1-V and figures 514.1-1 through 514.1-7 for each equipment category. If more than four significant resonant frequencies are found for any one axis, the four most severe resonant frequencies shall be chosen for the dwell test. If a change in the resonant frequency occurs during the test, its time of occurrence shall be recorded and immediately the frequency shall be adjusted to maintain the peak resonance condition. The final resonant frequency shall be recorded.

4.5.1.3 Cycling. - The test item shall be vibrated along each axis in accordance with the applicable test levels, frequency range, and times from tables 514.1-I through 514.1-VII and figures 514.1-1 through 514.1-7. The frequency of applied vibration shall be swept over the specified range logarithmically in accordance with figure 514.1-10. The specified sweep time is that of an ascending plus a descending sweep and is twice the ascending sweep time shown on figure 514.1-10 for the specified range. Linear sweep rates may be substituted for the logarithmic sweep rate. When linear sweep rates are used, the total frequency range shall be divided into logarithmic frequency bands having similar time intervals such that each time interval is the time of ascending plus a descending sweep for the corresponding band. The sum of these time intervals shall equal the sweep time specified for the applicable frequency range. The linear sweep rate for each band is then determined by dividing each bandwidth in cps by one-half the sweep time in minutes for each band. The logarithmic frequency bands may be readily determined from figure 514.1-10. The frequency bands and linear sweep rates shown in table 514.1-IX shall be used for the 2 (or 5) to 500 cps and 5 to 2,000 cps frequency ranges. For test frequency ranges of 100 cps or less, no correction of the linear sweep rate is required.

4.5.2 Random vibration test. - The test item shall be subjected to random vibration along each of three mutually perpendicular axes according to one specified curve AE through AP from the applicable figure 514.1-4 or 514.1-5. Test times shall be according to the applicable schedule from tables 514.1-IV or 514.1-V. The instantaneous random vibration acceleration peaks may be limited to three times the rms acceleration level. The power spectral density of the test control signal shall not deviate from the specified requirements by more than +40, -30 percent (+/-1.5 dB) below 500 cps and +100, -50 percent (+/-3 dB) between 500 cps and 2,000 cps, except that deviations as large as +300, -75 percent (+/-6 dB) shall be allowed over a cumulative bandwidth of 100 cps, maximum, between 500 and 2,000 cps.

Tolerance levels in terms of dB are defined as:

$$dB = 10 \log_{10} \frac{W_1}{W_0}$$

Where W_1 = measured acceleration power spectral density in G^2/cps units. The term W_0 defines the specified level in G^2/cps units.

Confirmation of these tolerances shall be made by use of an analysis system providing statistical accuracies corresponding to a bandwidth-time constant product, BT = 50, minimum. Specific analyzer characteristics shall be as specified below or equivalent.

(a) On-line, contiguous filter, equalization/analysis system having a bandwidth = B = 50 cps, maximum.

(b) Swept frequency analysis systems characterized as follows:

1. Constant bandwidth analyzer.

a. Filter bandwidth as follows:
B = 20 cps, maximum between 20 to 200 cps
B = 50 cps, maximum between 200 to 2,000 cps

b. Analyzer averaging time = T = 2 RC = 1 second, minimum, where T = True averaging time and RC = analyzer time constant

c. Analysis sweep rate (linear) = $R = \frac{B}{4RC}$ or $\frac{B^2}{8}$, (cps/second) maximum, whichever is smaller.

2. Constant percentage bandwidth analyzer.

a. Filter bandwidth = pf_c = one-third octave maximum ($.23\ f_c$) where p = percentage and f_c = analyzer center frequency.

b. Analyzer averaging time = $T = \frac{50}{pf_c}$, minimum

c. Analysis sweep rate (logarithmic) = $R = \frac{pf_c}{4RC}$ or $\frac{(pf_c)^2}{8}$ (cps/second), maximum, whichever is smaller.

(c) Digital power spectral density analysis system employing quantization techniques providing accuracies corresponding to the above approach.

The composite G-rms test level shall not be less than the value given on figure 514.1-4 or 514.1-5 for each test curve. Accelerometer(s) employed for test level control shall be mounted in accordance with 4.1. Where more than one accelerometer is employed for test level control, the power average of the several accelerometer signals shall be used as the test level signal control.

4.15 Procedure X. - Proceed the same as in 4.5.1.1, 4.5.1.2, and 4.5.1.3. The test level shall be according to specified curve(s) AV, AW, AX, AY, AA and AQ from figure 514.1-7 as applicable. Test time schedules shall be as specified for Procedure X as shown in table 514.1-VII. When test item resonances below 5 cps are measured or expected the test curves shall be extended to 2 cps.

4.16 Procedure XI. -

4.16.1 Part 1. - Proceed the same as in part 1 of Procedure IX.

4.16.2 Part 2, bounce, loose cargo. -

4.16.2.1 Purpose.- To determine that the equipment, as prepared for field use, shall be capable of withstanding the vibrations normally induced during transportation as loose cargo. Equipment in this class is normally transported in a shipping case, transit case, or combination case.

4.16.2.2 Apparatus. - A package tester capable of 1 inch (double amplitude) displacement and of suitable capacity for testing military equipment.

4.16.2.3 Test conditions. - The test bed of the package tester shall be covered with a panel of 1/2-inch plywood, with the grain parallel to the drive chain. The plywood shall be secured with sixpenny nails, with top of heads flush with or slightly below the surface. Nails shall be spaced at 6-inch intervals around all four edges. If the distance between either pair of fences is greater than 24 inches, the plywood shall also be nailed at 3-inch intervals in a 6-inch square at the center of the test area. Using suitable wooden fences, constrain the test item to a horizontal motion of note more than 2 inches in a direction parallel to the axes of the shafts, a distance more than sufficient to insure the test item will not rebound from fence to fence.

4.16.2.4 Performance of test. - The test item, as secured in its shipping case, transit case, or combination case, or as otherwise prepared for field transportation, shall be placed on the package tester within the constraints outlined above. The package tester shall be operated in the synchronous mode with the shafts in phase. (In this mode any point on the bed of the package tester will move in a circular path in a vertical plane perpendicular to the axes of the shafts). The package tester shall be operated at 1-inch double amplitude and 284 rpm +/-2 rpm for a total of 3 hours. At the end of each 1/2-hour period, turn the test item to rest on a different face, so that at the end of the 3-hour period the test item will have rested on each of its six faces (top, bottom, sides, and ends). At the end of the 3-hour period, the test item shall be operated and the results compared with the data obtained in accordance with section 3, General Requirements, paragraph 3.2.1. The test item shall then be inspected as specified in section 3, General Requirements, paragraph 3.2.4. The package tester shall be operated in the vertical linear mode (straight up and down in the vertical plane) instead of in the synchronous mode when one of the following conditions occurs:

(a) Bouncing of the test item is very severe and presents a hazard to personnel.

(b) Forward and rear oscillations cannot be reduced. When operated in the vertical linear mode, wooden fences shall be placed on all four sides of the test item to constrain its motion to not more than 2 inches in either direction.

Drop Test (ends)

The set shall be dropped from a height of 6 inches.

Railroad Impact Test

4.8.6 Drop (ends). The set shall be dropped from a height of 6 inches.

4.8.7 Railroad impact. Perform Method 740.5 of MIL-STD-705 with the sets positioned 180 degrees with respect to each other for a total of four impacts at 10 miles per hour (± 0.5 mph). Two impacts shall be made with sets positioned longitudinally with respect to the axis of the car and two impacts with the sets rotated 90 degrees from the longitudinal position. The sets shall not be packaged for the railroad hump tests except as otherwise specified (see 3.1). Impact speed shall be measured within 60 inches of impact and the speed measurement interval shall not exceed 60 inches in length. Accuracy of the speed measurement shall be ± 5 percent. The engine oil shall be at its normal operating level, the fuel tank shall be drained and dummy or dry batteries shall be used during the impact portion of the test.

Humidity -

METHOD 507

HUMIDITY

1. **Purpose.** The humidity test is applicable to all equipment and is conducted to determine the resistance of equipment to the effects of exposure to a warm, highly humid atmosphere such as is encountered in tropical areas. This is an accelerated environmental test, accomplished by the continuous exposure of the equipment to high relative humidity at an elevated temperature. These conditions impose a vapor pressure on the equipment under test which constitutes the major force behind the moisture migration and penetration. Corrosion is one of the principal effects of humidity. Hygroscopic materials are sensitive to moisture and may deteriorate rapidly under humid conditions. Absorption of moisture by many materials r[illegible]lts in swelling, which destroys their [illegible]tional utility and causes loss of physical strength and changes in other important mechanical properties. Insulating materials which absorb moisture may suffer degradation of their electrical and thermal properties.

2. **Apparatus.** Humidity-temperature chamber and associated equipment.

2.1 **Chamber.** The chamber and accessories shall be constructed and arranged in such a manner as to avoid condensate dripping on the test item. The chamber shall be trap-vented to the atmosphere to prevent the buildup of total pressure. Relative humidity shall be determined from the dry bulb-wet bulb thermometer comparison method or an equivalent method approved by the procuring activity. When readout charts are used, they shall be capable of being read with a resolution within 0.6° C (1° F). When the wet bulb control method is used, the wet bulb [illegible] tank shall be cleaned and a new wick [illegible]alled at least every 30 days. The air velo[illegible]ity flowing across the wet bulb shall be not less than 900 feet per minute. Provisions shall be made for controlling the flow of air throughout the internal test chamber area where the velocity of air shall not exceed 150 feet per minute. Steam, or distilled, demineralized, or deionized water having a pH value between 6.0 and 7.2 at 23° C (73° F) shall be used to obtain the specified humidity. No rust or corrosive contaminants shall be imposed on the test item by the test facility.

3. **Procedures.**

3.1 **Procedure I.**

Step 1—Place the test item in the test chamber in accordance with section 3, paragraph 3.2.2. Prior to starting the test, the internal chamber temperature shall be at standard ambient with uncontrolled humidity.

Step 2—Gradually raise internal chamber temperature to 71° C (160° F) and the relative humidity to 95 percent over a period of 2 hours.

Step 3—Maintain condition of step 2 for not less than 6 hours.

Step 4—Maintain 85 percent, or greater, relative humidity and reduce internal chamber temperature in 16 hours to 28° ±10° C (82° F).

Step 5—Repeat steps 2, 3, and 4 for 10 cycles (not less than 240 hours). Figure 507-1 is an outline of the humidity cycle for this procedure.

Step 6—Remove the test item from chamber and allow the test item to return to 28° ±10° C (82° F).

B.2 Military Specifications For Long-Term Stability Tests

4.8 Tests.

4.8.1 Test procedures. Tests shall be conducted in accordance with MIL-STD-705, measurements and instrumentations in accordance with MIL-HDBK-705 and as specified herein. During tests, operating instructions shall be explicitly followed for the test conditions specified. New lubricants as specified (see 3.6.3), shall be used during all tests, except that the lubricant used during the individual tests (see 4.4) and the quality conformance tests (see 4.6) shall conform to MIL-L-21260, Grade 2, and shall remain in the crankcase during engine preservation (see 5.1). Fuel conforming to VV-G-1690, regular grade, class A shall be used for all tests. Test instruments shall have been calibrated within 30 days prior to the start of testing and at intervals

MIL-G-52732A

not greater than 6 months thereafter. Direct-reading instruments shall have at least 0.5 percent instrument manufacturer's rated accuracy. The recording meters shall be the combination frequency and voltmeter Texas Instrument (TI) Model PDEHXF HXVA-A16-XT in accordance with TI Drawing Number 162782 for Mode II and III sets and dc voltmeter Texas Instrument, Model PRHHX-A16-AT in accordance with TI Drawing Number 164117 for Mode IV sets. Oscillograph galvanometer frequency response shall be flat (± 5 percent) to 3,000 cps. When recording meters are specified for any part of a test, turn on the recording meters prior to starting the warmup period of the set and record continuously for the duration of the test. The recording meters shall be operated at a minimum speed of 6 inches per hour during the portions of the test where steady-state loading conditions exist and shall be operated at a minimum speed of 6 inches per minute at least 30 seconds before, during, and after a load change. Unless otherwise specified herein, Mode II and III sets shall be tested in the 120-volt single phase connection. Tests may be performed in any order except that the endurance test shall be performed last.

METHOD 608.2

FREQUENCY AND VOLTAGE STABILITY TEST

(LONG-TERM)

608.2.1 GENERAL. The generator-regulator-exciter combination must be capable of maintaining constant voltage and the engine-governor combination must be capable of maintaining constant speed for constant loads over long periods of time.

Frequency stability describes the tendency of the frequency to remain at a constant value. Generally, the instantaneous value of frequency is not constant but varies randomly above and below a mean value. Stability may be described as either short-term or long-term stability depending upon the length of time that the frequency is observed. Another term, bandwidth, describes the limits of these variations. Bandwidth is expressed as a percentage of the rated frequency of the generator set. Voltage stability is described similarly.

608.2.2 APPARATUS. Instrumentation for measuring load conditions, field voltage and current, and ambient temperatures shall be as described and illustrated in MIL-HDBK-705. In addition, recording meter(s) shall be as described and illustrated in MIL-HDBK-705, Methods 101.1 and 104.1 unless otherwise specified in the procurement document.

608.2.3 PROCEDURE.

608.2.3.1 Preparation for test.

(a) Connect the load and field instrumentation in accordance with the applicable figure of MIL-HDBK-705, Method 205.1, Paragraph 205.1.10 for the applicable voltage connection and frequency. Unless otherwise specified, connect the signal input of the recording meter(s) to the convenience receptacle of the set or to the generator coil which is used as the voltage sensing input to the voltage regulator. (Power the recording meter(s) from the commercial utility.)

(b) The following items shall be recorded on both the data sheets and the recording chart(s):

1) the date
2) the serial number(s) of the recording meter(s)
3) generator set identification
4) recording chart speed(s)
5) data reading number

608.2.3.2 Test.

(a) Start and operate the generator set and allow the set to stabilize at rated load, rated voltage and rated frequency. During this period operate the recording meter(s) at a chart speed of not less than 6 inches per hour, and record all instrument readings including thermal instrumentation at minimum intervals of 10 minutes. If necessary, adjustments to the load, voltage and frequency may be made to maintain rated load at rated voltage and frequency. Adjustments to the voltage and frequency shall be limited to those adjustments available to the operator, specifically adjustments to the voltage or frequency adjust devices. On sets utilizing a droop-type speed control system as the prime speed control, the speed and droop portions of the control may be adjusted. No other adjustments to the voltage and frequency control systems shall be made unless permitted by the procurement document. Adjustments to load, voltage or frequency controls shall be recorded on both the data sheet and the recording chart(s) at the time of adjustment. Unless otherwise specified in the procurement document, stabilization shall be considered to have occurred when four consecutive voltage and current recorded readings of the generator (or exciter) field either remain unchanged or have only minor variations about an equilibrium condition with no evident continued increase or decrease in value after the last adjustment to the load, voltage, or frequency has been made.

(b) After step (a) above, no further adjustments may be made to the voltage or frequency controls or control systems for the remainder of this test.

(c) Determine the short-term stability prior to the start of the long-term rated load test by operating the recording meter(s) at a chart speed of 12 inches per minute for 30 seconds. During this 30 second period, record all instrument readings. At the end of the 30 second period reduce the recording meter(s) chart speed to 12 inches per hour and continuing to record, proceed with the test at rated load for a 4 hour period. During this period record all instrument readings at maximum intervals of 30 minutes.

(d) Immediately after the long-term stability period [Step (c)] reduce the load to zero and allow the set to stabilize at no load. During this period record all instrument readings including ambient temperature at minimum intervals of 10 minutes. No adjustments to the set shall be made before, during or following this stabilization period. Unless otherwise specified in the procurement document, stabilization shall be considered to have occurred when four consecutive voltage and current readings of the generator (or exciter) field either remain unchanged or have only minor variations about an equilibrium condition with no evident continued increase or decrease in value.

(e) Immediately after the set has stabilized at no load repeat Step (c) above except at no load.

(f) Immediately after the no load operate the recording meter chart speed at 12 inches per minute and in one step apply the following load conditions to the generator set for a minimum of 40 seconds. No adjustments to the set shall be made before or during this portion of the method.

1) Rated load
2) No load
3) Rated load
4) No load
5) Rated load
6) No load

(g) Repeat Paragraph 608.2.3 for each voltage connection and frequency specified in the procurement document.

608.2.4 RESULTS.

(a) Determine the long-term rated load voltage stability as follows (see Fig. 608.2-I):

(1) Using the rated load short-term voltage stability trace run prior to the long-term rated load voltage stability test, determine the maximum and minimum trace excursions. The maximum trace excursion is the point of maximum voltage during the 30 second period prior to the start of the long-term stability test and the minimum trace excursion is the point of minimum voltage during the same time period.

(2) Calculate the middle of the observed steady state band by adding the values obtained in (1) above and dividing by 2.

(3) Draw the center line of the observed steady state band on the chart at the value determined in (2) above.

(4) Construct the prescribed steady state band by drawing two lines parallel to and equidistant from the center line of the observed band. Extend this band the entire length of the long-term steady state stability test.

(b) Repeat Step (a) for the long-term rated load frequency stability chart.

(c) Repeat Step (a) for the long-term no load voltage stability chart.

(d) Repeat Step (a) for the long-term no load frequency stability chart.

(e) Analyze the recording chart data taken in paragraph 608.2.3.2(f) in accordance with Method 608.1, Paragraph 608.1.4.

(f) The tabulation sheet shall contain for each trace: the observed maximum and minimum excursions during the short-term steady state stability period; and the observed maximum and minimum excursions during the long-term steady state stability tests.

(g) Compare the tabulated results with the requirements of the procurement document.

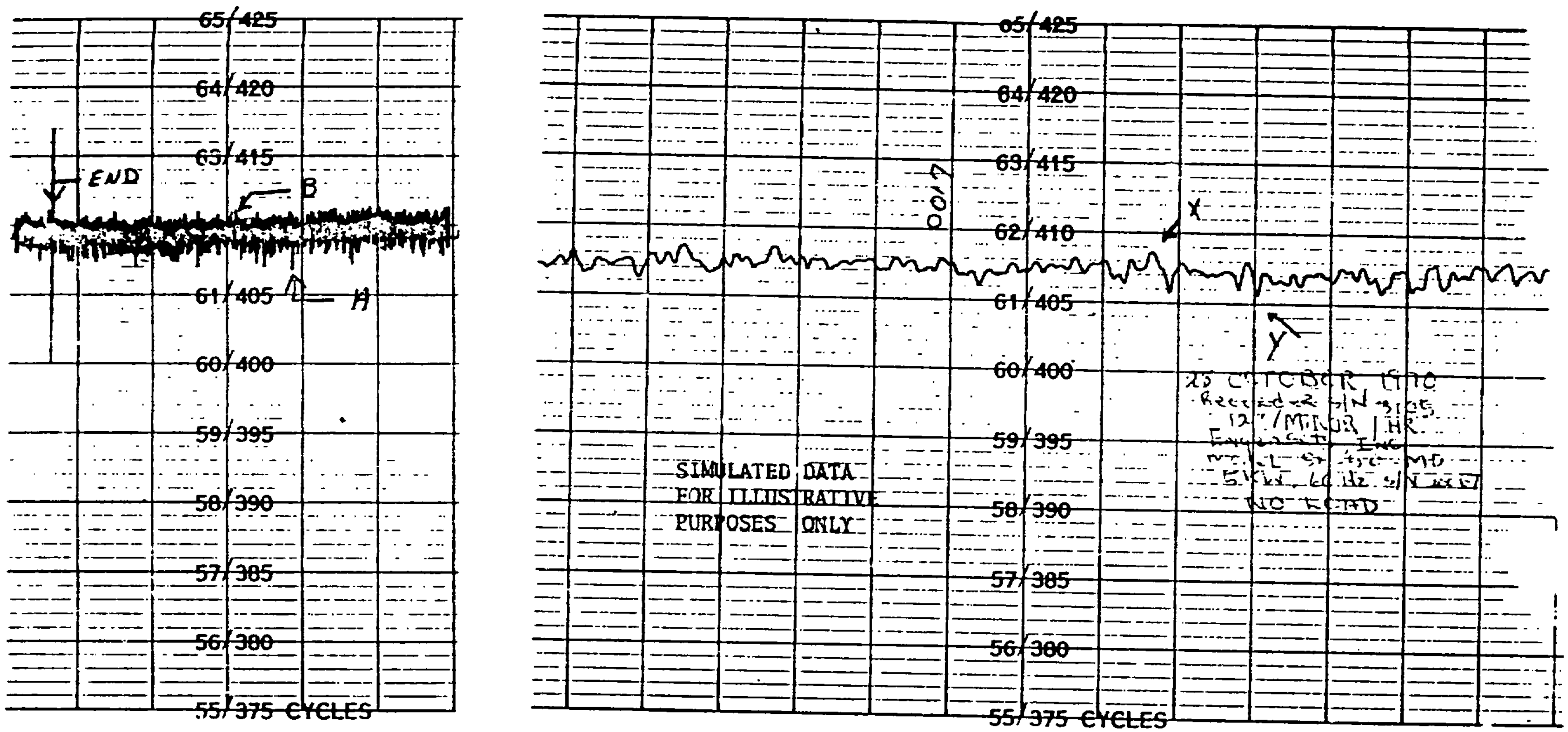
608.2.5 PROCUREMENT DOCUMENT REQUIREMENTS. The following items must be specified in the individual procurement document:

(a) Maximum allowable long-term voltage stability bandwidth or deviation in percent of rated voltage.

(b) Maximum allowable long-term frequency stability bandwidth or deviation in percent of rated frequency.

(c) Voltage connection(s) and frequency(ies) at which this method is to be performed.

(d) Length of time for the long term stability runs, if other than four (4) hours at rated load and four (4) hours at no load.



X - Maximum trace excursion, short-term, steady-state stability.

Y - Minimum trace excursion, short-term, steady-state stability.

A - Minimum trace excursion, long-term, steady-state stability.

B - Maximum trace excursion, long-term, steady-state stability.

FIGURE 608.2-I. Portion of a four hour long-term stability run.

APPENDIX C

SPECIFICATIONS FOR STANDARD FAMILY UNITS

MIL-STD-633C
29 October 1971

1. SCOPE

1.1 Scope. This standard provides detailed information on the physical and electrical characteristics and logistical data on the DoD approved family of mobile electric power engine generator sets.

1.2 Application. The standard has been prepared for use by all Departments and Agencies of the Department of Defense in selecting engine generator sets for applications requiring mobile sources of electric power and to assist the Project Manager for Mobile Electric Power in effecting management and standardization of such sources of power within the Department of Defense. The engine generator sets listed herein are the only sets in the 0.5 KW through 1500 KW size range authorized for procurement. Persons with mobile electric power requirements in this range, whose needs cannot be satisfied by one of the listed generator sets must obtain the approval of the Project Manager before taking any procurement action. See referenced Army, Navy, and Air Force Regulation for deviation requests.

1.3 Organization. This standard is organized into five sections, as follows:

- Section I. DoD Standard Family, Tactical, Utility, Gasoline Engine Driven Sets.
- Section II DoD Standard Family, Tactical, Utility, Diesel Engine Driven Sets.
- Section III. DoD Standard Family, Tactical, Precise, Diesel Engine Driven Sets.
- Section IV. DoD Standard Family, Prime, Utility Diesel Engine Driven Sets.
- Section V. Interim Standard Family, Gas Turbine Engine Driven Sets.

Sections I through IV are comprised of gasoline and diesel engine driven generator sets identified as DoD Standard Family Items. Section V contains turbine engine driven generator sets. These sets are considered Interim Standard Items since, in most instances, they are of an existing, single service, design which has been adopted by Project Manager, Mobile Electric Power as the standard item of supply for an indefinite period of time.

2. REFERENCE DOCUMENTS

MIL-STD-1332, Definitions of Tactical, Prime, Precise, and Utility Terminologies for Classification of the DoD Mobile Electric Power Engine Generator Set Family.

INDEX OF THE INTERIM AND DOD STANDARD FAMILY OF GENERATORS

Section I. Tactical utility gasoline engine driven:

DATA SHEETS

KW Rating	Model	28 VDC Item	60 Hz Item	400 Hz Item	Page
0.5	MEP-014A		1		101
0.5	MEP-019A			2	105
0.5	MEP-024A	3			109
1.5	MEP-015A		4		113
1.5	MEP-025A	5			117
3	MEP-016A		6		121
3	MEP-021A			7	125
3	MEP-026A	8			129
5	MEP-017A		9		133
5	MEP-022A			10	137
10	MEP-018A		11		141
10	MEP-023A			12	145

FIGURES

Photographs and outline drawing showing dimensions

Rating	Model	Figure	Page
0.5 KW, 60 Hz	MEP-014A	I-1	103
0.5 KW, 400 Hz	MEP-019A	I-2	107
0.5 KW, 28 VDC	MEP-024A	I-3	111
1.5 KW, 60 Hz	MEP-015A	I-4	115
1.5 KW, 28 VDC	MEP-025A	I-5	119
3 KW, 60 Hz	MEP-016A	I-6	123
3 KW, 400 Hz	MEP-021A	I-7	127
3 KW, 28 VDC	MEP-026A	I-8	131
5 KW, 60 Hz	MEP-017A	I-9	135
5 KW, 400 Hz	MEP-022A	I-10	139
10 KW, 60 Hz	MEP-018A	I-11	143
10 KW, 400 Hz	MEP-023A	I-12	147

Section I Item 1

0.5 KW, 60 Hz, Gasoline Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-014A. FSN: 6115-923-4469. Specification: MIL-G-52448.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 1.

VOLTAGE CONNECTIONS

120 volts, 2 wire, 1 phase.

Rating: 0.5 KW, 60 Hz, 125°F, sea level; 107°F, 5000 ft; 95°F, 8000 ft.

GENERAL DESCRIPTION

Mounted on a skid base (tubular frame).
Weight 85 pounds. Dimension (inches) 19-5/8 long, 17 wide, 17 high.
Ambient temperature limits for operation:
Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Shock and rough handling test: Railroad hump, drop, vibration.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 2.
Transient performance:
Application of rated load: Dip %: 30. Recovery sec: 2.
Rejection of rated load: Rise %: 30. Recovery sec: 2.
Application of simulated motor load: Dip %: N/A. Recovery sec: N/A.
Wave form: Maximum deviation factor %: N/A. Individual harmonic %: 5.
Regulation %: 4.
Adjusting range for standard voltage connections:
120 V conn: 114 to 126 V.

Frequency:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 3. Long term (4 hours): 3.
Transient performance:
Application of rated load: Undershoot %: 3. Recovery sec: 4.
Rejection of rated load: Overshoot %: 5. Recovery sec: 6.
Regulation %: 3. Frequency adjustment range: 60 Hz: N/A.

Reliability:
Mean time between failures (MTBF): 250 hours (specified).

Engine mechanical data:
Make: Military. Model: 1A08. Std: MS39297. No. of cyl: 1.
Operating speed: 3600. Horsepower: 1.5. Cycle: 4.
Air cooled. Rope start. Type of fuel: Gasoline.
Fuel tank capacity: 1 gallon. Fuel pump lift: 3 feet.
Fuel consumption: 0.25 gph at rated load. Industrial noise level.

Electrical data:
Dripproof generator enclosure. Fungus and moisture treatment.
Solid state voltage regulator. Brushless rotary exciter.
Electromagnetic interference suppression.

Instrumentation:
Voltmeter.

Auxiliary equipment:
Receptacle (convenience 120 VAC).

Optional equipment:
Canvas cover (D13213E0083). FSN: 6115-990-8770.

Technical manuals:

TM5-6115-329-15	TO 35C2-3-440-1	TM03935V-14
TM5-6115-329-25P	TO 35C2-3-440-14	SL-4-03520A
TM5-2805-256-14	TO 38G2-102-2	
TM5-2805-256-24P	TO 38G2-102-4	

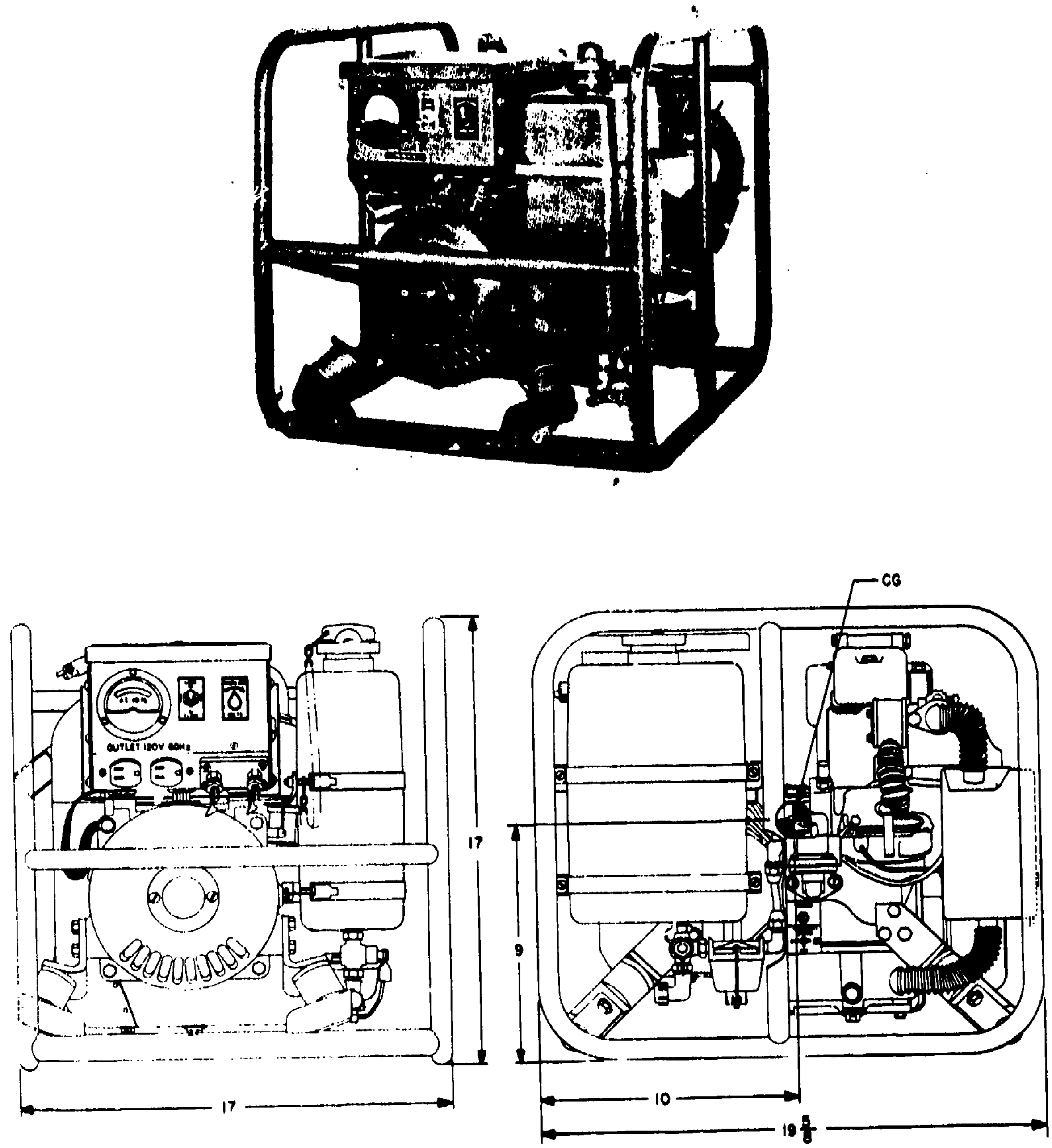


Figure I-1. PHOTOGRAPH AND OUTLINE DRAWING SHOWING DIMENSIONS

Section I Item 4

1.5 KW, 60 Hz, Gasoline Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-015A. FSN: 6115-889-1446. Specification: MIL-G-52282.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 1.

VOLTAGE CONNECTIONS

120 volts, 2 wire, 240 volts, 2 wire.

Rating: 1.5 KW, 60 Hz, 125°F, sea level; 107°F, 5000 ft; 95°F, 8000 ft.

GENERAL DESCRIPTION

Mounted on a skid base (tubular frame).
Weight 125 pounds. Dimension (inches) 27-3/8 long, 20-3/8 wide, 18-1/2 high.
Ambient temperature limits for operation:
  Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Shock and rough handling test: Railroad hump, drop, vibration.
Lifting attachments provided.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
  Steady state stability (variation) (bandwidth %):
    Short term (30 seconds): 2. Long term (4 hours): 2.
  Transient performance:
    Application of rated load: Dip %: 30. Recovery sec: 2.
    Rejection of rated load: Rise %: 30. Recovery sec: 2.
    Application of simulated motor load: Dip %: N/A. Recovery sec: N/A.
  Wave form: Maximum deviation factor %. N/A. Individual harmonic %: 3.5.
  Regulation %: 4; 5 for 240 volt, 2 wire.
  Adjusting range for standard voltage connections:
    120 V conn: 114 to 126 V. 240 V conn: 228 to 252 V.

Frequency:
  Steady state stability (variation) (bandwidth %):
    Short term (30 seconds): 3. Long term (4 hours): 3.
  Transient performance:
    Application of rated load: Undershoot %: 3. Recovery sec: 4.
    Rejection of rated load: Overshoot %: 5. Recovery sec: 6.
  Regulation %: 3. Frequency adjustment range: 60 Hz: N/A.

Page 2 of Item 4

Reliability:
Mean time between failures (MTBF): 250 hours (specified).

Engine mechanical data:
Make: Military. Model: 2A016. Std: MS39298. No. of cyl: 2.
Operating speed: 3600. Horsepower: 3. Cycle: 4.
Air cooled. Rope start. Type of fuel: Gasoline.
Fuel tank capacity: 1.5 gallons. Fuel pump lift: 3 feet.
Fuel consumption: 0.54 gph at rated load. Industrial noise level.

Electrical data:
Dripproof generator enclosure. Fungus and moisture treatment.
Solid state voltage regulator. Brushless rotary exciter.
Electromagnetic interference suppression.

Instrumentation:
Voltmeter. Frequency meter.

Auxiliary equipment:
Receptacle (convenience 120 VAC). Fuel lines.

Optional equipment:
Canvas cover D13214E0156). FSN: 6115-941-1655.

Technical manuals:

TM5-6115-323-15	TO 35C2-3-385-11	TM03521A-14
TM5-2805-257-14	TO 38G2-103-2	SL-4-03521A
TM5-2805-257-24P	TO 38G2-103-4	
LO5-2805-257-12		

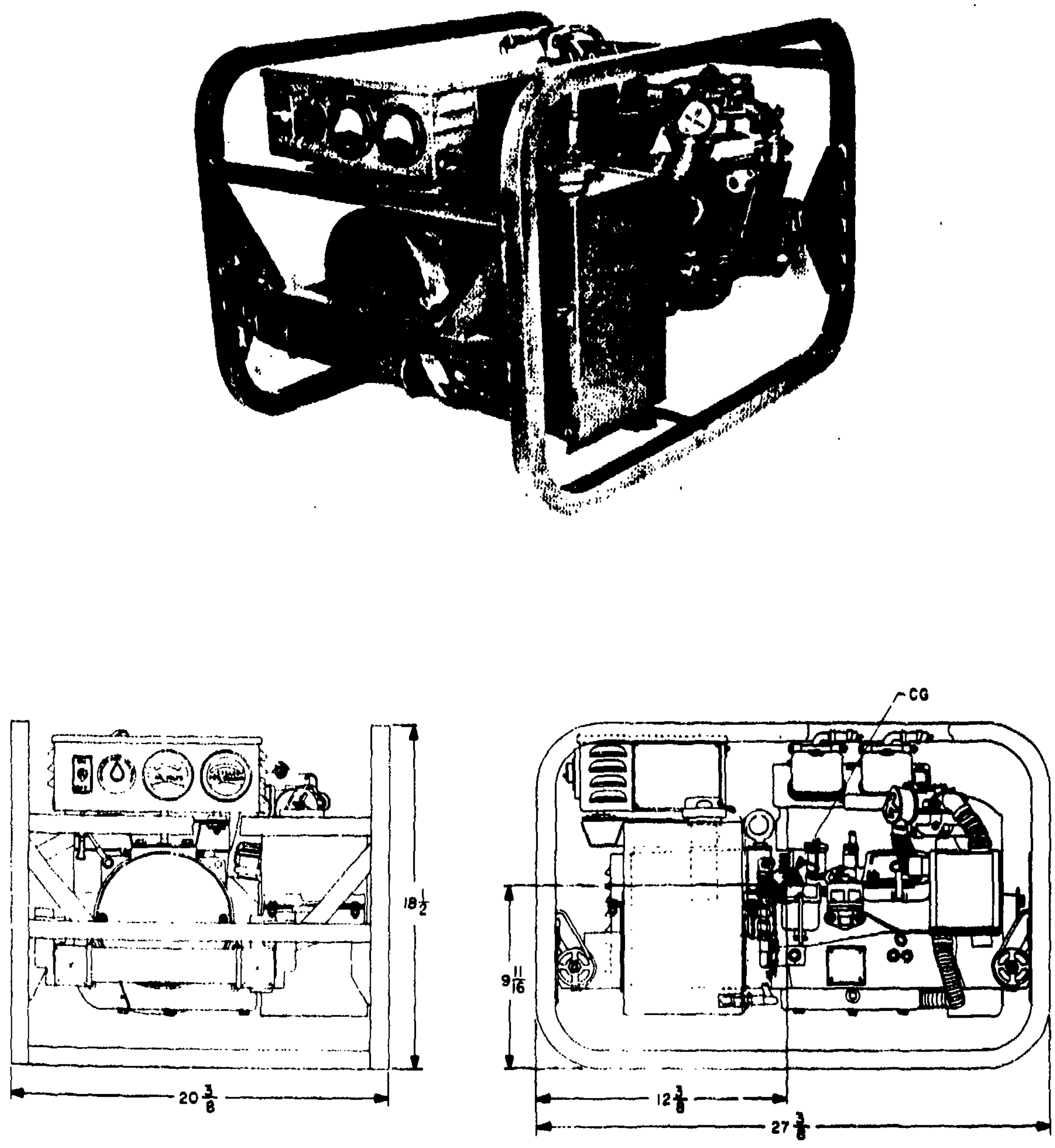


Figure I-4 PHOTOGRAPH AND OUTLINE DRAWING SHOWING DIMENSIONS

Section I Item 6

3 KW, 60 Hz, Gasoline Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-016A. FSN: 6115-017-8237. Specification: MIL-G-52367.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 0.8.

VOLTAGE CONNECTIONS

120 volts, 2 wire, 1 phase; 240 volts, 2 wire, 1 phase;
120 volts, 3 wire, 3 phase; 120/208 volts, 4 wire, 3 phase.

Rating: 3 KW, 60 Hz, 125°F, sea level; 107°F, 5000 ft; 95°F, 8000 ft.

GENERAL DESCRIPTION

Mounted on a skid base (tubular frame).
Weight 285 pounds. Dimension (inches): 35 long, 24-9/64 wide, 25 high.
Ambient temperature limits for operation:
Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
With winterization system: Minus 65°F (53.9°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Shock and rough handling test: Railroad hump, drop, vibration.
Lifting and tie-down attachments provided.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 2.
Transient performance:
Application of rated load: Dip %: 30. Recovery sec: 2.
Rejection of rated load: Rise %: 30. Recovery sec: 2.
Application of simulated motor load: Dip %: N/A. Recovery sec: N/A.
Wave form: Maximum deviation factor %: N/A. Individual harmonic %: 3.
Regulation %: 4. 5 for 240 V, 2 wire.
Adjusting range for standard voltage connections:
120/208 V conn: 197 to 218 V; 240 V conn: 228 to 252 V.
120 V, 1 phase conn: 114 to 126 V; 120 V, 3 phase conn: 114 to 126 V.

Frequency:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 1. Long term (4 hours): 2.
Transient performance:
Application of rated load: Undershoot %: 3. Recovery sec: 4.
Rejection of rated load: Overshoot %: 5. Recovery sec: 6.
Regulation %: 3. Frequency adjustment range: 60 Hz: N/A.

Reliability:
Mean time between failures (MTBF): 250 hours (specified).

Engine mechanical data:
Make: Military. Model: 4A032. Std: MS39299. No. of cyl: 4.
Operating speed: 3600. Horsepower: 6. Cycle: 4.
Air cooled. Rope start. Type of fuel: Gasoline.
Fuel tank capacity: 3.6 gallons. Fuel pump lift: 3 feet.
Fuel consumption: 0.84 gph at rated load. Industrial noise level.

Electrical data.
Dripproof generator enclosure. Fungus and moisture treatment.
Solid state voltage regulator. Brushless rotary exciter.
Short circuit protection. Electromagnetic interference suppression.

Instrumentation:
Voltmeter. Frequency meter. Percent-of-load meter (current).

Auxiliary equipment:
Receptacle (convenience 120 VAC). Fuel lines.

Optional equipment:

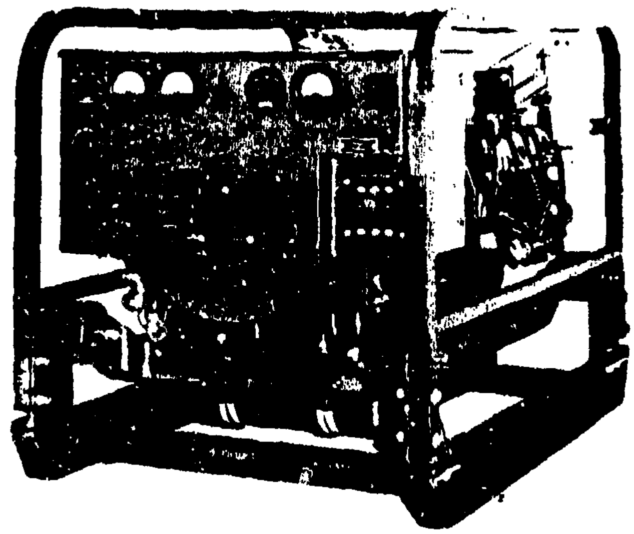
Description	FSN
Winterization kit (D13213E4430)	
Torch (MIL-H-52112, type I)	4520-710-4341
Canvas cover (D13208E5907)	6115-960-2703
Starter kit (D13208E5819)	2920-075-1710

Technical manuals:

TM5-6115-271-14	TO 35C2-3-386-1
TM5-6115-271-20P	TO 35C2-3-386-4
TM5-6115-271-34P	TO 35C2-3-386-25
TM5-2805-203-14	TO 38G2-90-1
TM5-2805-203-24P	TO 38G2-90-14

Special features:
Trailer mounting:

PU-617/M	(2 sets)	M101 Trailer	FSN 6115-738-6335
PU-625/G	(2 sets)	M101 Trailer	FSN 6115-873-3915
PU-628/G	(2 sets)	M101 Trailer	FSN 6115-087-0873



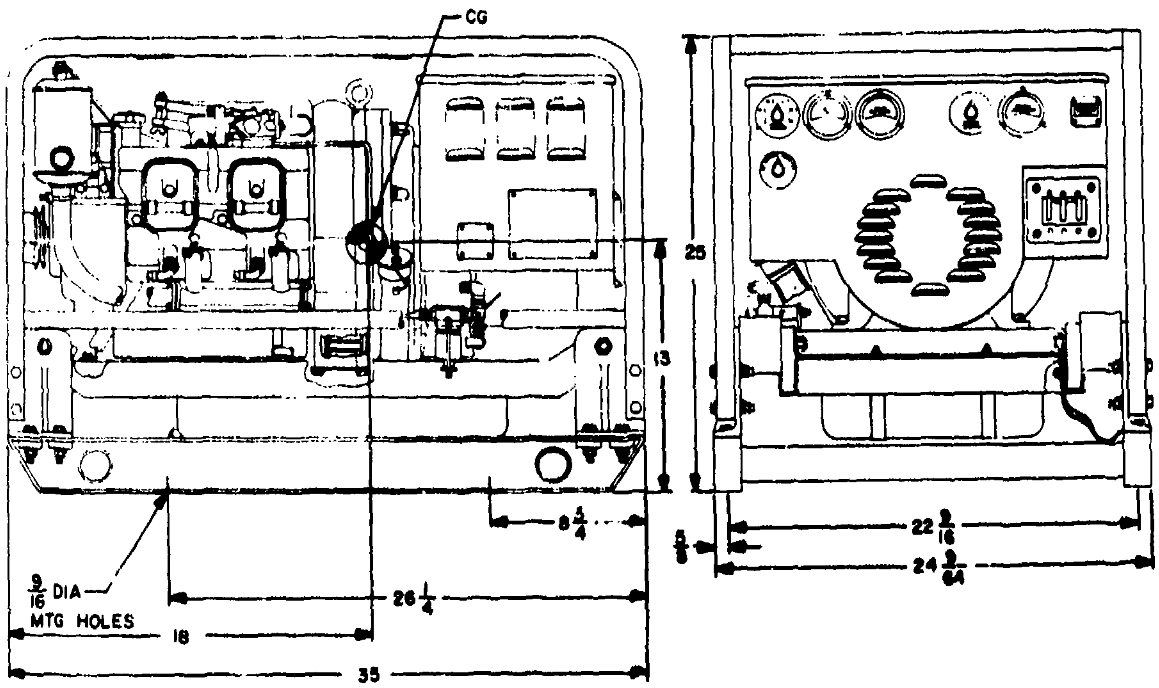


Figure I-6 PHOTOGRAPH AND OUTLINE DRAWING SHOWING DIMENSIONS

Section I Item 9

5 KW, 60 Hz, Gasoline Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-017A. FSN: 6115-017-8240. Specification: MIL-G-52279.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 0.8.

VOLTAGE CONNECTIONS

120 volts, 2 wire, 1 phase; 240 volts, 2 wire, 1 phase;
120 volts, 3 wire, 3 phase; 120/208 volts, 4 wire, 3 phase.

Rating:m 5 KW, 60 Hz, 125°F, sea level; 107°F, 5000 ft; 95°F, 8000 ft.

GENERAL DESCRIPTION

Mounted on a skid base (tubular frame).
Weight 488 pounds. Dimension (inches): 39-21/32 long, 30 wide, 25 high.
Ambient temperature limits for operation:
  Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
  With winterization system: Minus 65°F (53.9°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Shock and rough handling test: Railroad hump, drop, vibration.
Lifting and tie-down attachments provided.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
  Steady state stability (variation) (bandwidth %):
    Short term (30 seconds): 2. Long term (4 hours): 2.
  Transient performance:
    Application of rated load: Dip %: 30. Recovery sec: 2.
    Rejection of rated load: Rise %: 30. Recovery sec: 2.
    Application of simulated motor load: Dip %: N/A. Recovery sec: N/A.
  Wave form: Maximum deviation factor %: N/A. Individual harmonic %: 3.
  Regulation %: 4. 5 for 240 V, 2 wire.
  Adjusting range for standard voltage connections:
    120/208 V conn: 197 to 218 V; 240 V conn: 228 to 252 V.
    120 V, 1 phase conn: 114 to 126 V; 120 V, 3 phase conn: 114 to 126 V.
Frequency:
  Steady state stability (variation) (bandwidth %):
    Short term (30 seconds): 1. Long term (4 Hours): 2.
  Transient performance:
    Application of rated load: Undershoot %: 3. Recovery sec: 4.
    Rejection of rated load: Overshoot %: 5. Recovery sec: 6.
    Regulation %: 3. Frequency adjustment range: 60 Hz. N/A.

Reliability:
Mean time between failures (MTBF): 250 hours (specified).

Engine mechanical data:
Make: Military. Model: 2A042. Std: MS39300. No. of cyl: 2.
Operating speed: 3600. Horsepower: 10. Cycle: 4.
Air cooled. Rope and 24 VDC electric start. Type of fuel: Gasoline.
Fuel tank capacity: 5 gallons. Fuel pump lift: 6 feet.
Fuel consumption: 1.4 gph at rated load. Industrial noise level.

Electrical data:
Dripproof generator enclosure. Fungus and moisture treatment.
Solid state voltage regulator. Brushless rotary exciter.
Short circuit protection. Electromagnetic interference suppression.

Instrumentation:
Hour meter. Voltmeter. Frequency meter. Low oil pressure gage.
Percent-of-load meter (current). Battery charging ammeter.

Auxiliary equipment:
Remote stop and start. Fuel line . Receptacle slave 24 VDC.
Receptacle (convenience 120 VAC). Battery charging rectifier.

Optional equipment:

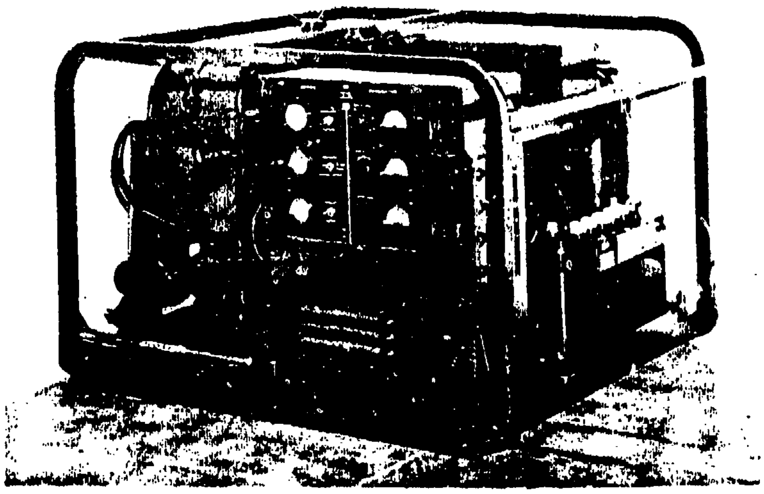
Description	FSN	Wt (lb)
Winterization kit (DL13218E8063)		
Torch (MIL-H-52112, type I)	4520-710-4341	
Canvas cover (D13211E6769-1)	6115-945-7545	
Batteries	6140-059-3528	35
Fire extinguisher w/bracket	4210-555-8837	10
Fuel can (MIL-C-1283)	7240-222-3086	
Fuel drum adapter (DL13211E7541)	2910-066-1235	

Technical manuals:

TM5-6115-332-12	TO 35C2-3-424-1	
TM5-6115-332-34	TO 35C2-3-424-22	
TM5-6115-332-25P	TO 35C2-3-424-4	
TM5-2805-258-14	TO 38G2-89-21	TM03523B-15
TM5-2805-258-24P	TO 38G2-89-34	SL-4-035-23B

Special features:
Trailer mounting

PU-409A/M	(1 set)	M101 Trailer	FSN 6115-738-6338
PU-618/M	(2 sets)	M103 Trailer	FSN 6115-738-6337
PU-620/M	(2 sets)	M116 Trailer	FSN 6115-738-6340
PU-629/G	(2 sets)	M103 Trailer	FSN 6115-937-5555
PU-631/G	(2 sets)	M103 Trailer	FSN 6115-059-5172
PU-686/TCC-23	(2 sets)	M103 Trailer	FSN 6115-132-4497



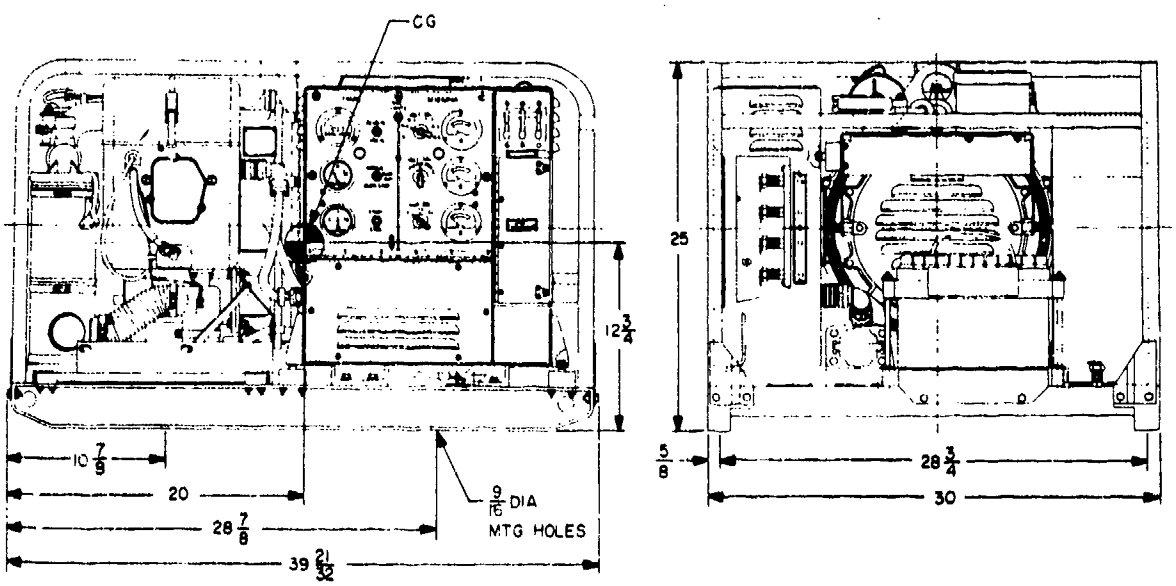


Figure I-9 PHOTOGRAPH AND OUTLINE DRAWING SHOWING DIMENSIONS

Section I Item 11

10 KW, 60 Hz, Gasoline Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-018A. FSN: 6115-389-1447. Specification: MIL-G-52280.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 0.8.

VOLTAGE CONNECTIONS

120 volts, 2 wire, 1 phase; 120/240 volts, 3 wire, 1 phase;
120 volts, 3 wire, 3 phase; 120/208 volts, 4 wire, 3 phase.

Rating: 10 KW, 60 Hz, 125°F, sea level; 107°F, 5000 ft; 95°F, 8000 ft.

GENERAL DESCRIPTION

Mounted on a skid base (tubular frame).
Weight 850 pounds. Dimension (inches): 57 long, 30 wide, 28-3/8 high.
Ambient temperature limits for operation:
Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
With winterization system: Minus 65°F (53.9°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Shock and rough handling test: Railroad hump, drop, vibration.
Lifting and tie-down attachments provided.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 1. Long term (4 hours): 1.
Transient performance:
Application of rated load: Dip %: 20. Recovery sec: 2.
Rejection of rated load: Rise %: 20. Recovery sec: 2.
Application of simulated motor load: Dip %: 40. Recovery sec: 4.
Wave form: Maximum deviation factor %: N/A. Individual harmonic %: 2.
Regulation %: 3. 4 for 120/240 V, 3 wire.
Adjusting range for standard voltage connections:
120/208 V conn: 197 to 218 V; 120/240 V conn: 228 to 252 V.
120 V, 1 phase conn: 114 to 126 V; 120 V, 3 phase conn: 114 to 126 V.

Frequency:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 1. Long term (4 hours): 2.
Transient performance:
Application of rated load: Undershoot %: 3. Recovery sec: 4.
Rejection of rated load: Overshoot %: 5. Recovery sec. 6.
Regulation %: 3. Frequency adjustment range: N/A.

Reliability:
Mean time between failures (MTBF): 250 hours (specified).

Engine mechanical data:
Make: Military. Model: 4A084. Std: MS39302. No. of cyl: 4.
Operating speed: 3600. Horsepower: 20. Cycle: 4.
Air cooled: Rope and 24 VDC electric start. Type of fuel: Gasoline.
Fuel tank capacity: 5 gallons. Fuel pump lift: 6 feet.
Fuel consumption: 2.4 gph at rated load. Industrial noise level.

Electrical data:
Dripproof generator enclosure. Fungus and moisture treatment.
Solid state voltage regulator. Brushless rotary exciter.
Short circuit protection. Electromagnetic interference suppression.

Instrumentation:
Hour meter. Voltmeter. Frequency meter. Low oil pressure gage.
Percent-of-load meter (current). Battery charging ammeter.

Auxiliary equipment:
Remote stop and start. Fuel lines. Receptacle slave 24 VDC.
Receptacle (convenience 120 VAC). Battery charging rectifier.

Optional equipment:

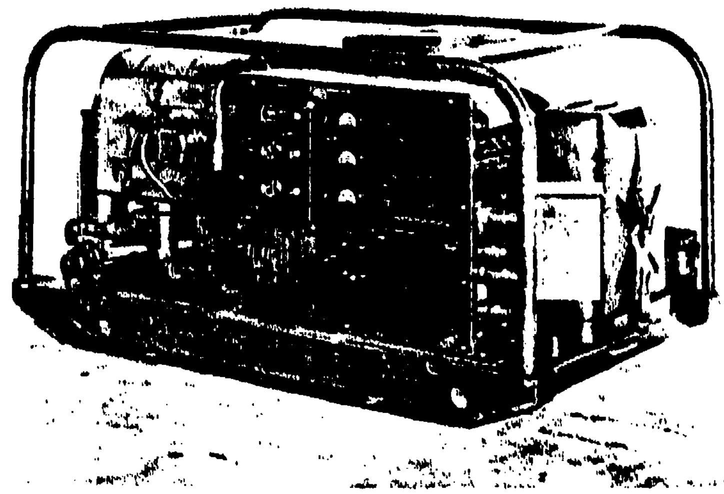
Description	FSN	Wt (lb)
Winterization kit (DL13218E8059)		
Torch (MIL-H-52112, type I)	4520-710-4341	
Canvas cover (DL13211E6769-2)	6115-066-4933	
Batteries	6140-059-3528	35
Fire extinguisher w/bracket	4210-555-8837	10
Fuel can (MIL-C-1283)	7240-222-3086	
Fuel drum adapter (DL13211E7541)	2910-066-1235	

Technical manuals:

TM5-6115-275-15		
TM5-6115-275-25P		
TM5-2805-259-14	TO 38G2-89-41	TM03524B-14
TM5-2805-259-24P	TO 38G2-89-54	SL-4-03524B

Special features:

PU-332A/G	(1 set)	M101 Trailer	6115-738-6336
PU-564B/G	(1 set)	M103 Trailer	6115-179-2789
PU-619/M	(2 sets)	M103 Trailer	6115-738-6339



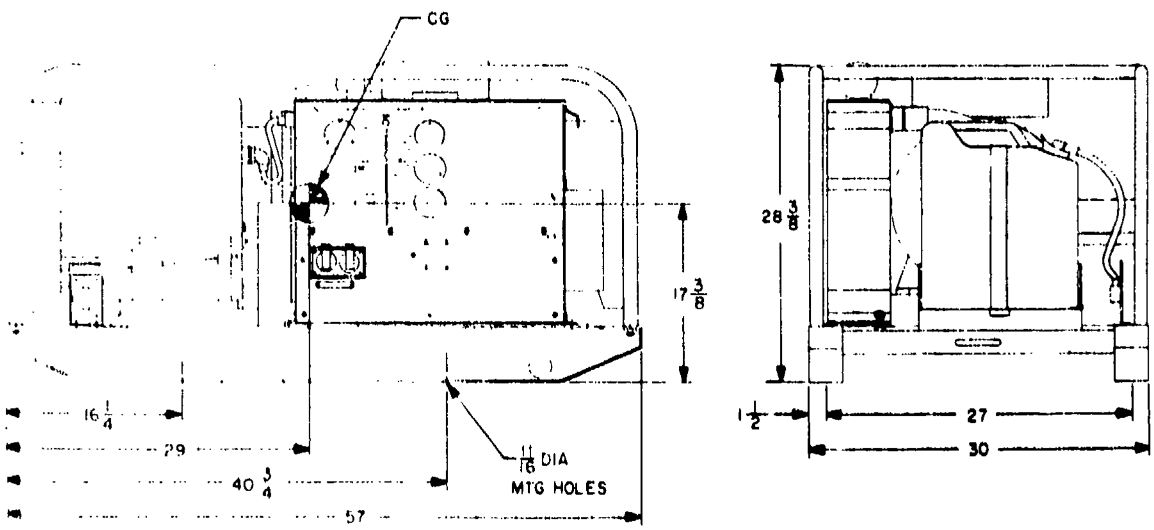


Figure 1-11 PHOTOGRAPH AND OUTLINE DRAWING SHOWING DIMENSIONS

Section II Item 1

5 KW, 60 Hz, Diesel Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-002A. FSN: 6115-465-1044. Specification: PD-4-22-71.
Type: I(Tactical). Class: 2(Utility). Mode: II(60 Hz). Power factor: 0.8.

VOLTAGE CONNECTIONS

120 volts, 1 phase, 2 wire. 120/240 volts, 1 phase, 3 wire. 120/208 volts, 3 phase, 4 wire.

Rating: 5 KW, 60 Hz, sea level, 125°F; 5000 ft, 115°F.
4 KW, 60 Hz, 8000 ft, 95°F.

GENERAL DESCRIPTION

Mounted on a skid base. Weight: 900 pounds.
Dimension (inches): 51 long, 32 wide, 39 high.
Ambient temperature limits for operation:
Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
With winterization system: Minus 65°F (53.9°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Lifting, towing, and tie-down attachments provided. Forklift provision.
Shock and rough handling test: Railroad hump, road, drop.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 4.
Transient performance:
Application of rated load: Dip %: 20. Recovery sec: 3.
Rejection of rated load: Rise %: 20. Recovery sec: 3.
Application of simulated motor load: Dip %: 40. Recovery sec: 5.
Wave form: Maximum deviation factor %: 5. Individual harmonic %: 2.
Regulation %: 3.
Adjusting range for standard voltage connections:
120 V, conn: 114 to 126; 120/240 V, conn: 228 to 252;
120/208 V, conn: 198 to 228.

Frequency:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 3.
Transient performance:
Application of rated load: Undershoot %: 3. Recovery sec: 3.
Rejection of rated load: Overshoot %: 4. Recovery sec: 3.
Frequency adjustment range %: ± 3.
Regulation %: 3.

Reliabilty:
Mean time between failures (MTBF): 500 hours (specified).

Engine mechanical data:
Make: ONAN. Model: DJE-99E. Spec: MIL-E-11276.
Operating speed: 1800 RPM. Horsepower min: 10. Air cooled. Cycle: 4.
24 VDC electric start. Residential noise level.
Fuel type: VV-F-800, DF-1, DF-2, or DF-A. MIL-T-5624, JP-4.
Fuel tank for 8 hours operation. Fuel pump lift 6 ft.
Fuel consumption: 0.57 gph at rated load. Battery charging alternator.

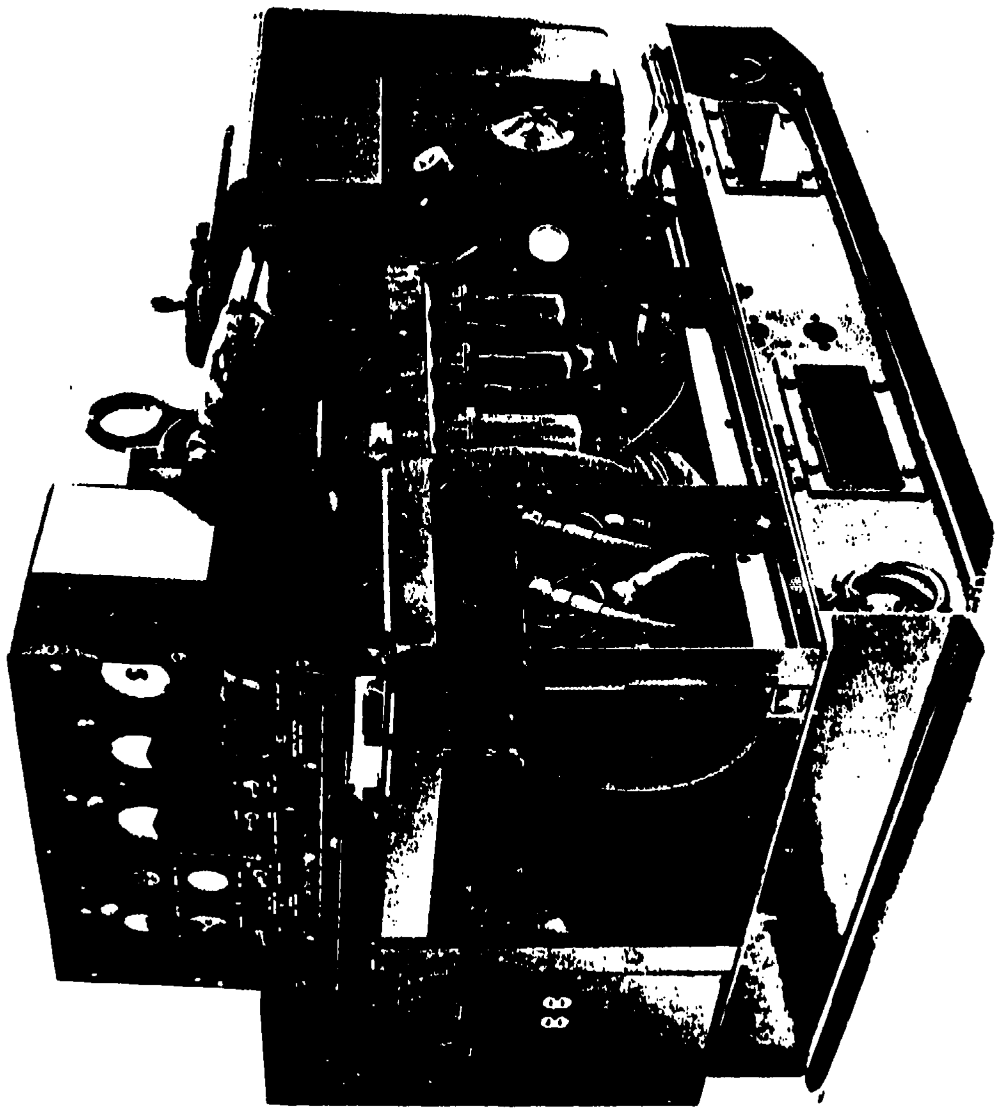
Electrical data:
Dripproof generator enclosure.
Fungus and moisture treatment. Solid state voltage regulator.
Brushless rotary exciter. Overload protection.
Electromagnetic interference suppression. Short circuit protection.

Instrumentation:
Voltmeter. Ammeter. Frequency meter.

Auxiliary equipment:
Fuel lines. Receptacle (convenience 120 VAC).

Optional equipment:
Ground rod: MIL-R-11461, type II, style 2.
Fire extinguisher w/bracket: FSN: 4210-555-8837.
Winterization kit (fuel burning): Max weight: 350 pounds.
Batteries (MS35000).

Technical manuals:



PHOTOGRAPH

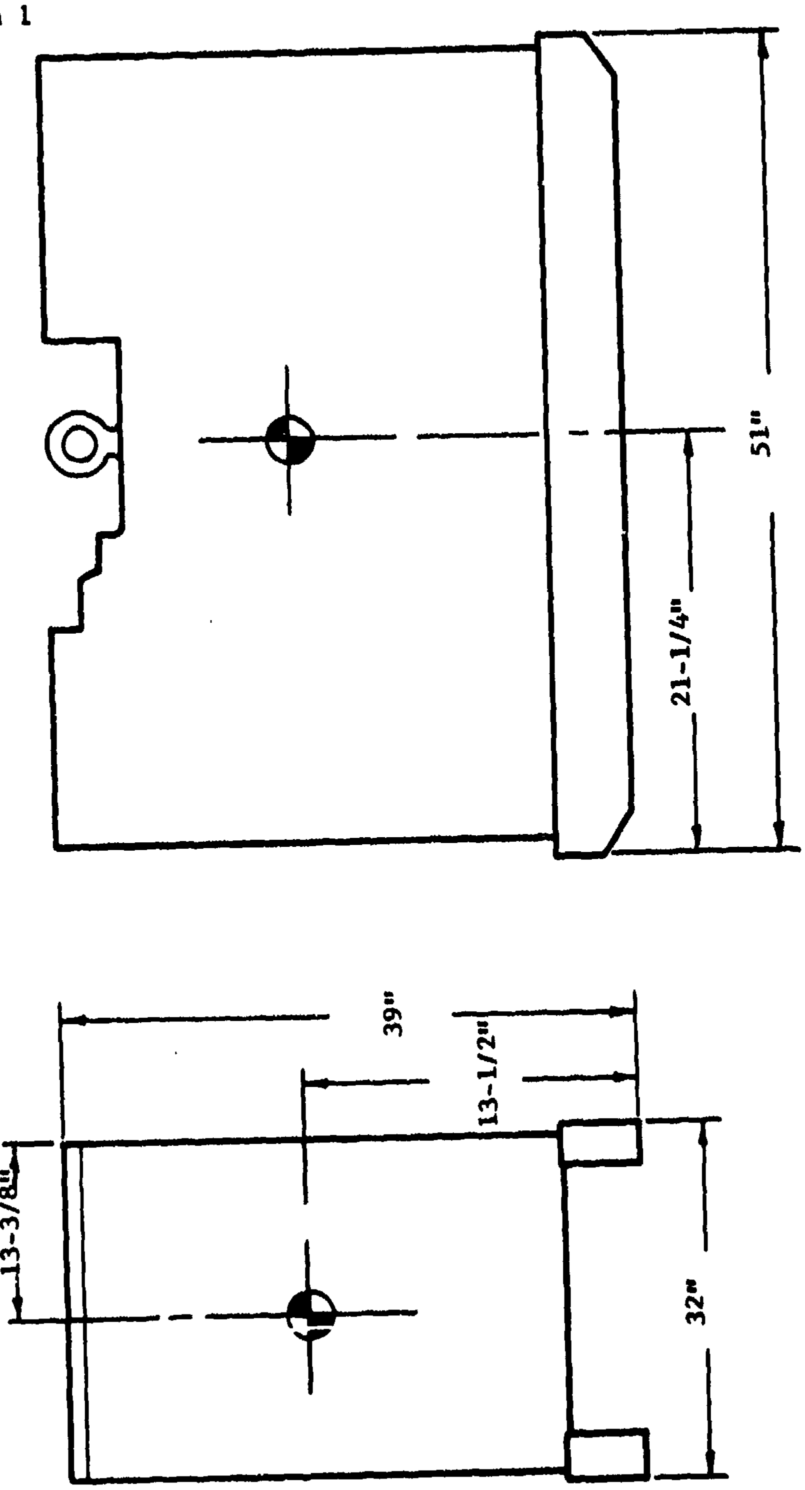


Figure II-1-2 OUTLINE DRAWING SHOWING DIMENSIONS

Section II Item 3

10 KW, 60 Hz, Diesel Engine-Generator Set

GENERAL APPLICATION CHARACTERISTICS

Model: MEP-003A. FSN: 6115-465-1030. Specification: PD-4-22-71.
Type: I(Tactical). Class: 2(Utility). Mode: III(60 Hz). Power factor: 0.8.

VOLTAGE CONNECTIONS

120 volts, 1 phase, 2 wire. 120/240 volts, 1 phase, 3 wire. 120/208 volts, 3 phase, 4 wire.

Rating: 10 KW, 60 Hz, sea level, 125°F; 5000 ft, 115°F.
8 KW, 60 Hz, 8000 ft, 95°F.

GENERAL DESCRIPTION

Mounted on a skid base. Weight: 1100 pounds.
Dimension (inches): 62 long, 32 wide, 39 high.
Ambient temperature limits for operation:
Without winterization system: Minus 25°F (31.7°C) to plus 125°F (51.7°C).
With winterization system: Minus 65°F (53.9°C) to plus 125°F (51.7°C).
Operation with base level or inclined to not more than 15° from level.
Lifting, towing, and tie-down attachments provided. Forklift provision.
Shock and rough handling test: Railroad hump, road, drop.

PERFORMANCE CHARACTERISTICS
(Parametric values are the maximum allowable limits:)

Voltage:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 4.
Transient performance:
Application of rated load: Dip %: 20. Recovery sec: 3.
Rejection of rated load: Rise %: 20. Recovery sec: 3.
Application of simulated motor load: Dip %: 40. Recovery sec: 5.
Wave form: Maximum deviation factor %: 5. Individual harmonic %: 2.
Regulation %: 3.
Adjusting range for standard voltage connections:
120 V, conn: 114 to 126; 120/240 V, conn: 228 to 252;
120/208 V, conn: 198 to 228.

Frequency:
Steady state stability (variation) (bandwidth %):
Short term (30 seconds): 2. Long term (4 hours): 3.
Transient performance:
Application of rated load: Undershoot %: 3. Recovery sec: 3.
Rejection of rated load: Overshoot %: 4. Recovery sec: 3.
Frequency adjustment range %: ± 3.
Regulation %: 3.

Reliabilty:
Mean time between failures (MTBF): 500 hours (specified).

Engine mechanical data:
Make: ONAN. Model: DJF-99E. Spec: MIL-E-11276.
Operating speed: 1800 RPM. Horsepower min: 20. Air cooled. Cycle: 4.
24 VDC electric start. Residential noise level.
Fuel type: VV-F-800, DF-1, DF-2, or DF-A. MIL-T-5624, JP-4.
Fuel tank for 8 hours operation. Fuel pump lift 6 ft.
Fuel consumption: 1.09 gph at rated load. Battery charging alternator.

Electrical data:
Dripproof generator enclosure.
Fungus and moisture treatment. Solid state voltage regulator.
Brushless rotary exciter. Overload protection.
Electromagnetic interference suppression. Short circuit protection.

Instrumentation:
Voltmeter. Ammeter. Frequency meter.

Auxiliary equipment:
Fuel lines. Receptacle (convenience 120 VAC).

Optional equipment:
Ground rod: MIL-R-11461, type II, style 2.
Fire extinguisher w/bracket: FSN: 4210-555-8837.
Winterization kit (fuel burning): Max weight: 350 pounds.
Batteries (MS35000).

Technical manuals:

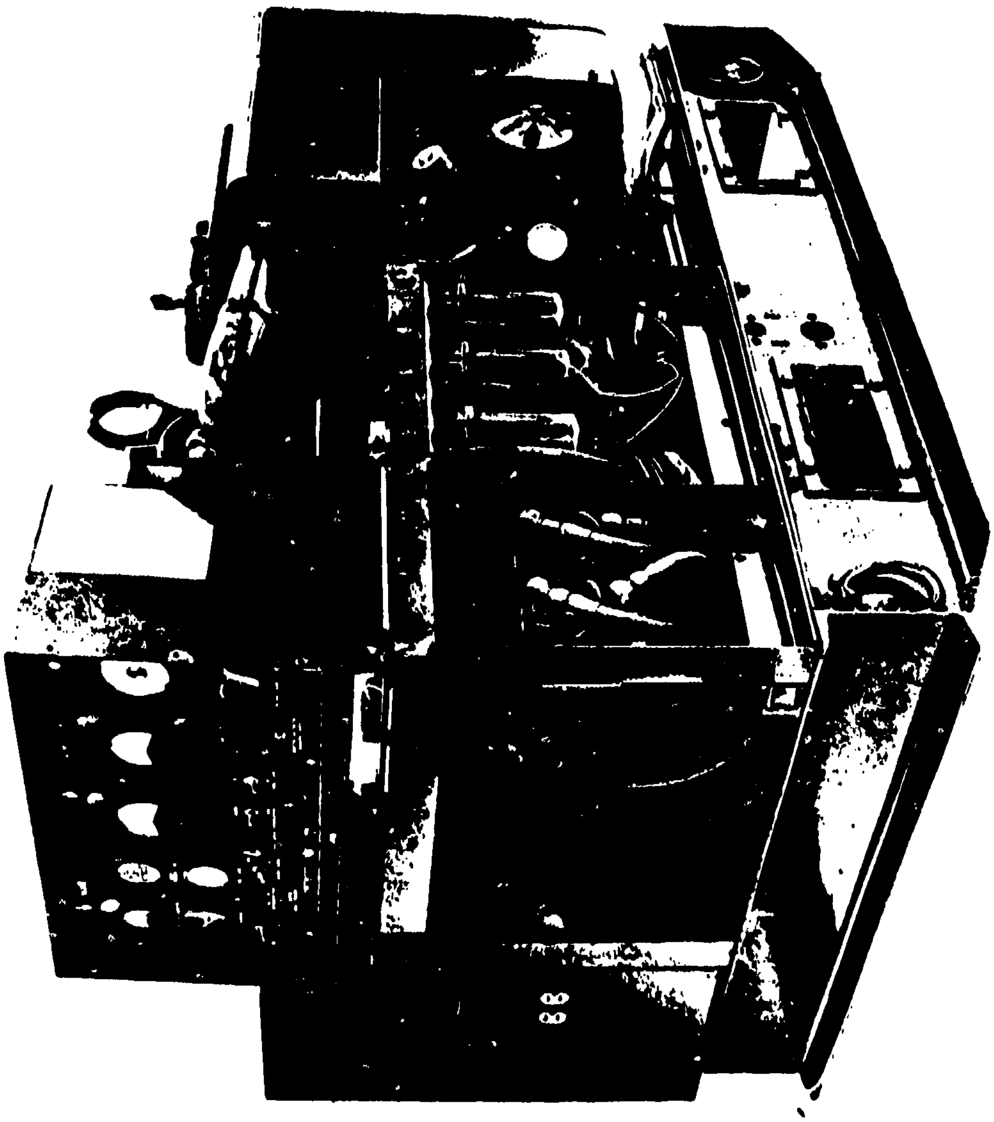


Figure II-3-1 PHOTOGRAPH

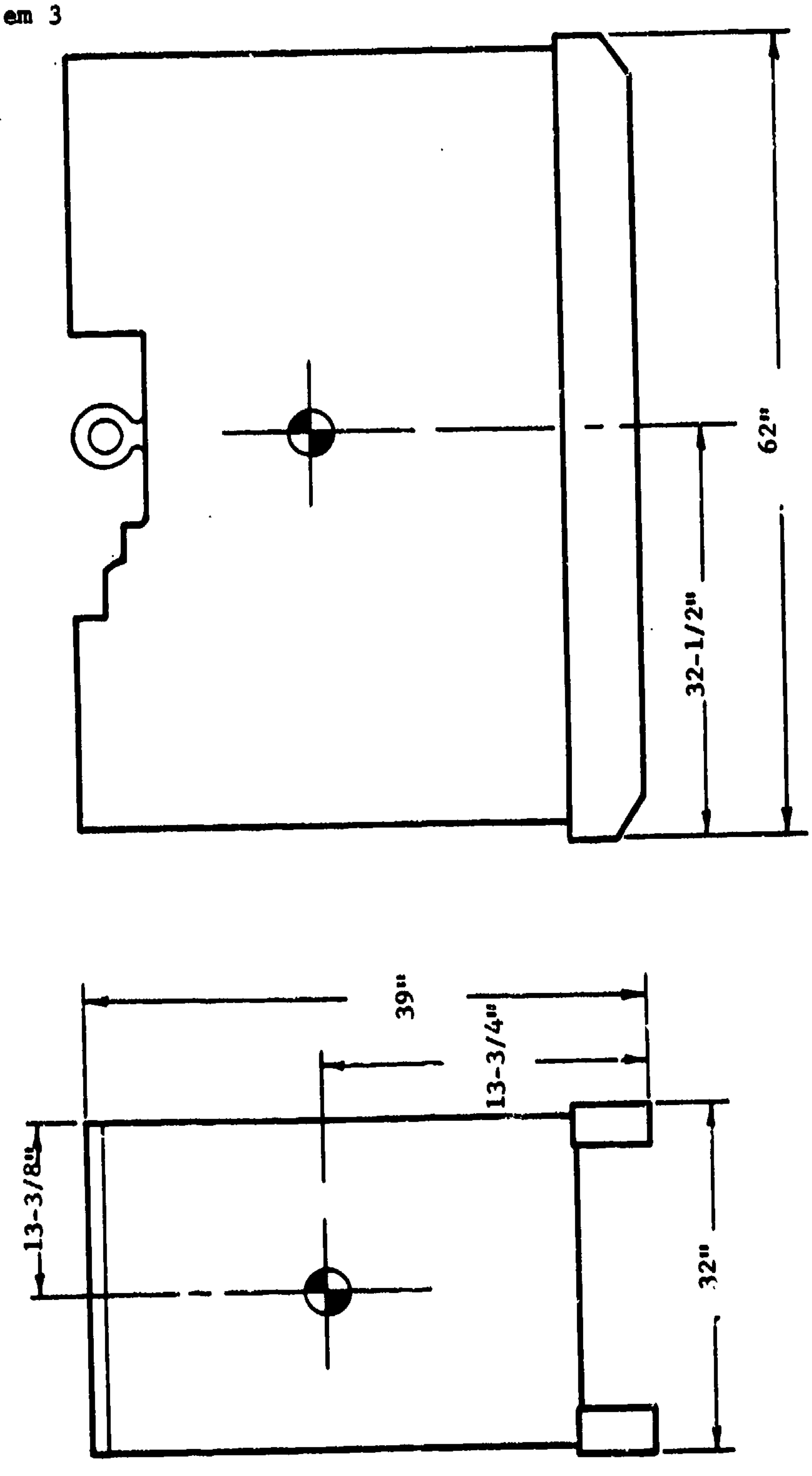


Figure II-3-2 OUTLINE DRAWING SHOWING DIMENSIONS

MILITARY STANDARD
MOBILE ELECTRIC POWER
ENGINE GENERATOR STANDARD FAMILY
MEP-412A, 10 kW, 60 Hz, GAS TURBINE ENGINE-DRIVEN GENERATOR SET
CHARACTERISTICS DATA SHEET

CLASSIFICATION

Description: 10 kW @ 0.8 power factor, 60 Hz, 120 V, 120/240 V, 120/208 V
Not type classified for Army use.

Model:	MEP-412A	Type:	I (tactical)
NSN:	To be determined	Class:	2 (utility)
Spec:	PD 10 Aug 78	Mode:	III (60 Hz)

PHYSICAL CHARACTERISTICS

mensions: See Figures 16 and 17 on pages 76 and 77.

Weight: 456 lbs (206.8 kg).

Mobility: Mounted on skid base. Lifting, and tie-down attachments provided. Towing provision.

Engine: Gas turbine. Horsepower: 28 @ 93,500 RPM. Air cooled. 24 VDC electric start. Operating speed: 93,500 RPM/with gear reduction to 3600. Internal fuel tank: 4 minutes operation. Fuel pump lift: 6 feet. Auxiliary fuel hose: 12 feet.

Fuel:
Primary: MIL-T-5624 Aviation Turbine Fuels, grades JP-4 and JP-5. VV-F-800, Diesel Fuel Oil, types DF-1, DF-2 and DF-A and MIL-F-16884, Marine Diesel Fuel Oil.
Emergency fuel: MIL-G-3056 and VV-G-76 Automotive Gasolines and MIL-G-5572 Aviation Gasolines. Grades 80/87, 100/130 and 115/145.

Electrical Data: Fungus and moisture treatment. Solid state voltage regulator. Brushless rotary exciter.

Voltage Connection: 120 V, 1 phase, 2 wire. 120/240 V, 1 phase 3 wire, 120/208 V, 3 phase 4 wire.

Protective Devices: Short circuit protection. Overload. Engine overspeed and exhaust temperature protection. Low oil pressure cut-off switch. Low fuel (4 minutes operation). Malfunction indicator for each protective device.

Instrumentation: Voltmeter. Ammeter. Hourmeter. Frequency Meter.

FUNCTIONAL/OPERATIONAL CHARACTERISTICS

Reliability: Mean Time Between Failures (MTBF): 750 hours (specified)

Fuel Consumption: 3.4 gph at rated load.

Electromagnetic Interference: Suppressed to MIL-STD-461 limits.

	Voltage	Frequency
Steady State Stability (variation)		
Short Term (30 sec)	2% Bandwidth	2% Bandwidth
Long Term (4 hours)	4% Bandwidth	3% Bandwidth
Transient Performance		
Application of rated load	20% Dip	3% Undershoot
recovery	3 Sec	3 Sec
Rejection of rated load	20% Rise	4% Overshoot
recovery	3 Sec	3 Sec
Waveform		
Maximum Deviation Factor	5%	
Individual Harmonic	2%	
Regulation:	3%	3%

Adjustment Range for Standard Voltage Connections: 205 to 220 V for 120/208 V connection. 114 to 126 V for 120 V connection. 228 to 252 V for 240 V connection.

Adjustment Range for Frequency: 58.2 to 61.8 Hz.

ENVIRONMENTAL DATA

Power Output at Environmental Conditions

10 kW, 60 Hz, Sea Level: Minus 65° F (-53.9° C) to plus 125° F (+51.7° C)
10 kW, 60 Hz, 5000 feet: Minus 65° F (-53.9° C) to plus 107° F (+41.7° C)
9 kW, 60 Hz, 8000 feet: Minus 65° F (-53.9° C) to plus 95° F (+35.0° C)

Shock and Rough Handling: 10 mph railroad impact. 12 inch drop. 12 inch end drop. Truck and trailer transportation.

<u>Attitude</u>: Operate with base level or inclined no more than 15 degrees from level.

<u>Noise Level</u>: 79 dbA @ 25 feet.

OPTIONAL EQUIPMENT

None.

REFERENCE DOCUMENTS

<u>Technical Manuals</u>: Not published.