DOE/NASA/50112-76
NASA TM-100978

NASA-TM-100978
19880018596

Phase I Results from the Stirling-Powered Vehicle Project

Richard K. Shaltens
National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

Prepared for the
Fourth International Conference on Stirling Engines
sponsored by the Japan Society of Mechanical Engineers (JSME)
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Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes[1]
Printed copy: A02
Microfiche copy: A01

[1]Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

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Office of Vehicle and Engine R&D
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-85CE50112

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PHASE I RESULTS FROM THE STIRLING-POWERED VEHICLE PROJECT

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E-4270

ABSTRACT

The NASA Technology Utilization (TU) Office is sponsoring a multiyear, multiphase demonstration program to assess the technology developed under the DOE/NASA automotive Stirling engine (ASE) program with engines installed in various Air Force vehicles while being evaluated by independent third parties under realistic conditions. This paper reviews the operational history of Phase I with a Mod I Stirling engine installed in an Air Force multistop van in a variety of missions. Ten months of operation were with Air Force personnel at Langley Air Force Base, VA, where over 1100 hr and 4000 mi were logged on the Langley flight line. The Stirling-powered van was operated on unleaded gasoline, JP-4 aircraft fuel, and diesel fuel at Langley Air Force Base. Two months of operation were completed with Deere & Company personnel in the Moline, IL area where over 175 hr and 2650 mi were logged on a Deere mail delivery route.

INTRODUCTION

The Automotive Heat Engine Program was begun in 1971 with the initial objective of developing alternative automotive heat engines with significantly reduced emissions. The objectives of improved fuel economy and multifuel capability were added in 1973. The Stirling engine was selected as one of the promising candidates in 1975 for detailed evaluation. The DOE assigned the management responsibility for the ASE Project to the NASA Lewis Research Center in 1977. In 1978, a Stirling engine development contract, funded by DOE and managed by Lewis, was awarded to MTI. As of January 1988, seven experimental, first-generation, Mod I automotive Stirling engines (ASE's) were built and operated in test cells and vehicles for over 18 000 hr. Additional information about the DOE/NASA ASE Program activities is given by Beremand and Tabata in Refs. (1) through (3).

STIRLING-POWERED VEHICLE PROJECT

The Stirling-Powered Vehicle Project (SPVP) is a technology demonstration program funded by the NASA Technology Utilization (TU) Office and DOE, and is directed toward placing commercial manufacturers and end users "on the path to commercialization" of the Mod II ASE. The SPVP is cofunded with an industry/government team that includes NASA Lewis, the Department of Energy, the Department of the Air Force, Deere & Company, Mechanical Technology Inc., and the American Trucking Associations. MTI is the prime contractor responsible for the implementation of the NASA TU SPVP. A multiyear, multiphase demonstration program was created by the industry/government team described in detail in Ref. (4). The prime objectives of the SPVP are as follows: (1) to obtain early operation and performance data while gaining initial experience in operating the Stirling engine in a typical user environment, (2) to evaluate the Stirling engine in terms of establishing Stirling integrity, reliability, and durability, and (3) to accelerate the development of Stirling engines and enable the earliest possible use of the second-generation Mod II ASE. Phase I plans were to operate a first-generation Mod I Stirling engine up to 1000 hr using unleaded gasoline and JP-4 aircraft fuel in an Air Force van under realistic conditions. Langley AFB was chosen because it had an Air Force evaluation team (the Management and Equipment Evaluation Program (MEEP)) and because of the moderate Virginia climate. Phase II would be in a second Air Force vehicle and would evaluate the Mod I ASE in different climates and user conditions.

VEHICLE INTEGRATION

The Air Force provided a 1986 General Motors (GM) multistop (delivery) van (Fig. 1) powered by a standard 6.2-L (379-in^3) V-8, diesel engine (145 hp (108.8 kW) at 3600 rpm). Curb weight of this vehicle is 6800 lb (2677 kg), with a maximum gross vehicle weight (GVW) of 8600 lb (3386 kg). Engine specifications and a power and torque curve are shown in Table 1 and Fig. 2. When the GM multistop van arrived at MTI, it was driven approximately 1100 mi to break in the drivetrain to ensure that the vehicle was sound. After the vehicle break-in was completed, the diesel engine was removed and a Mod I Stirling engine mockup was installed to determine what modifications would be required. The only major alteration required was a cutout in the front crossmember. This modification was needed so that the engine and transmission could be properly installed and aligned.

The original transmission for the diesel-powered van was a vacuum-modulated, three-speed automatic. The Stirling engine is an external combustion engine and does not have intake manifold vacuum. Therefore, to match the Stirling engine, a Chrysler nonvacuum-modulated, three-speed automatic transmission replaced the vacuum modulated, three-speed automatic. Additional details on the engine installation are contained in Ref. (5).

A used Mod I ASE from the DOE/NASA Program was rebuilt by MTI personnel and installed in a dynamometer test cell for checkout, characterization, and piston ring break-in. A cross section of the Mod I ASE is shown in Fig. 3. The Mod I ASE included all auxiliaries that would be used for the complete system when installed in the Air Force van. These included a 130-A alternator, atomizing air compressor, blower, and the starter and upstart motor that are required to operate the Stirling engine. Characterization included operation on both unleaded gasoline and JP-4 aircraft fuel. The Stirling specifications and the resultant power and efficiency curves are shown in Table 2 and Fig. 4. A detailed discussion of the multifuel development with unleaded gasoline and JP-4 fuel are contained in Ref. (6).

Characterization included operation at various heater head temperatures (720 °C, 770 °C, and 820 °C) and radiator temperatures (50 °C, 60 °C, 70 °C, and 80 °C) and at a variety of idling points. MTI predictions indicated that the Mod I ASE, operated at a heater head temperature of 770 °C (nominal 75 hp), was adequate for the Phase I familiarization and the Air Force mission (both the flight line and on-base) at Langley. MTI engine/vehicle codes were used to compare the multistop operation with diesels at 145 hp, 100 hp, and 60 hp and the Stirling engine at 75 hp. Performance predictions are shown in Table 3.

After completion of the test cell characterization, the Mod I ASE with auxiliaries was installed in the Air Force van. Additional changes included the installation of a 12-gal auxiliary fuel tank, a hydrogen charging system, a larger radiator, a rear-compartment gas-fired personnel heating system, an accelerator assembly, a gas-fired front window defogger, and a hydraulic system for the power-control valve. Modification of the exhaust system included the removal of the muffler and the catalytic converter that are not required for use with the Stirling engine.

A comparison of the diesel and Stirling-powered vans is shown in Table 4 and the engine installations are shown in Fig. 5.

Also installed was a Digital Engine Control (DEC) and the necessary diagnostic equipment (i.e., CRT monitor, simulator and switch panels) shown in Fig. 6. All mechanical and electrical systems were completed in June 1986. Fine-tuning of the controls was completed on a chassis dynamometer, followed by operation and checkout of the Stirling-powered van. Over 30 hr and 220 mi of operation were successfully completed "on-the-road" in the Albany, NY area and with a simulated Air Force mission duty cycle on the MTI chassis dynamometer. The van performance of 0-30 mph in 10.5 sec is in good agreement with the MTI predictions (see Table 2) and was considered adequate for the Air Force mission on the Langley flight line. Checkout included operation on both unleaded gasoline and JP-4 aircraft fuel.

AIR FORCE FLIGHT-LINE EXPERIENCE

The Stirling-powered van was delivered to Air Force MEEP personnel at Langley AFB in August 1986. MEEP personnel are responsible for the normal maintenance and monitoring of vehicle operations for the Air Force. Operational data were obtained from sources such as daily log sheets, weekly inspection records, and tachograph charts. Operation of the vehicle provided the first "real world" data for determining the operational readiness of the first-generation Stirling engine for evaluation by the industry/government team. The Air Force experience is documented in Refs. 7 and 8.

The Air Force delivery van, designated a "multistop", was operated by regular Air Force operators assigned to the 27th Aircraft Maintenance Unit (AMU), Tactical Air Command at Langley Air Force Base, VA. The evaluation was for a period of 10 months, from September 1986 through June 1987. The multistop was designed to transport personnel and light cargo in a stop-and-go duty cycle. The multistop was used for the "expediter" mission by the 27th AMU that provides maintenance control on the Langley flight line while serving from 15 to 20 aircraft. Over 1100 hr and 4000 mi were successfully logged with the expediter mission. The Stirling-powered multistop was operated on unleaded gasoline, JP-4 aircraft fuel, and diesel fuel during the 10-month evaluation period (Fig. 7). The multistop successfully towed a variety of support equipment without difficulty. Air Force personnel stated that the operation was "not a big deal" and was "better than anticipated". MTI support personnel were available to the Air Force on a daily basis to troubleshoot and make minor repairs required during the evaluation.

Training Procedures

Startup and operation of the Stirling-powered van appears to be comparable to commercial diesel vehicles. Over 20 Air Force operators were trained and familiarized without difficulty during the evaluation period at Langley. A few operators initially experienced stalling of the engine when making hard left or right turns while at idle (400 rpm) or low vehicle speed. This is attributed to the use of an underpowered (80 hp) engine for this vehicle. Air Force operators quickly adapted, however, and the Stirling-powered van accomplished the expediter mission without difficulty.

Duty Cycle

Documentation of the duty cycle on the Langley flight line was accomplished with a 7-day, 24-hr tachograph chart recorder. Daily readings of vehicle speed, engine speed, and miles traveled were recorded in order to provide a day-to-day record of the expediter duty cycle experienced by the Stirling-powered van. A typical chart, that of October 30, 1986, is representative of the expediter mission (Fig. 8). As can be seen, the engine idled for very long periods and had many short trips, with many starts and stops being recorded. Continuous duty over long periods did not present any problems. Fuel usage with unleaded gasoline was reported to be as good as or better than the standard gasoline-powered multistop.

The multistop was available on a 24-hr basis, as needed by the Air Force. Availability of the van ranged from 55 percent during the early months to an average of 86 percent at the completion of the operational period at Langley. This is considered good for a single-unit demonstration at this stage of development. Vehicle operation was limited to the Langley flight line, where the authorized speed is from 15 to 25 mph, and on-base, where the authorized speed is limited to 35 mph. At times, the vehicle usage ranged from only a few minutes during a specific day to continuous around-the-clock operation during Air Force readiness exercises (Fig. 9). Air Force personnel found the Stirling-powered multistop to be as reliable as a standard vehicle for the expediter mission.

Multifuel Evaluation

Multifuel operation of the Stirling-powered van on the Langley flight line is shown in Table 5 and in Fig. 7. Characteristics of the fuels used are shown in Table 6.

Operation with both unleaded gasoline and JP-4 had been planned for Phase I and presented no difficulties during the evaluation period. The air/fuel ratio had been adjusted on the MTI chassis dynamometer for both fuels prior to delivery of the multistop. The air/fuel ratio with gasoline and JP-4 was checked at the time of the switch-over in mid-March 1987 and no adjustments were required. JP-4 aircraft fuel was substituted for the unleaded gasoline using the same fuel tank. Minor adjustments were required to the air/fuel ratio in order to eliminate flameouts during the initial startup of the engine. Subsequent operation and vehicle performance with the JP-4 aircraft fuel was reported to be as good as or better than operation with unleaded gasoline.

At the request of the NASA TU industry/government team, limited operation with diesel fuel was tried. Changeover to a summer grade of diesel fuel (DF-2) was accomplished in mid-May 1987. Modification to the air/fuel system was required in order to incorporate a gasoline start and warm-up prior to switching to diesel. An auxiliary fuel tank that had been added during the initial vehicle modification (for potential additional multifuel evaluations) was used for diesel storage. The gasoline startup was required primarily because of an inadequate ignition source to ignite the diesel fuel. Operation on diesel fuel was successful and vehicle performance appeared to be adequate for the Air Force mission on the Langley flight line.

Fuel Economy

Fuel economy for the Stirling-powered van in the expediter mission was reported by the Air Force to be 6.3 mpg with all fuels used during the 10-month evaluation period. Fuel economy numbers include fuel usage for both the gas-fired, front-window defogger and the rear-compartment heating system. This compares with an average of 4.3 mpg for four gasoline-powered vans and 8.1 mpg for nine diesel-powered vans used at Langley in similar missions during the same period.

Load-Carrying Characteristics

In addition to carrying personnel to the aircraft on the flight line, the Stirling-powered multistop towed a variety of support equipment (up to 6000 lb (2362 kg)) on the Langley flight line with no difficulties.

Emission Data

The catalytic converter was removed from the exhaust system in the Stirling-powered van. No particulate traps were installed. However, because of the absence of a chassis dynamometer and necessary emission-testing equipment at Langley, no evaluation could be obtained. It is planned to evaluate the emissions of the Phase II Stirling-powered vehicle (D-150 truck) at Eglin AFB.

Noise Evaluations

A general noise evaluation was conducted by the Air Force on the Stirling-powered multistop (with no muffler or resonator) and a diesel-powered multistop. Measurements were made using Dupont Mark I dosimeters. The survey consisted of attaching a dosimeter to each driver and driving the two vehicles along the same routes for 25 min. A comparison of the noise readings for both engines is as follows:

Noise level,	Stirling	Diesel
	dBa	
Average	80.1	81.1
Peak	104.8	100.1

It was concluded that there were no appreciable differences in noise levels generated by the two vehicles under similar operating conditions. Additional measurements made directly in front of the Stirling-powered van (83.7 dBA) and the diesel-powered van (80.5 dBA) were below the Air Force criterion of 84 dBA. It was observed that the major noise in front of the Stirling van was emitted from the auxiliaries, primarily from the cooling fans and the atomizing air compressor.

Oil Evaluations

Oil samples were taken 10 times during the one-year evaluation period and sent to Deere & Company for detailed analysis. No degradation of the oil was noted and Air Force operators and maintenance personnel observed that the oil appeared to be in "like new" or "virgin" condition.

DEERE & COMPANY EXPERIENCE

The Stirling-powered Air Force van was delivered to Deere & Company Headquarters at Moline, IL in July 1987. The delivery van, shown in Fig. 10, was used for intraplant mail and package delivery service to a variety of Deere facilities in the Moline area. The van operated during a normal 8-hr shift on a delivery circuit that made about 35 stops and logged about 130 mi per day. Operation of the van was expanded from the Air Force flight line (speeds up to 25 mph) mission to operation on city streets and highways (up to 55 mph) in the Moline area. Fig. 11 is a tachograph from July 22, 1987 and represents the typical duty cycle that includes long idle time, many stops, and operation on local roads and highways. This duty cycle would be representative of a rural postal delivery route. Over 175 hr and 2650 mi

were successfully logged with the van operating on unleaded gasoline on the Deere intraplant delivery route during July and August.

During the months of July and August, the air temperature in the Moline area ranged from a low of 40 °F (4.4 °C) to an extreme of 103 °F (40 °C). More than two weeks of continuous daytime temperatures of over 90 °F (32.2 °C) were experienced during the last two weeks of July. The operation of the Stirling-powered van was normal during this period of extreme temperatures, haze, and fog. A commercial fuel pump that experienced vapor lock was the only weather-related problem. After additional cooling for the fuel pump was provided, no more difficulties were experienced during the extremes of temperature and humidity.

CONCLUSIONS

Operational experience with the Stirling-powered Air Force van is providing the first "real world" data for transportation applications. Independent operations by Air Force and Deere personnel have logged over 1300 hr and nearly 7000 mi of successful vehicle operation (Fig. 12). Multifuel operation has been demonstrated by using unleaded gasoline, JP-4 aircraft fuel, and diesel fuel. No problems were identified for the basic Stirling engine. The 75-hp automotive Stirling engine, although underpowered for the Air Force multistop, has demonstrated that it has the potential to be a viable multifuel engine for light-duty trucks and vans of the future.

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Table 1 Diesel engine specifications

Engine type	Valve-in-head
Piston displacement, L ($in.^3$)	6.2 (379)
Bore & stroke (nominal), in. (mm)	3.98 x 3.82 (101 x 97)
Compression ratio	21.3:1
Exhaust	Dual
SAE net power at 77 °F, hp (kW)	145 (108.8) @ 3600 rpm
SAE net torque at 77 °F, lb-ft (N-m)	248 (333) @ 2000 rpm

Table 2 Stirling engine specifications

Engine type	Upgraded Mod I ASE
Heater head temperature, °C	770
Working gas	Hydrogen
Piston displacement, L ($in.^3$)	0.492 (30)
Bore & Stroke, in. (mm)	2.68 x 1.34(68 x 34)
Drive system	Dual crank "U" configuration
Exhaust	Dual
Muffler	None
Aftertreatment for emissions	None
Net power, hp (kW)	74 (55.5) @ 4000 rpm
Net torque, lb-ft (N-m)	140 (188) @ 1000 rpm
Net efficiency, percent	35 @ 1700 rpm

Table 3 Multistop performance predictions

[Axle ratio, 4.10]

Acceleration	Diesel			Stirling
	145 hp (108.8 kW)	100 hp (75 kW)	60 hp (45 kW)	75 hp (56.2 kW)
Percent Grade; 6 500 lb				
0-30 mph, sec	4.8	7.2	16.2	10.5
0-50 mph, sec	14.1	23.4	60.0	38.2
0-60 mph, sec	20.7	38.9	----	----
Percent Grade; 11 550 lb				
0-30 mph, sec	7.9	12.5	33.4	18.9
Percent Grade; 6 550 lb				
0-5 mph, sec	1.3	2.4	----	12.5
Maximum speed, mph	21.4	13.0	----	5.8

Table 4 Comparison of diesel and Stirling-powered vans

Feature	Diesel	Stirling
Style	Hi-Cube GM C-30	Cube w/internal modifications
Engine	V-8, model LL4, diesel, 6.2 L	U4, Mod I ASE, multifuel, 0.5 L
Rated bhp (kW)	145 (108.8) @ 3600 rpm	74 (55.5) @ 4000 rpm
Alternator, A	66	130
Transmission	GM Turbo three-speed hydramatic	Chrysler 904 three-speed automatic
Axle ratio	4.10	3.08
Chassis	G31303	G31303 modified
Curb weight, lb	6800	6250
Gross vehicle weight, lb	8600	8000
Gross tow capability, lb	13 500	13 000
Maximum speed, mph	80	55
Exhaust temperature, °C (°F)	800 (1472)	250 (482)
Coolant temperature, °C (°F)	100 (212)	50 (122)
Coolant pressure, psi	20	14.7

Table 5 Multifuel operation of the Stirling-powered van

Type of fuel	Hours used	Miles driven	Period
Unleaded gasoline	440	1671	Sep 86 - Mar 87
JP-4 aircraft fuel	536	1882	Mar 87 - May 87
Diesel fuel (DF-2)	145	634	Jun 87
Totals	1121	4187	

Table 6- Characteristics of fuel used

Type of fuel	Heating value, Btu/lb	Flash point, °F (°C)
Unleaded gasoline	18 600	-30 (-34.4)
JP-4 aircraft fuel	18 800	-9 (-22.7)
Diesel fuel (DF-2)	18 300	192 (88.9)

FIG. 1 AIR FORCE MULTISTOP VAN

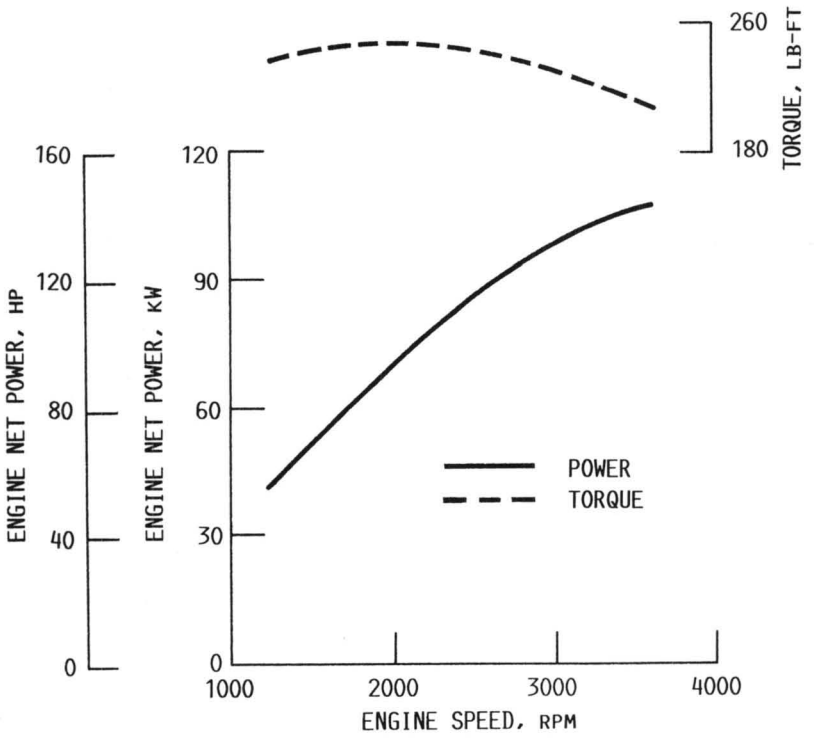

FIG. 2 POWER AND TORQUE CURVES OF 6.2-L, V-8 DIESEL ENGINE

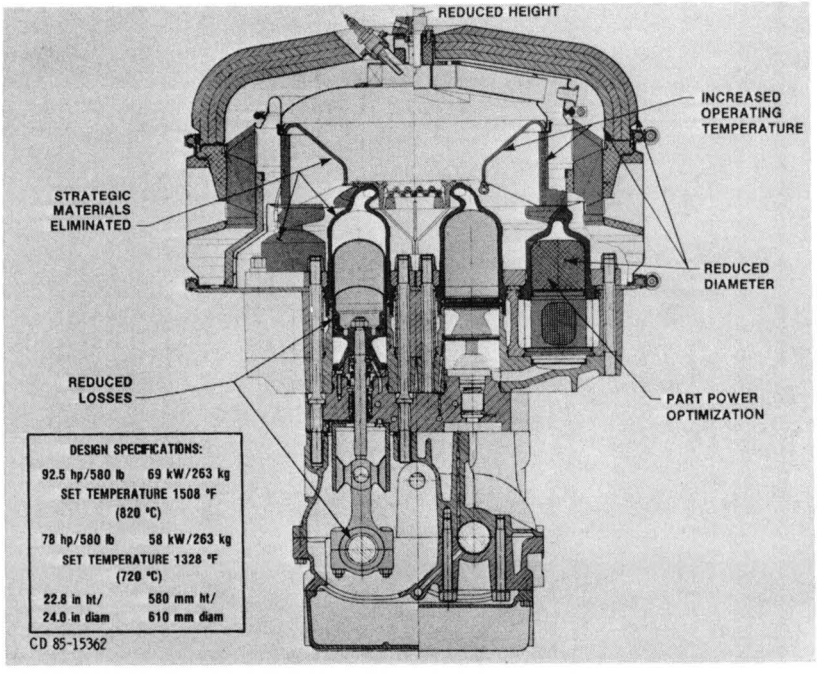

FIG. 3 CROSS SECTION OF MOD I AUTOMOTIVE STIRLING ENGINE

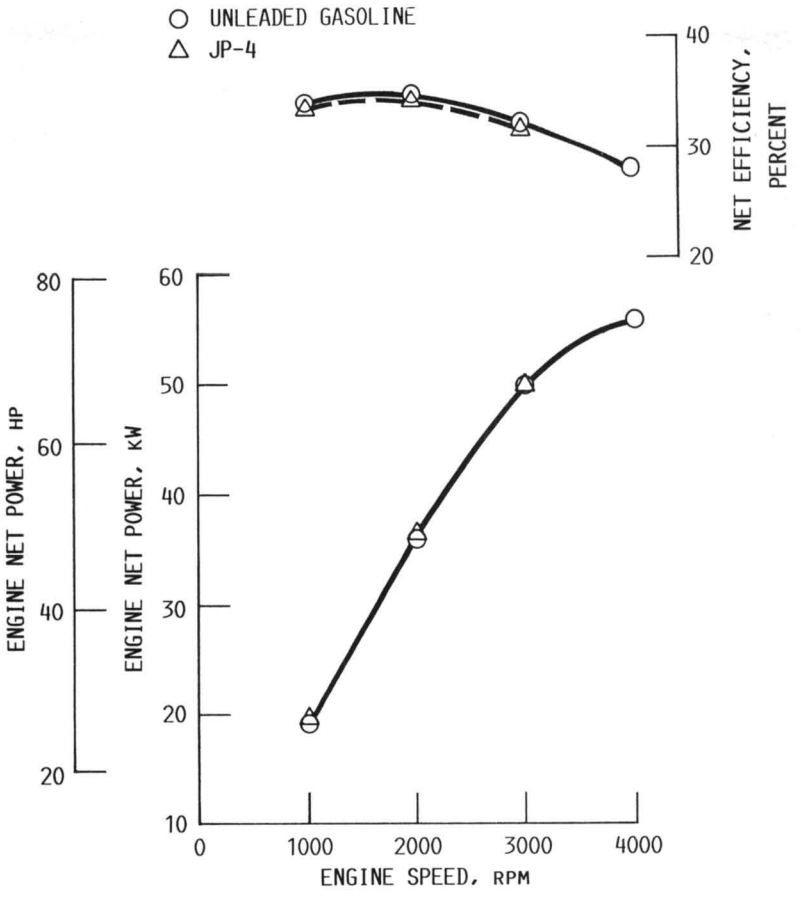

FIG. 4 MOD I AUTOMOTIVE STIRLING ENGINE POWER AND EFFICIENCY CURVES WITH UNLEADED GASOLINE AND JP-4 AIRCRAFT FUEL

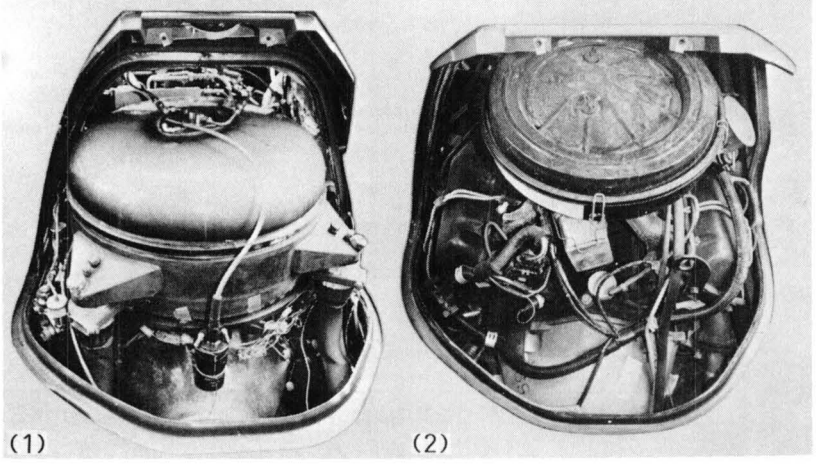

FIG. 5 COMPARISON OF STIRLING AND DIESEL ENGINE INSTALLATIONS
(1) STIRLING, 80 HP
(2) DIESEL, 150 HP

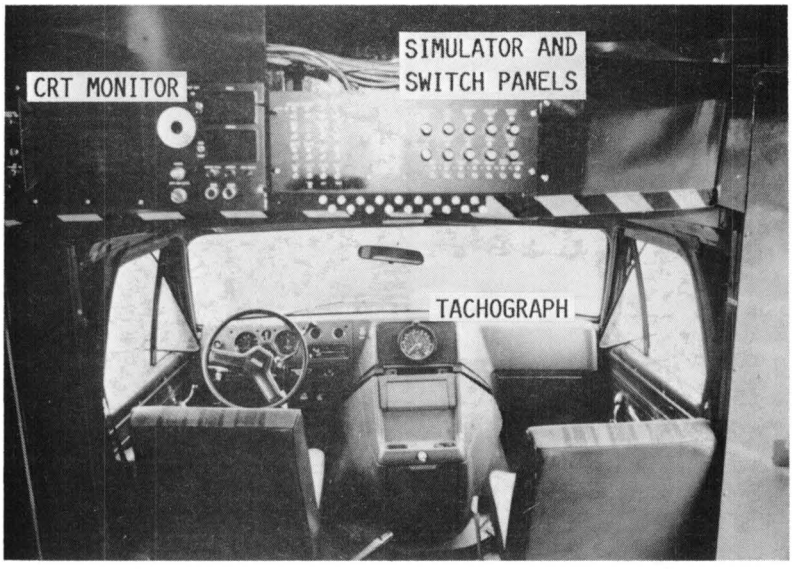

FIG. 6 STIRLING DIGITAL ENGINE CONTROL AND DIAGNOSTICS PANELS INSTALLED IN VAN

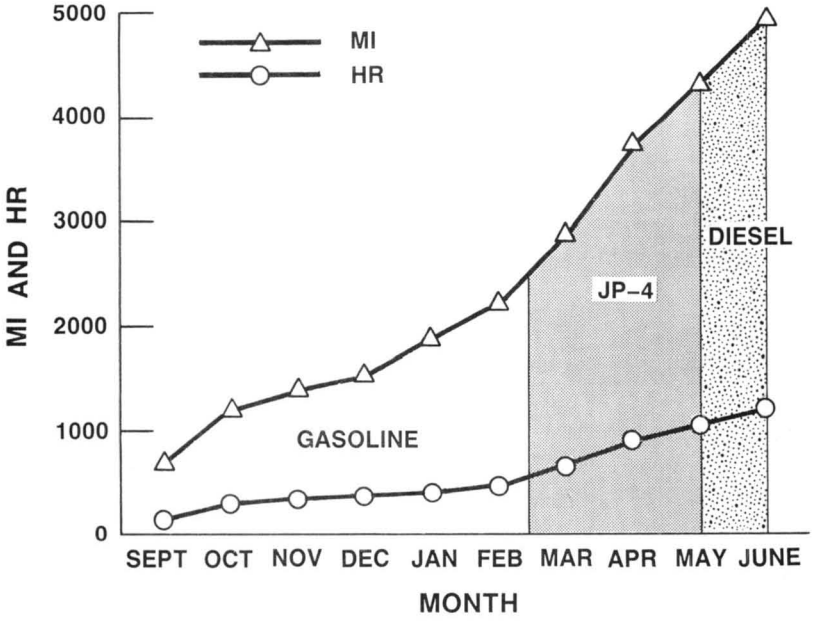

FIG. 7 LANGLEY AFB OPERATIONAL HISTORY

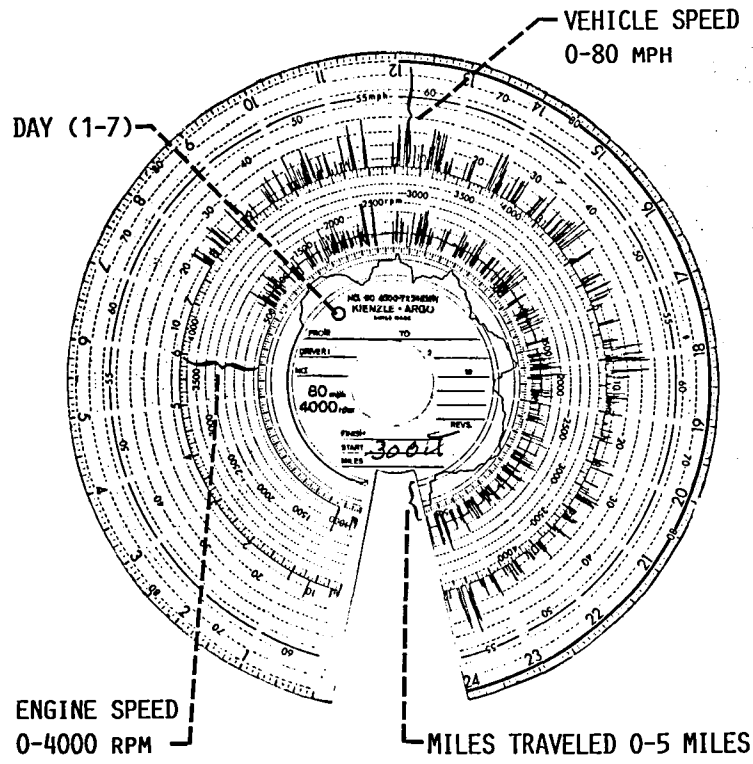

FIG. 8 TACHOGRAPH OF TYPICAL DUTY CYCLE ON LANGLEY FLIGHT LINE, OCTOBER 30, 1986

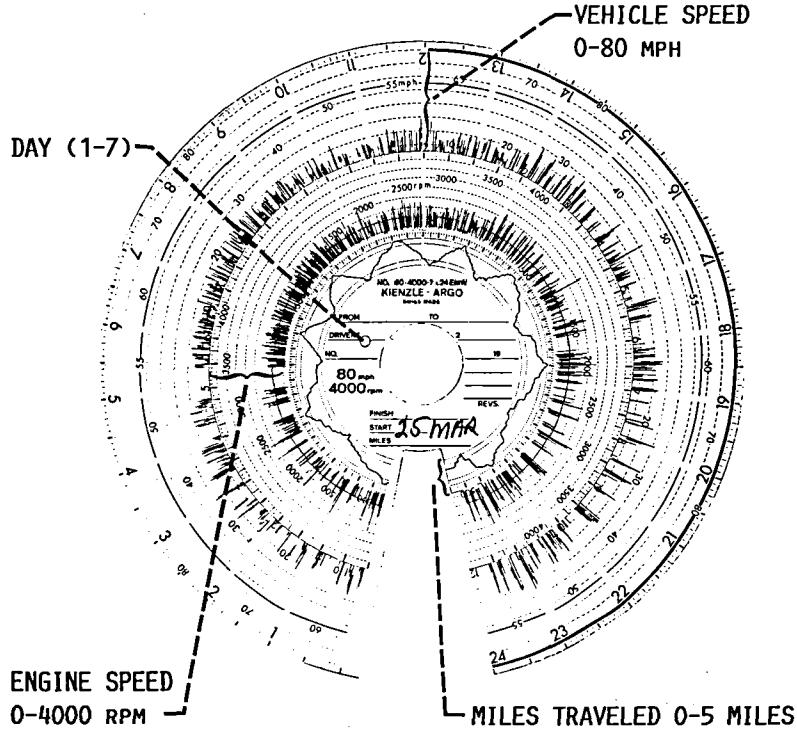

FIG. 9 TACHOGRAPH OF CONTINUOUS 24-HR OPERATION ON LANGLEY FLIGHT LINE, MARCH 25, 1987

FIG. 10 AIR FORCE MULTISTOP VAN EVALUATED BY DEERE & COMPANY

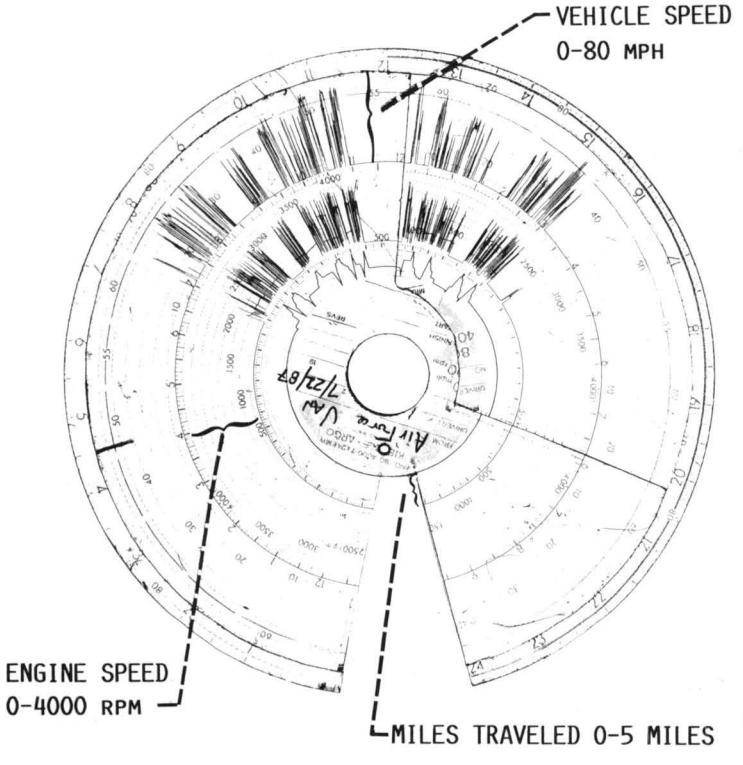

FIG. 11 TACHOGRAPH OF TYPICAL DUTY CYCLE IN MOLINE, IL AREA, JULY 22, 1987

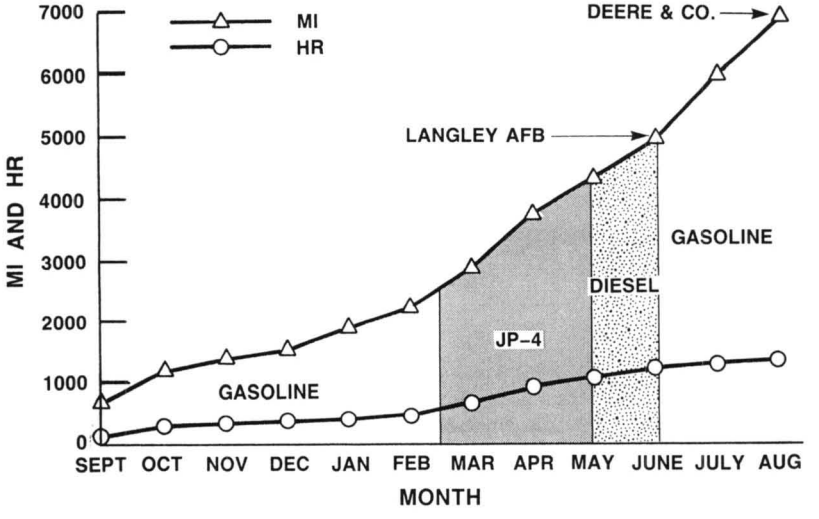

FIG. 12 PHASE I OPERATIONAL HISTORY

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-100978		

4. Title and Subtitle

Phase I Results from the Stirling-Powered Vehicle Project

5. Report Date

6. Performing Organization Code

7. Author(s)

Richard K. Shaltens

8. Performing Organization Report No.

E-4270

10. Work Unit No.

778-35-13

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

U.S. Department of Energy
Office of Vehicle and Engine R&D
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

DOE/NASA/50112-76

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AI01-85CE50112. Prepared for the Fourth International Conference on Stirling Engines, sponsored by the Japan Society of Mechanical Engineers (JSME), Tokyo, Japan, November 7-10, 1988.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Stirling; Kinematic automotive Stirling engine; Vehicle demonstration; Stirling technology	Unclassified - Unlimited Subject Category 85 DOE Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	16	A02

NASA FORM 1626 OCT 86

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