DOE/NASA/1040-79/7
NASA TM-79222

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Work performed for

U.S. DEPARTMENT OF ENERGY
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Prepared for
International Conference on Energy Use Management
Los Angeles, California, October 22-26, 1979

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Under Interagency Agreement EC-77-A-31-1040

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ABSTRACT

The automobile is one of the most difficult of engine applications, combining the requirements for low cost mass production with those for high efficiency, low emissions, extensive low part power operation and fast response. The ability of the Stirling engine to meet these requirements utilizing existing and near term technology is assessed. In this assessment the results of recent and ongoing automobile Stirling engine development efforts (Ford Motor Company, MTI/USS/AMG, and others) are reviewed and technology status and requirements are identified. Key technology needs include those for low cost, high temperature (1300°-1500° F) metal alloys for heater heads, and reliable long-life, low-leakage shaft seals. Various fuel economy projections for Stirling powered automobiles are reviewed and assessed. It is concluded that a 50-60 percent fuel economy (mpg) improvement over a conventional spark ignition engine powered automobile is within the development range of existing and near term technology.

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INTRODUCTION

This paper reviews the background and technical history of the automobile Stirling engine, discusses it's technology status and reviews its fuel economy potential. The only significant automobile Stirling engine development effort currently being conducted is that being done under the Department of Energy (DOE) Automotive Heat Engine Program with project management by the NASA Lewis Research Center (LeRC). The history of this effort and of the automobile Stirling engine are briefly reviewed and the goals and objectives of the DOE program are presented. The technology status of the engine is discussed and fuel economy projections and presented and stressed.

BACKGROUND

The Stirling engine has excellent potential for broad alternative fuel capabilities, good fuel economy, low exhaust emissions, and low noise. For these reasons, it was selected for investigation in the government's Automotive Heat Engine Program in 1975. The Automotive Heat Engine Program was begun by the Environmental Protection Agency (EPA) in 1971 and had the initial objective of developing alternative automotive heat engines with significantly reduced exhaust emissions. In 1973, the objectives of improved fuel economy and multifuel capability were added. In this program all known types of heat engines were evaluated and more detailed investigations of the more promising candidates were carried out. Today, the Heat

Engine Program has converged on the two most promising alternative engine candidates, Gas Turbine and Stirling.

With the formation of the Energy Research and Development Agency (ERDA), the EPA automotive propulsion system activities were transferred to ERDA and additional emphasis was placed on developing alternative propulsion systems with substantially improved fuel economy and adaptability to various fuels while at the same time meeting the legislated emission standards. In this revised program, project management responsibility for implementation of the Automotive Heat Engine Program was assigned to the NASA-Lewis Research Center (LeRC). This relationship was continued when the transportation conservation activities of ERDA were transferred to the newly formed Department of Energy (DOE) and continues today.

In February 1978, the President signed into law Title III, P.L. 95-238 entitled, "Automotive Propulsion Research and Development Act of 1978." This law specifically directs the Department of Energy to "establish and conduct new projects and accelerate existing projects which may contribute to the development of advanced automobile propulsion systems and give priority attention to the development of advanced propulsion systems, with appropriate attention to these advanced propulsion systems which are flexible in the type of fuel used." Consistent with these and other directives of P.L. 95-238 and with specific guidelines provided by the DOE Office of Transportation Programs, the Advanced Automotive Heat Engine Program now has the following goal:

To develop and demonstrate by September 1984 advanced gas turbine and Stirling automobile propulsion systems that meet the following objectives:

- At least 30 percent improvement in fuel economy (mpg) over a 1984 production vehicle of the same class and performance, powered by conventional spark ignition engines (based on equal BTU content of fuel used).

- Emissions levels that meet or exceed the most stringent Federal research standards; 0.4/3.4/0.4 g/mi, HC/CO/NO_x - (particulate levels will be added when defined).

- Ability to use a broad range of liquid fuels derived from crude oil as well as synthetic fuels from coal, oil shale and other sources.

- Suitability for cost competitive mass production.

For these objectives to have practical value to the nation in terms of real fuel savings, reduced emissions, etc., the successful engine must be placed into production. For automobile engine manufacturers to decide to initiate prototype engine development as a step toward actual production, it is anticipated that most, if not all, of the following are likely to be significant criteria:

1. Significant fuel economy advantage over conventional or other competitive engines.

2. Production costs not excessively greater than conventional engines, with acceptable mass production manufacturing processes identified.

3. Vehicle performance equivalent to conventional vehicles.

4. Interchangeable packaging with coventional engines to allow initial introduction as an optional engine.

5. Anticipated repair and maintenance costs and frequency.

6. Anticipated frequency of servicing and complexity of servicing.

7. Vehicle safety and public perception of vehicle safety.

Technology History

The Stirling engine is a relatively undeveloped engine with no current base of production engine experience for any application. Further the technology base for these engines resides primarily in Europe with N. V. Philips, United Stirling of Sweden, and Maschinenfabriek Augsberg Nuremberg (M.A.N.). General Motors Corporation (GMC) conducted an extensive Stirling engine effort from 1958 to 1970 under a license agreement with N. V. Philips. They performed substantial development work on the Stirling engine during this period, Ref. 1, but apparently never seriously pursued its application to the conventional automobile. The Ford Motor Company established a licensing agreement and undertook a joint effort with N. V. Philips in 1971. Under this agreement Ford set out to specifically assess the Stirling engine for the automobile. As part of this effort N. V. Philips designed and built the four cylinder, 120 HP, swashplate drive, 4-215 Stirling engine (Fig. 1) for installation and test by Ford in a 1975 Torino vehicle (Fig. 2). Results of these tests, published in Ref. 2, yielded fuel economies from 10 to 20 percent below the baseline spark ignition powered Torino vehicle and 13 to 23 percent below predicted values. In spite of these relatively poor initial results, it was believed that the Stirling engine did have significant fuel economy improvement potential. This view was supported by the Automobile Power Systems Evaluation Study, Ref. 3, completed by the Jet Propulsion Laboratory in 1975.

In September 1977 the Ford Motor Company initiated work on a seven year, cost shared Stirling Engine Development contract funded by DOE and managed by NASA. The first year of this effort was an intensive fuel economy assessment effort aimed at firmly establishing the fuel economy potential of the Stirling engine in the automobile.

This activity utilized the Ford 4-215 Stirling engine as a data base and estimated fuel economy improvement potential of a projected fourth generation (1984) engine based on both analytical and experimental evaluations of potential improvements. Even though the results indicated excellent fuel economy potential (see below), substantially exceeding the program goal, Ford Motor Co. chose to terminate their Stirling engine activities due to their need to devote available resources to more near term problems.

The primary engine development effort in the Stirling Engine Program is now being conducted by a team consisting of Mechanical Technology Inc. (MTI), United Stirling of Sweden (U.S.S.) and AM General (AMG) - a wholly-owned subsidiary of American Motors Corp. This DOE funded, NASA contracted effort was initiated on March 22, 1978. This effort is directed to the development of an advanced experimental Stirling engine for automotive application which will meet the program goal and achieve the transfer of Stirling engine technology to the United States. MTI is responsible for overall program management, development of component and subsystem technology, and transfer of Stirling engine technology to U.S. manufacturers. USS is primarily responsible for engine development. AMG is responsible for engine-vehicle integration, testing, and evaluation. In addition, it is intended to add to the project team during the course of development an American engine manufacturer who will be licensed to produce the Stirling automotive engine and will be an additional recipient of the technology transfer.

Technology Status

As stated earlier, the Stirling engine, as a class, is relatively undeveloped. While there is wide interest in Stirling engines for a variety of applications due to its characteristically high efficiency, low emissions and low noise, there is no current base of production engine experience for any application. Further, the automobile application is one of the most difficult ones, combining the requirements for low cost mass production with those for high efficiency, low emissions and fast response over a broad operating range.

The starting point of the MTI engine development effort is the current USS P-40 engine, a four cylinder, 40 kW, dual crank drive engine (Fig. 3). This engine was designed for stationary applications and has a much higher specific weight than desired for the automotive application (13.4 lb/HP vs 4.5-5 lb/HP for a standard S.I. engine). When installed in an Opel vehicle for initial vehicle integration evaluation (Fig. 4), it provided fuel economy approximately equal to that of a standard S.I. engine and met all the emission requirements.

In order to meet the project goal, it will be necessary to develop a light weight engine design and at the same time significantly improve the fuel economy. The Ford 4-215 Stirling engine at 4.7 lb/HP, while far short of the fuel economy and durability goals, provides a reasonable indication that an acceptable weight engine can be achieved. However, achievement of the low specific weight engine tends to dictate the use of hydrogen as the working fluid (hydrogen offers a significantly better combination of heat transfer, fluid flow, and thermodynamic characteristics than other candidate fluids such as helium or air) introducing the associated requirements for hydrogen compatibility, permeability, and safety.

The Ford fuel economy assessment studies and recent reference engine design studies by MTI and USS indicate very good potential for meeting and exceeding the 30 percent fuel economy improvement goal. Key approaches to achieving the <u>improved fuel economy</u> compared to the current 4-215 and P-40 designs include:

1. Increasing mean heater tube temperatures and minimizing tube temperature variations
2. Optimization of engine efficiency in the low part power regions most critical to drive cycle fuel economy
3. Reduction of engine and vehicle auxiliary and accessory losses through improved drive systems and better matching to real needs
4. Minimization of conduction losses through cylinder and regenerator walls
5. Improved controls to provide more efficient part power operating modes
6. Utilization of a ceramic preheater (existing technology developed for the rotary regenerator in the automotive Gas Turbine Program) to provide more effective recuperation of hot exhaust gases

Performance and response of a Stirling powered vehicle are key criteria in providing an acceptable engine/vehicle system. Performance, or acceleration capability, must be similar to that of the S.I. engine it would replace if it is to achieve public acceptance. Response, or the quickness of vehicle reaction to movement of the accelerator, is critical to driving safety. Both performance and response are critical functions of the engine control system which must provide both acceptable performance and response while maintaining good part power efficiency. Both the 4-215 and P-40 engines vary engine pressure level to control power. This requires a fairly complex system of electronic controls, values, working fluid compressor and a storage bottle to add and subtract working fluid to the engine in response to vehicle power demands, and leads to some inefficiencies and concern for reliability. Alternative approaches, such as the hybrid system combining pressure level and dead volume control suggested by Ford or a variable stroke arrangement currently being tested in an engine at N. V. Philips, should be investigated further and may offer more effective solutions to the power control requirement.

Durability and maintenance questions for the Stirling center about the heater tubes and piston rod seals. The heater tubes represent a key life limiting element of the engine from a material standpoint and require a critical design tradeoff between increasing efficiency and power density and decreasing life as the heater tube temperature is increased. The piston rod seal is one of the elements of the engine most subject to wear and failure during the engine life. Its failure can lead to contamination of the engine heat exchangers with oil and its replacement requires major disassembly of the engine. Therefore, it is essential that the seal be developed to provide a highly reliable long life capability. Substantial effort has been expended over the years by N. V. Philips, GMC, Ford and USS on seal development, with both sliding seals and rolling diaphragm type seals being investigated. While much progress has been made, the required long life, reliable, and highly effective seal remains to be developed.

Mass productibility and competitive production costs are essential if the Stirling engine is to become a viable automotive engine. To meet these criteria the engine design must be compatible with mass production fabrication techniques and the use of high cost materials must be minimized. The most critical engine element in this regard is the heater head which, in current engines, utilizes high cost high cobalt content alloys and requires expensive brazing operations. Cobalt is a scarce strategic material, most of which is imported from Africa. As indicated above, heater head materials are critical to engine success. No materials are currently available which offer the desired combination of low cost, hydrogen compatibility, and high temperature (1300^{o}-1500^{o} F) strength desired for the heater tubes and piston cylinders. However, it is expected that near term developments involving the modification of existing iron and nickel based alloys should yield acceptable cost alloys with the necessary properties.

Emissions are not expected to be a severe problem in the Stirling engine since the low pressure, external combustion systems offer the most favorable conditions for low emissions, though exhaust gas recirculation (EGR) may be required. However, design of the combustion system is expected to be important to achieving uniform heater temperatures and to minimizing the amount of EGR required.

FUEL ECONOMY POTENTIAL

To this time the Ford Fuel Economy Assessment, completed in September 1978, is the most complete and comprehensive study performed to evaluate the fuel economy potential of the Stirling engine in the automobile. It should be noted that this assessment was based on existing and near term technologies. Advanced technologies, such as the use of ceramic components to achieve a higher operating temperature, were not considered.

The results of the Ford assessment effort are shown in Fig. 5 along with the results of a NASA evaluation of the Ford results. In summary, Ford projects a fuel economy improvement of 38 to 81 percent beyond that of the baseline spark ignition engine vehicle of the same class and performance. The NASA evaluation is in essential agreement with projected improvements of 40 to 74 percent. The two most significant improvements resulted from engine reoptimization efforts including optimizing efficiency in the normal low power operating region and from modifications to the power control system. The values shown under the NASA columns are the result of a LeRC evaluation of the Ford results. A more detailed description of the Ford assessment and of the NASA evaluation are contained in papers published in the proceedings of the DOE Highway Vehicle Contractors' Coordination Meeting, Ref. 4.

The MTI/USS/AMG Stirling engine effort has not included a fuel economy assessment study similar to Ford's. Instead, that contract effort has concentrated initially on a broad Stirling engine technology assessment, which is nearing publication, and on preliminary reference engine design studies to select a reference engine configuration. At this point a reference engine design concept has been selected and preliminary fuel economy estimates have been completed. Figure 6 shows how the fuel economy of this preliminary reference engine concept in a 3200 pound inertia weight vehicle compares with the equivalent spark ignition engine powered vehicle. This information was presented by MTI and USS at the April 1979 Highway Vehicle Contractors Coordination Meeting. As shown, USS projects a 54 percent fuel economy improvement for the reference Stirling engine compared to the equivalent spark ignition engine powered vehicle. In the USS reference engine design concept, two of the key approaches to improved fuel economy were part power optimization, similar to that done by Ford, and minimization of auxiliary power consumption, also an area addressed by Ford. While there is some concern that the auxiliary power assumptions may be too optimistic, there are further potential fuel economy improvements not yet incorporated in this initial reference design. These include utilization of a rotary ceramic preheater and improved power controls, both of which could yield significant fuel economy improvements. Thus, the 54 percent improvement projected by USS appears reasonable and could prove to be conservative when a more complete assessment of potential fuel economy improvements is completed. Figure 7 summarizes the resulting Ford and MTI/USS fuel economy improvement numbers.

CONCLUSIONS

Based on the Ford fuel economy assessment, the NASA evaluation of this assessment, the MTI/USS reference design efforts to date, and the current status of Stirling engine technology, it now appears that a 50 to 60 percent improvement in metro-highway fuel economy is a reasonable goal for an automobile Stirling engine. This goal should be achievable with an all metal engine incorporating existing and near term technology. This might also include the use of an existing technology ceramic preheater. Such an engine should be capable of meeting the most stringent statutory emission standards, and also provide a broad alternative fuel capability. There are, of course, still several questions and problems to be overcome. These include the ability to achieve a competitive production manufacturing cost; the need for improved low cost metal alloys; the requirement to develop effective piston rod seals and provide adequate hydrogen containment; and the need to develop the necessary invehicle durability. With the substantial fuel economy improvement potential of this engine, there would appear to be ample margin to make some compromises in fuel economy, if needed to overcome some of these or other problems that may occur in the development effort, and still have a very attractive alternative engine in terms of fuel economy emissions, and alternative fuel capability.

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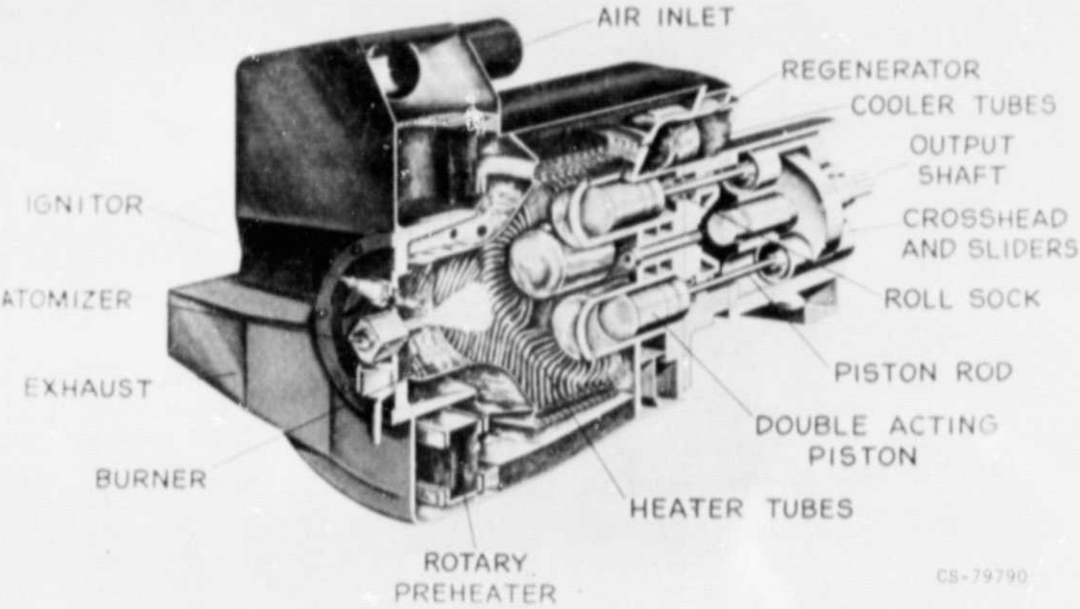

Fig. 1. Ford/Philips stirling engine.

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Fig. 2. Torino stirling car.

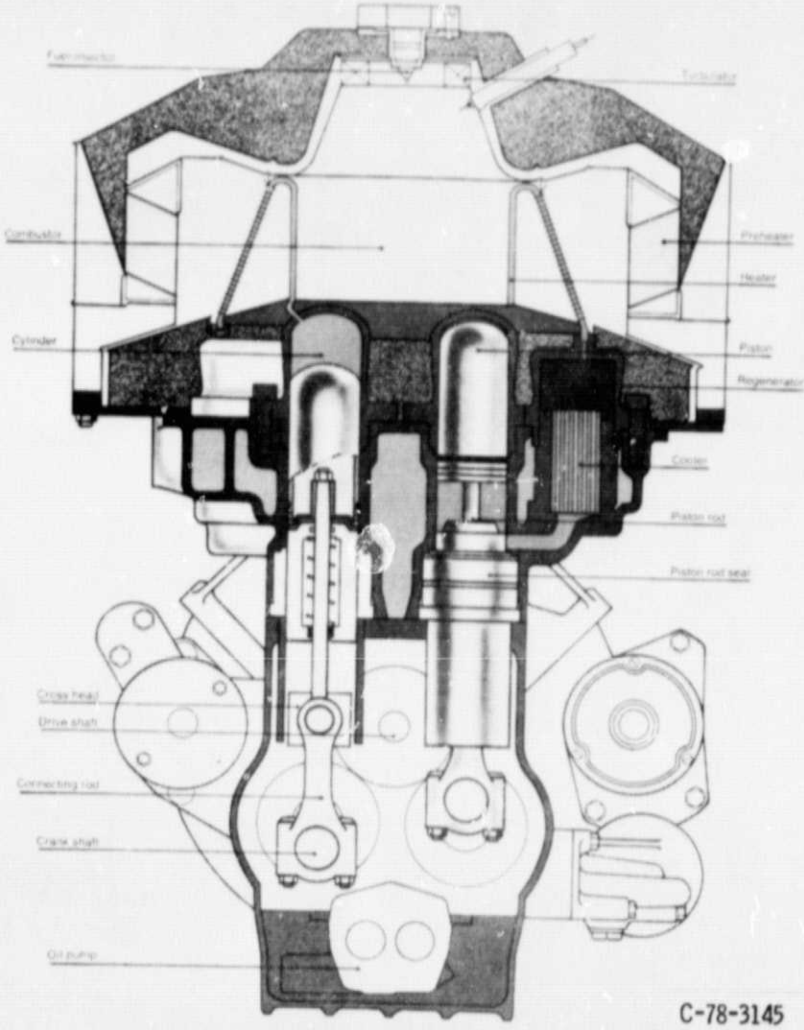

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Figure 3. - United Stirling of Sweden, P-40 engine.

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Figure 4. - P-40 Stirling Opel vehicle.

CHANGES REQUIRED FOR IMPROVEMENTS	M-H FUEL ECONOMY (mpg) IMPROVEMENTS MINIMUM FORD	NASA	MAXIMUM FORD	NASA
ENGINE REOPTIMIZATION	3.5	3.5	4.3	4.2
DRIVE FRICTION REDUCTION	1.2	.9	1.9	1.4
REDUCED HEAT LOSSES	.5	.7	1.9	1.5
NEW POWER CONTROL	2.3	2.8	3.1	3.1
PREHEATER IMPROVEMENTS	.4	.4	.6	.4
BURNER AND BLOWER CHANGES	.3	.2	.5	.5
OTHER	.3	.3	1.8	1.8
TOTAL	8.5	8.8	14.1	12.9
PRESENT ENGINE CAPABILITY*	12.9	12.9	14.0	14.0
NEW PROJECTED CAPABILITY	21.4	21.7	28.1	26.9
BASELINE*	15.5	15.5	15.5	15.5
IMPROVEMENT VERSUS BASELINE				
mpg	5.9	6.2	12.6	11.4
PERCENTAGE IMPROVEMENT	38%	40%	81%	74%

*4500 lb, (IWC), C4 AUTO. TRANS., 100 k TORQUE CONV., 2.5 REAR AXLE, 14.0 hp (PAU), 13.3 sec. (0 TO 60 mph TIME).

Fig. 5. Ford fuel economy improvements and NASA evaluation.

PART POWER EFFICIENCY PERCENT	34
FULL POWER EFFICIENCY PERCENT	33
HORSEPOWER	86
SPECIFIC WEIGHT, lb/hp	5.5
FUEL ECONOMY, mpg	36.3
VEHICLE INERTIA WEIGHT, lb	3200
I. C. ENGINE COMPARISON, mpg	23.5
PERCENT IMPROVEMENT OVER COMPARISON I. C. ENGINE	+54

Fig. 6. Stirling reference engine concept.

	FORD	MTI
GASOLINE FUELED STIRLING	38 TO 81 PERCENT	54 PERCENT

Fig. 7. Summary of stirling engine fuel economy improvement (percent improvement over equivalent S. I. engine powered vehicle of same class and performance).