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THE AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM -- A SUCCESS

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Abstract

The original 5 yr Automotive Stirling Engine Development Program has been stretched to a 10 yr program due to reduced annual funding levels. With an estimated completion date of April 1988, the technical achievements and the prospectives of meeting the original program objectives are reviewed. Various other applications of this developed Stirling engine technology are also discussed.

Program Background

The Automotive Stirling Program resulted from the Congressional passage in 1978 of Public Law 95-238, the Automotive Propulsion Research and Development Act. This Act directed the Department of Energy (DOE) to develop advanced automotive engines. One of these advanced engine development programs was the Automotive Stirling Program. Technical project management of the program was delegated by DOE to the National Aeronautics and Space Administration, (NASA), Lewis Research Center by an interagency agreement.

The Automotive Stirling Program has two parts, as shown in Fig. 1; the Automotive Stirling Engine Development (ASE) Program and the Automotive Stirling Research and Technology Programs. The ASE program is the major engine development effort and the subject of this paper. The Automotive Stirling Research and Technology Programs are specific technology programs to support the engine development. Typical technologies are materials, combustion, controls, analysis codes, etc.

The ASE program (NASA Contract DEN 3-32) was signed with Mechanical Technology Incorporated (MTI) of Latham, NY, in 1978. MTI provides the program management and technology transfer expertises. Two major sub-contractors were United Stirling AB and Company (USAB) of Malmo, Sweden, and AM General Corporation (AMG) of Detroit, MI. USAB provided the Stirling engine background technology to the program and AMG provided the vehicle integration skills.

The original ASE program was a $97 million, 5 yr program; but due to annual funding cutbacks (Recision, Deferral, Gramm-Rudman, etc.), the ASE program has been stretched into a 10 yr program costing $107 million. Unfortunately, the scope of technical tasks and the test hardware had to be reduced to minimize the cost of the program stretchout.

The ASE program started with the USAB P40 engine as a baseline engine and then developed two generations of Stirling engines designed for the automotive application -- the Mod I and Mod II engines. During the period of program stretchout, an upgraded Mod I engine was added to the Mod I engine development. Currently, the Mod II engine is under test. The demonstration of ASE program objectives is planned for April 1988 with the Mod II engine installed in a General Motors Celebrity vehicle.

ASE Program Objectives

The original and current ASE program objectives are to develop a Stirling engine when installed in a production spark-ignition vehicle will:

(1) Provide 30 percent improvement in the EPA combined driving cycle fuel economy
(2) Provide exhaust emissions which satisfy the Federal Research Standards
(3) Provide comparable acceleration and response.

Further, the automotive Stirling engine should:

(4) Be capable of operation on various alternate liquid fuels
(5) Have comparable initial manufacturing costs and life cycle costs as the spark-ignition engine

And, finally,

(6)the transfer of the existing European Stirling engine technology to the United States.

Technical Achievements

After 9 yr and over $100 million of Government funding, what has been accomplished in the ASE program? Some technical achievements have been:

Improvement in Net Engine Efficiency

The baseline USAB P40 engine in 1978 had a maximum engine net efficiency of 31 percent (Fig. 2). In the ASE program, maximum engine net efficiency has been increased to 37 percent demonstrated by the Mod I engine, 40 percent projected for the current Mod II engine under development, and 42 percent projected for the paper-design Reference Engine System Design (RESD).

The Mod II engine efficiency is slightly less than the RESD by intention. The Mod II has been optimized for fuel economy and not necessarily for engine efficiency. In some cases, engine efficiency has been sacrificed for fuel economy. One example is the preheater. The preheater was designed lighter (smaller) to reduce the cold start penalty in the urban driving cycle. The lighter (smaller) preheater reduced its effectiveness and thus reduced engine efficiency for improved fuel economy.

Engine Tailored to Mission

Figure 2 also illustrates how the Stirling engine efficiency can be tailored for the automotive application. The maximum power at 4000 rpm engine speed is needed only for vehicle acceleration. The average operating point of the engine during the EPA combined urban/highway driving cycles is an engine speed of approximately 1000 rpm. Therefore, the maximum efficiency of the USAB P40 engine at 2000 rpm has been moved by design to approximately 1000 rpm for the Mod I and II engines.

Piston Rings and Piston Rod Seals

Piston rings and piston rod seals have been developed which demonstrate satisfactory operation for greater than 2000 hr in engine endurance tests. The automotive goal of 3500 hr life appears attainable. Further details of the seals testing can be found in Ref. 1.

Materials

The previously used metal alloys in the Stirling engine heater heads contained strategic cobalt -- HS31 for castings and N155 for tubes. These alloys have been replaced in the ASE program with alloys containing no cobalt. The new alloys XF818 for castings and CG27 for tubes have been successfully used for Mod I and Mod II heater heads. Their strength and fatigue properties have been demonstrated by extensive engine endurance testing.

Another promising casting alloy has been identified in an Automotive Stirling Research and Technology Program -- NASAUT-4GA1. This alloy has better properties and lower cost than XF818, but no heater heads have been made in the ASE program with NASAUT-4GA1 because of funding priorities. For additional information about these alloys, see Ref. 2.

Another material effort conducted in the ASE program was the ceramic preheater. A development effort was contracted with Coors Porcelain Company to develop a cost-effective ceramic preheater for the automotive Stirling engine. This activity did result in a preheater module made of mixed oxides which had thermal performance comparable to the metallic preheater and which demonstrated durability to thermal cycling. The ceramic preheater evaluation in an engine test had to be deferred due to funding limitations.

Endurance Testing

As mentioned previously, extensive engine endurance testing has been conducted in the ASE program. These tests simulated the EPA driving cycle. The total engine test hours in the ASE program are impressive. Over 8000 P40 test hours, 17 000 Mod I test hours, and 500 Mod II test hours have been accumulated as of April 1987. These test hours have been valuable in evaluating components and materials in true engine environments.

Vehicle Testing

Of the total engine test hours, approximately 2000 hr have been accumulated in vehicles. These tests have been valuable in evaluating system interactions and response rates in the transient environment of a vehicle installation.

Control Systems

A major contributor to the improved fuel economy demonstrated by Stirling engines in the ASE program is not improvements in engine efficiency alone, but also improvements in engine control systems. Extensive efforts have been expended to improve the Stirling engine control systems -- power control (engine pressure), heater head temperature control, combustion air/fuel control, and the digital engine control. The fuel economy losses due to slow power control response and heater head temperature "droops" have been eliminated. These controls have been developed so once installed in a vehicle, the driver is virtually unaware of any differences between the Stirling engine and a spark-ignition or diesel engine.

Alternate Fuels

The Mod I Stirling engine has been tested with various alternate liquid fuels -- diesel fuel, kerosene, JP4 aircraft fuel, alcohols, broad-base petroleum distilled fuels, and simulated shale oil fuel. Some ignition problems have been encountered (as could be expected), but no problems of engine operation have been encountered with the limited testing conducted to date. Engine power, engine efficiency, and exhaust emissions are very similar with all fuels tested.

Meeting Program Objectives

With 1 yr remaining in the ASE program, all indications are that all original program objectives will be met.

30 Percent Fuel Economy

The Mod II basic Stirling engine (engine without auxilaries or control systems) is currently undergoing development testing. In Fig. 3, the measured engine net efficiency is compared to predictions for a constant engine output power of 15 kW. The comparison is excellent. Based on the engine test results and the status of auxiliary and control system development activities, the fuel economy of the Mod II engine installed in the Celebrity vehicle is currently anticipated to be between 37 and 41 mpg.

In Fig. 4, the improvements in fuel economy achieved in the ASE program are illustrated. The P40 Opel, P40 Spirit, Mod I Lerma, and Mod I Spirit vehicles were under-powered (slow acceleration), so their fuel economies are biased high. The Mod II Celebrity is not under-powered. It will have the same acceleration characteristics as the spark-ignition Celebrity. In Fig. 4, the range of expected Mod II fuel economy is shown. Also shown are the comparable 1987 spark-ignition Celebrity (31 mpg) and the 1985 U.S. Fleet average for 3000 lb inertia weight passenger cars (27 mpg). As can be seen, the expected Mod II Celebrity fuel economy will be close to 30 percent better than the spark-ignition Celebrity and 50 percent better than the U.S. Fleet average.

Exhaust Emissions

Vehicle testing in the ASE program has given confidence that the Mod II Celebrity will satisfy all exhaust emission requirements.

Acceleration and Response

Mod II development testing using the Mod I engine in the Spirit test vehicle has demonstrated the Mod II control systems should satisfy all vehicle response requirements. Vehicle accelerations should also be comparable to the production spark-ignition vehicle.

Alternate Fuels

Based on the alternate fuel testing conducted in the ASE program, the use of most alternate fuels in the Mod II engine should cause no problems. For example, the direct substitution of JP4 or kerosene for gasoline is possible. Some ignition related, acid distillation, or particulate plugging problems could be encountered with some fuels.

Manufacturing/Life Cycle Costs

Detailed manufacturing cost study of the RESD was conducted by Pioneer Engineering Company. Recently, a value analysis/value engineering cost study of the Mod II engine was conducted by Deere and Company. Both studies indicate the manufacturing cost of the Stirling engine could be comparable to spark-ignition and diesel engines.

Life cycle cost should also be similar to spark-ignition and diesel engines. In fact, a potential for reduced maintenance costs exits -- no muffler, no catalytic converter, and "no" oil changes.

Technology Transfer

The transfer of Stirling engine technology from Europe to MTI has been accomplished as proven by the design, fabrication, and development testing of the Mod II engine. The further transfer of this technology to other U.S. industries is currently underway.

A Successful Program

The original 5 yr ASE program has been stretched into a 10 yr program. This stretchout had the benefits of providing more time for some key developments and allowing the accumulation of engine test hours to evaluate component durability. One disadvantage of the stretchout was the reduction in technical scope. Certain technology developments had to be drastically reduced or completely eliminated in order to minimize the additional costs for the program stretchout.

So after 10 yr and over $100 million, has the ASE program been successful?

Yes, the ASE program will demonstrate the achievement of all its original program objectives at approximately its original estimated cost. But besides the specific ASE program goals, the $100 million investment has demonstrated the kinematic Stirling engine's high performance, response, and endurance in realistic applications and duty cycles. The manufacturing costs have also been made competitive by proper design improvements in components.

At this time, the lack of any commercial experience and the high tooling costs of mass production of any new engine are not conducive for the introduction of Stirling engines into the automobile industry. However, this ASE technology can be adapted to a variety of nonautomobile applications where the necessary experience could be gained with lower production rates. Some nonautomobile applications are generator sets, heat pumps, agricultural irrigation, co-generation, and specialty vehicles. One of these applications currently being pursued is the specialty vehicle. Using NASA Technology Utilization funds, a Mod I engine has been installed in a U.S. Air Force flightline van (Ref. 3). The van is being evaluated by the Air Force flightline operation using gasoline, JP4, and diesel fuel. This initial evaluation will be followed next year with a second vehicle and ultimately with a Mod II engine powered vehicle.

Yes, the ASE program has been very successful in advancing and demonstrating the Stirling engine technology for the automotive and other nonautomotive applications. The program has brought the kinematic Stirling engine out of the laboratory and test cells and into realistic applications. The Stirling engine is not an exotic engine; it is a practical engine.

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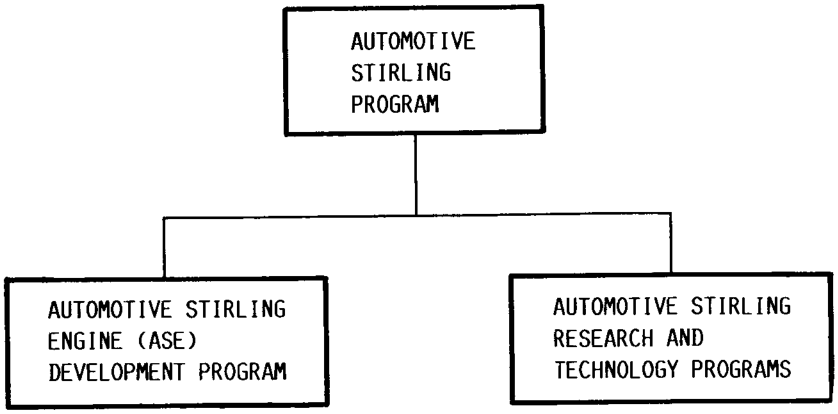

FIGURE 1. - DOE/NASA AUTOMOTIVE STIRLING PROGRAM.

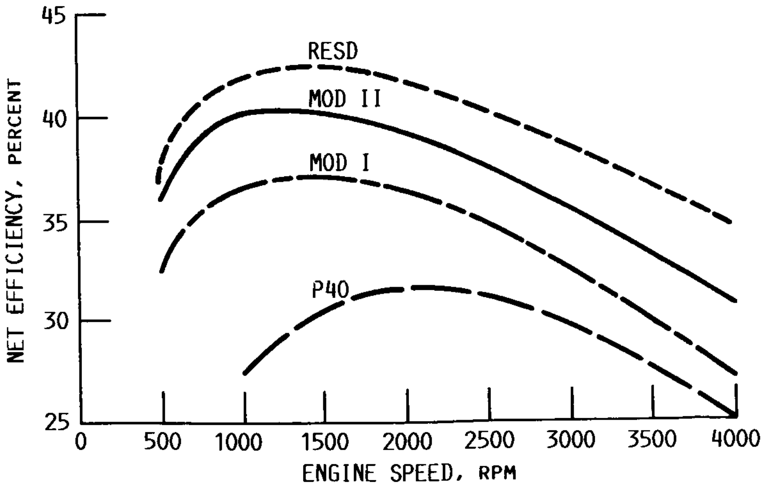

FIGURE 2. - STIRLING ENGINE NET EFFICIENCY. 15 MPA OPERATING PRESSURE, FULL STIRLING ENGINE SYSTEM.

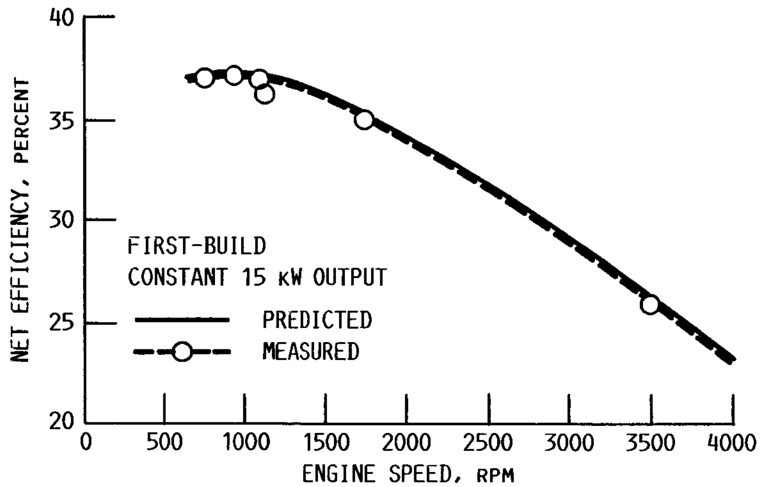

FIGURE 3. - MOD II ENGINE NET EFFICIENCY. BASIC STIRLING ENGINE.

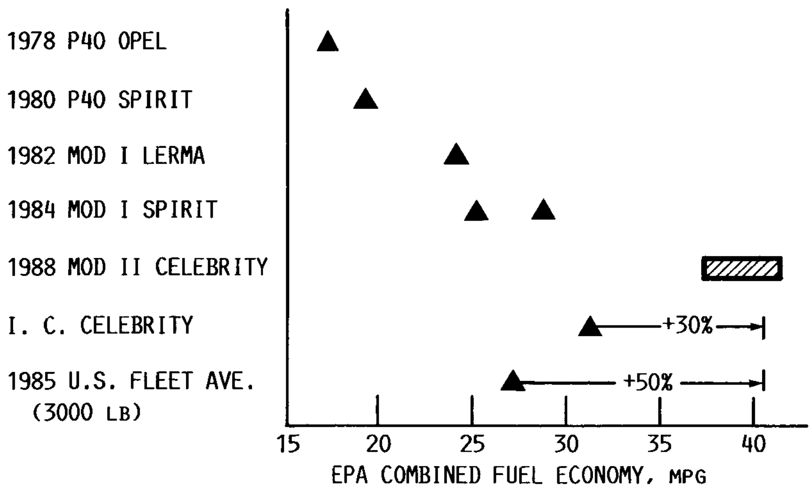

FIGURE 4. - ASE PROGRAM FUEL ECONOMIES.

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