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DOE/NASA Automotive Stirling Engine Project Overview '83

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DOE/NASA AUTOMOTIVE STIRLING ENGINE PROJECT OVERVIEW 83

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ABSTRACT

An overview of the DOE/NASA Automotive Stirling Engine Project is presented. The background and objectives of the project are reviewed. Project activities are described and technical progress and status are presented and assessed. Prospects for achieving the objective 30 percent fuel economy improvement are considered good. The key remaining technology issues are primarily related to life, reliability and cost, such as piston rod seals, and low cost heat exchangers.

E-1623

BACKGROUND AND OBJECTIVES

The Automotive Heat Engine Program was begun by the Environmental Protection Agency (EPA) in 1971 with 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 1975 the Stirling engine was selected as one of the promising candidates for detailed investigation. By 1978 the Heat Engine Program had converged on the two most promising alternative engine candidates for the automobile - Gas Turbine and Stirling.

With the formation of the Energy Research and Development Agency (ERDA) in 1978, 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 ofthe 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.

The first major effort of the Automotive Stirling Project was a one year fuel economy assessment effort initiated in September 1977 and carried out under contract by Ford Motor Company as the first step in a potential seven-year cost-shared development effort. This activity utilized the Ford/Philips 4-215 engine (designed and built under a joint Ford Motor Co., N.V. Philips effort initiated in 1971) as a data base and estimated the fuel economy improvement potential of a projected fourth generation (1984 Ref.1) engine. Even though the results indicated excellent fuel economy potential (40 to 80 percent improvement over the conventional spark ignition engine) Ford chose to terminate their Stirling activities due to their need to devote available resources to more near term problems.

The "Automotive Propulsion Research and Development Act of 1978" (Title III, P.L. 95-238) 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 following goal and objectives were established for the Advanced Automotive Heat Engine Program:

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).
- Emission levels that meet or exceed the most stringent Federal research standards; o.4/3.4/0.4/0.2 g/mi, HC/CO/NO_x.
- 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.

In 1981 the DOE directed a change of emphasis away from engine development and demonstration, toward a more technology oriented, lower cost, proof-of-concept effort. As a result the Stirling engine project goal and objectives have been modified as follows:

To develop and verify by September, 1985 the technology base necessary to meet the above propulsion system objective; and to provide confidence in that technology base by verifying the technology in appropriate test bed engines. Specific technology objectives are:

a. Develop metal alloys low in strategic element (particularly cobalt) content.
b. Develop the technology for seals with leakage, friction, and life characteristics suitable for the application.
c. Develop the technology necessary for low emission combustion systems.
d. Develop component technologies required to reduce engine cost and weight and improve engine performance and life in support of the program objectives.
e. Identify and evaluate advanced concepts, not expected to mature by 1985, that offer the potential to significantly impact life, cost, or performance.

PROJECT DESCRIPTION

Basic structure of the current project is shown in Figure 1. The primary technology development effort is being conducted by a team consisting of Mechanical Technology Inc. (MTI), United Stirling of Sweden (U.S.AB) and AM General (AMG) - a wholly-owned subsidiary of American Motors Corporation. This DOE funded, NASA contracted effort was initiated on March 22, 1978. This effort was originally directed to the development and demonstration of an advanced experimental Stirling engine for automotive application which would meet the original program goal and achieve the transfer of Stirling engine technology to the United States. It has now been modified to conform with the revised program goals and objectives. In this modified effort MTI is responsible for overall contract management, development of component and subsystem technology, and transfer of Stirling engine technology to the U. S. USAB is responsible for in-engine technology verification and AMG is responsible for engine transient testing.

This contract effort has been focused by means of a reference engine system design (RESD), intended to represent the best engine that could be designed to meet the program goals, and utilizing the technologies reasonably expected to be developed over the life of the program. Two generations of engines were planned toward the development of the reference engine. The MOD I engine utilized technology available early in the program and was a first step toward the reference engine design. The MOD II engine was then planned to incorporate all of the technologies incorporated in the reference engine design and would in theory be an experimental version of the reference engine. With the change in program emphasis it is no longer planned to build a MOD II engine. Instead those additional technologies, planned to be incorporated in the MOD II engine, will be tested and verified in modifications of the existing MOD I engines. (MOD IA and MOD 1B).

In addition to overall management of the Automotive Stirling Engine Project, the LeRC is carrying out through both in-house and contracted activities, a number of separate research and technology efforts, both to support the 1985 technology verification goal and to identify and evaluate more advanced concepts not expected to mature by 1985 but which offer the potential to impact life, cost or performance significantly. These activities have included in-house engine testing of three engines, the General Motors GPU-3, (Ref. 2) the USAB P-40, (Ref.3) and the N.V. Philips Advenco engine. Test objectives have included engine performance mapping to provide data for computer code validation as well as specific technology evaluations. These have included jet impingement heat transfer tests in the GPU-3, (Ref. 4) hydrogen permeation testing in the P-40 and variable stroke performance tests in the Advenco engine. Other technology efforts at LeRC have included extensive contract and in-house activities in materials, seals, controls, and Stirling engine computer codes.

TECHNICAL PROGRESS AND STATUS

System Technology

The RESD (Ref. 5) generated in the early phases of the program had a projected maximum efficiency of 43.4 percent and yielded a projected fuel economy improvement of 56 percent over the comparable projected 1984 spark ignition engine vehicle. Four MOD I engines incorporating technologies available at that early state of the program have since been built and tested and one engine has undergone transient testing in a test bed vehicle. Further, one of these engines has now been modified into the upgraded MOD IA configuration and testing has been initiated. Power and efficiency results at maximum engine pressure, for the four MOD I engines are presented in Figure 2. Power and efficiency for the four engines are reasonably consistant except for the initial No. 1 engine tests at USAB being noticeably higher in efficiency in the low speed range. While the power output data closely follows predictions, the efficiency data generally were a little low compared to predictions except for the low speed tests of No. 1. engine at USAB. Data at the important "average operating point", 5 Mpa and 2000 RPM, show a spread from 27 to 31 percent compared to an original prediction of 28.8 percent. Again the No. 1 engine test at USAB is significantly higher than the other engines. Over 2000 hours of test time have been accumulated on the four engines and the frequency of failure considering the early experimental nature of these engines is good. Accumulated engine test time on each of the four engines is shown in Table I along with the mean time between failure for each engine.

TABLE I. - MOD I EXPERIENCE

Engine No.	Total Hours	Mean Time Between Failure
1	701	50.9
2	607	101
3	362	121
4	238	26

In general the consistency between engines (with the exception of engine α1 as tested at USAB) has been good and the efficiencies have been close to projected values. These results combined with the efficiency and fuel economy projections of the RESD (56 percent improvement projected) provide high confidence that the 30 percent fuel economy improvement goal of the project will be achieved.

Materials

One of the more critical technology needs identified at the start of the program was the need for low cost, low strategic alloy, high temperature materials for the heater tubes, cylinders and regenerator housings. The United Stirling P-40 engine which served as the baseline engine for this automotive development project operated at a heater tube temperature of 720° C and utilized cobalt (a high cost strategic material) based alloys for these components. The reference engine has been designed for a heater tube temperature of 820° C in order to provide improved efficiency and power density. After screening the candidate alloys based on fabricability, cost, and strategic alloy content, as well as on high temperature strength, CG-27 was chosen as the primary candidate alloy for the heater tubes. Figure 3 presents the 3500 hour rupture strength of the baseline N-155, high cobalt material with two candidate heater head tube alloys. As shown, CG-27 has an ample strength margin above the required stress for the use temperature of 820° C. XF-818 was similarly selected as the primary candidate casting alloy for cylinders and regenerator housings. Figure 4 compares the 4,000 hour rupture strength of the baseline HS-31 cobalt base material and the 3 most promising iron base alloys CRM6D, XF-818 and SAF-11. It should be noted that the use temperature for the casting alloys is 775° C, about 45° C lower than the heater tube temperatures. As shown, the candidate iron base alloys all run about 15 percent lower in strength than the baseline HS-31 material and design changes have been incorporated in the engine in the attempt to accommodate this lower strength capability. It should be noted that two contract activities are underway attempting to develop improved high temperature strength properties for iron base alloys. One data point is shown in the figure for an experimental alloy (N10017) from the AiResearch Program. This is an initial result from first phase alloy screening task and considerably more testing is required to validate this result. The other contract, with United technologies Research Center (UTRC) is concentrating on iron-base eutectic alloys.

Another complicating factor in the materials selection for the heater tubes, cylinder and regenerator housing castings is the problem of hydrogen permeation through the metal walls at the high operating temperatures involved. It has been found that by doping the hydrogen working fluid with small percentages of CO or CO_2 the permeation rates can be brought down to an acceptable level. An acceptable level is currently defined as the need to replenish the hydrogen supply for the engine no more often than once very six months. The reduction in permeation apparently is the result of establishing and maintaining an oxide coating on the surface of the material. A complicating factor is that water vapor apparently plays a very important role in the process. In fact it may be the presence of the water vapor, generated in the reaction of the dopant with hydrogen, which is the primary factor in establishing and maintaining the oxide film on the surface. Water vapor, if present in sufficient quantities could obviously result in condensation and freezing of water in cold parts of the engine in cold weather. Efforts are currently being initiated at Lewis Research Center to determine the quantities likely to be present and, if necessary, to explore techniques for controlling the water vapor content of the engine during shut down periods to prevent condensation and freezing in critical parts of the engine.

Seals

The reciprocating rod seal of the Stirling engine has historically been one of the most critical technology problems in the Stirling engine development. The pumping Leningrader type seal recently developed by United Stirling currently shows promise of providing a solution to this critical problem. Experience to date with PL seals utilized in P-40, P-75, V-160 and MOD I engines indicate that it is possible to achieve the required seal operating life with acceptably low hydrogen leakage and satisfactory exclusion of oil from the working fluid. A number of engines have run successfully for over 3000 hours and a recent series of 500 hour engine tests has been consistently successful. However, reliability and repeatability have at times been poor. Some engines have had seal failures in less than 100 hours of operation.

It has become apparent that a better understanding is required of the specific factors of seal design that result in acceptable oil and hydrogen leakage as well as low friction, acceptably long operating life and start-stop cycle life. Since 1979 significant LeRC contracted efforts have been directed at developing and validating analytical design and performance prediction techniquest for pumping rings, a key element of the current seal design. In addition, the necessary quality control requirements must be established for satisfactory seal fabrication, installation, and operation. In the last year the seal test effort has been substantially expanded to provide significantly increased testing in engines as well as in motoring rigs and seal test rigs. Further intensive quality control efforts have been undertaken on seals to assure that seal material properties are consistent so that the seal design characteristic can be effectively correlated with seal performance, and that consistent performance can be achieved.

Piston rings are also an area of significant concern. These dry sliding seals utilize teflon based materials and have a finite wear rate influenced by loading, speed and temperature. Recent tests conducted in the program show a drastic impact of temperature on ring wear, Figure 5, with a five fold increase between 50° C and 90° C. It is obvious that ring-wall temperatures must be controlled to as low a temperature as practical and that some form of wear compensation will be necessary if the desired life is to be achieved. This is the approach currently being pursued by MTI. While substantial piston ring technology efforts remain to be completed and verified, it is believed that the approach will yield a satisfactory piston ring seal.

External Heat System

Two design approaches have been pursued to control emissions. These are shown schematically in Figure 6. The first, exhaust gas recirculation, (EGR) recirculates exhaust gas after having passed through the preheater whereas combustion gas recirculation (CGR) recirculates exhaust gas ahead of the preheater. Both are capable of meeting emission requirements. However, the CGR system offers the potential for improved efficiency and a smaller preheater. Some difficulty has been experienced with the CGR system to date, particularly in the areas of thermal stress and turndown ratios. The EGR system is being utilized as a work horse system in the current engines. However, it is still anticipated that the CGR combustion system will be validated in modified MOD I engines. A promising area of future work for the external heat system is the desire to reduce the spread of heater tube wall temperatures. Current spreads in the order of 50-100° C result in a significant lowering of average heater head temperatures in order to assure that peak allowable tube temperatures are not exceeded. Reduction of the heater tube temperature spread to the order of 20° C could yield significant gains in both efficiency and power density.

In an evaluation of alternative fuel capabilities, a P-40 engine was operated successfully on unleaded gasoline, gasohol, a broad specification aircraft turbine fuel, automotive diesel and a marine diesel from shale oil. Little or no impact was observed on power, emissions or smoke. These tests were run without changes to the engine except for an air/fuel ratio adjustment for each fuel. The diesel fuel runs were made after initial start-up on gasoline.

In a separate contract activity, Rasor Associates has investigated the application of jet impingement heat transfer augmentation to the Stirling engine with the objective of reducing emissions by reducing required combustion gas temperatures, and reducing required heater tube surface area as a result of the enhanced heat transfer. Under this effort a jet impingment system was designed, built and tested in the GPU 3 Stirling engine at NASA Lewis Research Center. For a small penalty in pumping power (less than 1/2 percent of engine output) the jet impingment heat transfer system provided a higher combustion gas heat transfer coefficient and also smoothed the heater temperature profiles resulting in lower combustion system temperatures and five to eight percent increase in engine power output and efficiency. Application of this technology to the automotive Stirling engine could have several beneficial effects including reduced heater tube surface area, significant smoothing of heater temperature profiles, an increase in the average heater tube operating temperature, and increased engine efficiency, while staying within the temperature limits of the heater tube materials.

Part Power Optimization

The automobile operates most of the time at relatively low power operating conditions. Thus, it is desirable to optimize engine efficiency in this region in order to achieve the best drive cycle fuel economy. This was the approach taken in generating the Reference Engine design. Since the resulting RESD design represented a significant departure from past USAB design practice, it was decided that the MOD I engine design should incorporate only an intermediate step toward complete part power optimization. As stated earlier, MOD I test results have generally shown good agreement with performance predictions in the low power region of interest, indicating the successful extension of the design tools into the part power optimization region. While no

MOD II engine is currently planned in the program, it is planned to test a MOD I modification incorporating complete part power optimization of the critical regenerator.

Cost

One of the critical criteria for an automobile engine is low cost which was a key goal of the RESD. To provide reliable cost estimates for automotive quantity mass production, a subcontracted cost study was performed by Pioneer Engineering and Manufacturing Co. of Warren, Michigan. This study was performed utilizing the detailed MOD I engine drawings and then extrapolatoring as necessary to the RESD. The results are presented in Table 2.

TABLE II - COSTS

90 HP Engine, 1981 Dollars		Sticker Premium
Stirling Cost	$1680)	
	)	$1500
I. C. Engine	720)	
With Learning Curve		
At Layout		$1500
At Start of Production		1125
Ten Years Later		800

This study assumed the availability of low cost regenerators, coolers and preheaters which could meet the performance requirements of the engine.

Screening tests are being conducted by MTI of candidate regenerator materials. At this time the ceramic Duocel material developed by Energy Research and Generation Inc. of Oakland, California, appears to have the necessary heat transfer and pressure drop characteristics and is anticipated to have production costs equal to or lower than those assumed in the Pioneer study. Intitial screening tests also show adequate structural integrity to tolerate the alternating flow forces in the engine application. Further validation tests are planned in the P-40 engine at LeRC to be followed, if successful, by tests in modified MOD I engines.

Another key component from a cost standpoint is the preheater. The current RESD design is a multiple plate design of stainless steel. MTI is currently evaluating designs for ceramic preheaters which could achieve the desired cost reduction for this component. Current tests indicate that heat transfer and pressure drop should be acceptable. Discussions are proceeding with vendors with the intent of building a ceramic preheater and testing it in a modified MOD I engine.

In the materials area both of the casting alloy modification efforts, mentioned above, have the potential of yielding lower cost as well as improved strength. The iron base eutectics being pursued by UTRC offer the potential of a 50 percent materials cost reduction relative to the currently selected XF-818 for the cylinder and regenerator housings.

In addition to the above efforts MTI and USAB have been continuing to upgrade the RESD design in an attempt to achieve additional design simplification and further cost reductions.

While cost remains a key outstanding question for the automotive Stirling engine, promising approaches to achieving the reductions assumed in the Pioneer study are being pursued and further reductions are expected from the continuing RESD design, component and material technology efforts. While it is not expected that the Stirling cost is likely to equal that of the spark ignition engine in the near future, it is believed that an acceptably low premium for the Stirling can be achieved which would make it commercially viable.

Computer Codes

At the initiation of the project, Stirling engine technology resided primarily in N.V. Philips and its European licensees USAB and MAN. One of the key technical tools provided by N.V. Philips to its licensees was their validated detailed performance prediction computer code. At that time any serious Stirling engine development in the automotive size range had to either utilize the N.V. Philips code and the technology it represented or anticipate an extended expensive development effort. The unavailability of such a validated code was considered a serious barrier to the development and commercialization of Stirling engines in the United States. Therefore, a significant effort was undertaken at LeRC to develop and validate a non-proprietary Stirling engine computer code that would be generally available to U.S. industry. The code was generated in-house and has been validated with data from tests of the General Motors GPU-3 Stirling engine and the United Stirling P-40 engine which were both tested at LeRC. Performance predictions are compared with test data in Figure 7. With the validation of this code, and considering the substantial code development efforts being carried on by various investigators, the availability of such codes should no longer be considered a barrier to Stirling engine development by U. S. companies.

Advanced Concepts

One of the specific technology objectives is to identify and evaluate advance concepts, not expected to mature by 1985 that offer the potential to significantly impact life, cost or performance. Two such concepts are described below.

Ceramic heater heads would appear to offer the potential for both low cost and improved performance. While development of a ceramic heater head is beyond the scope of the current program, ceramic heater head designs are being examined to define their true potential and to identify key technology requirements for their development. To this end two contract efforts have recently been initiated to carry out design studies for ceramic heater heads applicable to the automotive Stirling engine. Following these efforts it is planned to initiate preliminary hardware fabrication and assessment, though significant engine validation is unlikely within the current program schedule.

A free-piston hydraulic drive system for automotive application was evaluated in a study completed by LeRC in 1982 (Ref.5). This study indicated the potential for substantial fuel economy improvement, approximately 80 percent over the comparable 1984 spark ignition engine vehicle. However, more detailed studies are needed to generate a specific design and to assess cost, packaging and safety considerations of such a system. It is planned to conduct such studies, however, any technology development of such a system is beyond the scope of the current program.

SUMMARY TECHNOLOGY ASSESSMENT

At this point in the program it would appear that the objective of a 30 percent improvement in fuel economy is likely to be achieved. The RESD design projects a 56 percent fuel economy improvement and the MOD I engine experience indicates that fuel economies close to the predicted values can be achieved in the actual engine hardware.

The key technology issues at this point in the program are those relating to life, reliability and cost. These are summarized briefly below:

Piston Rod Seals - The key critical technology for the automobile Stirling engine remains the reciprocating shaft seal. It appears that the PL seal will likely provide adequate running life. However, two major questions remain: (1) Can adequate start-stop cycle life capability be achieved, and (2) Can the seals be produced and utilized on a mass production basis and still achieve the necessary performance, repeatably and reliably.

Piston Rings - This is still a difficult technology effort, with ring design requiring careful balance of leakage losses, friction and wear. While much work must still be done, the approach of wear compensated designs along with an adequate temperature environment for the rings are expected to yield a satisfactory design with the required life.

Materials - Materials efforts are critical to achieving low cost and low strategic alloy content, at an adequate level of performance. Currently identified, existing alloys now under test (e.g. CG-27, XF-818) appear to be adequate, while the ongoing alloy modification efforts show promise of yielding better strength and lower cost.

Regenerators - The key technology need here is for a low cost material that will also provide the required high effectiveness with reasonable pressure drop. One such material has been identified through heat transfer and pressure drop tests of sample elements. Preparations are underway for in-engine validations, and other alternative materials are still being evaluated.

Preheater - Again the key issue here is cost. This technology effort has proceeded slowly and most of the work, in terms of component fabrication and test, is yet to be done.

While much work remains to be done in the combustion system and controls area, these are not currently considered to be key technology issues. The current technology appoaches, EGR for the combustor, and pressure level control can probably be utilized and meet the program objectives; though the more advanced technologies might possibly improve performance, life and reliability.

OUTLOOK TOWARD ADOPTION BY INDUSTRY

The automotive Stirling engine project has long suffered the lack of participation of a major automotive engine manufacturer. To address that issue, a program is underway to provide MOD I experimental engines on a loan basis to such manufacturers for their test and evaluation. This effort is intended to both update engine manufacturers on the Stirling technology status and to provide a feedback of manufacturers comments to the program. Hopefully, this may constitute a first small - but significant step in the direction of commercialization.

Another potential factor relative to adoption by industry may be the interest of foreign manufacturers in Stirling. Daimler-Benz has been conducting tests with USAB P-40 engines in vans and the Japanese seem to be interested in similar tests in cars.

CONCLUSIONS

In conclusion we believe the program is going well, though several key technology problems remain. We expect that the program goal and objectives will be achieved within the required time frame. Further the prospect for adoption by industry, though a light at the end of long tunnel, may now be improving.

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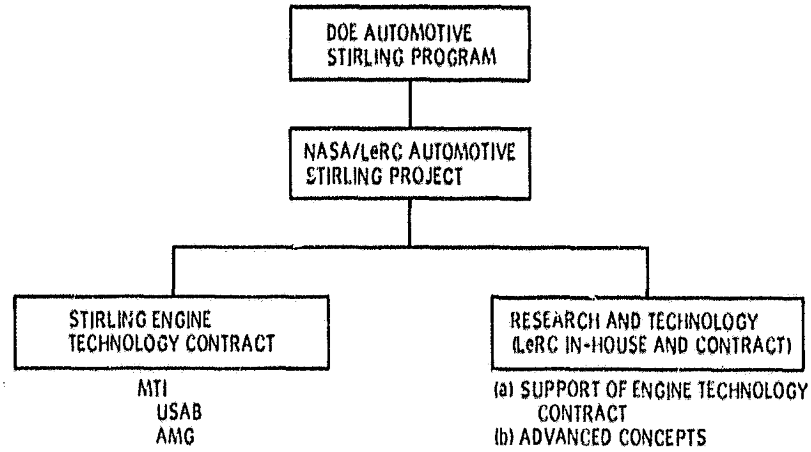

Figure 1. - Project organization.

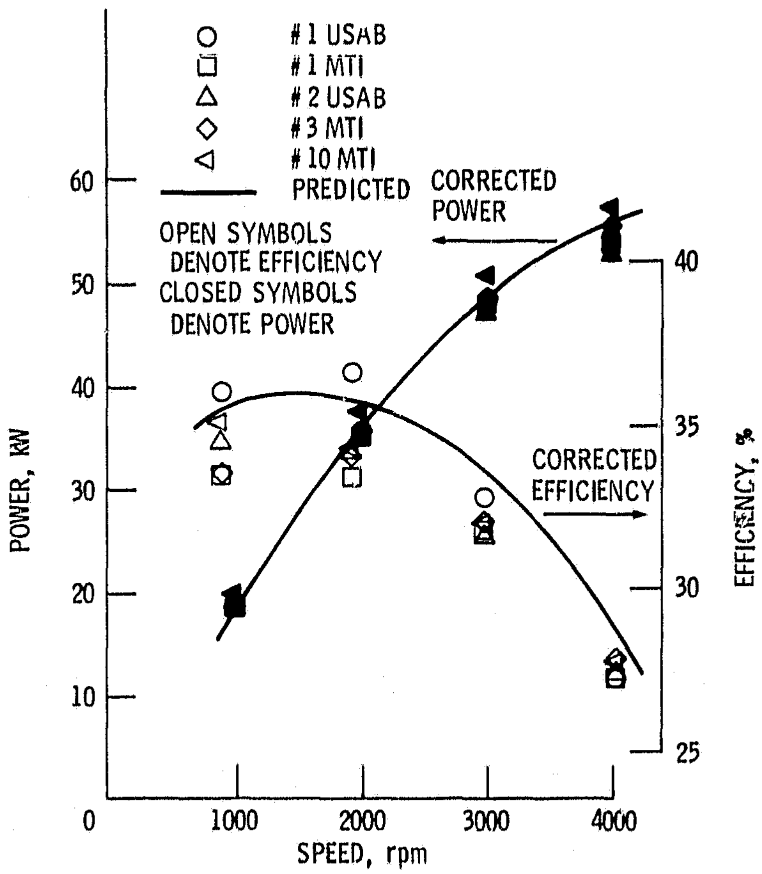

Figure 2. - Mod I engine comparison; 15 MPa mean pressure.

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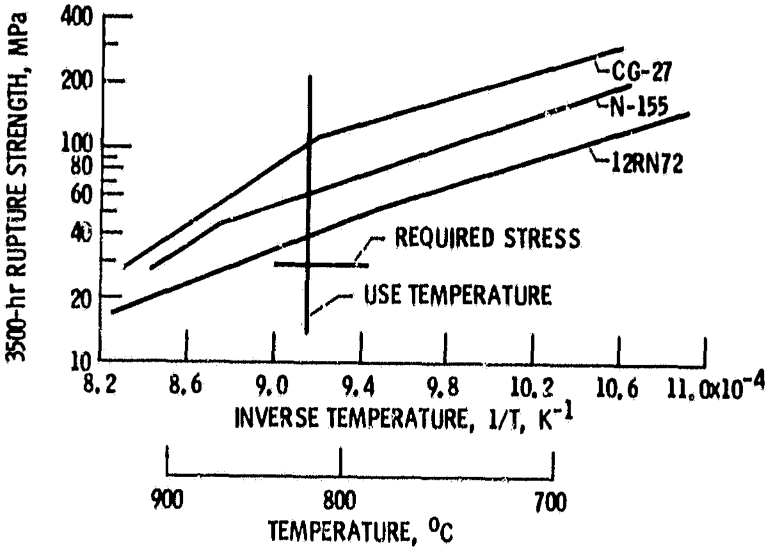

Figure 3. - Stress-rupture strength of candidate heater-head tube alloys.

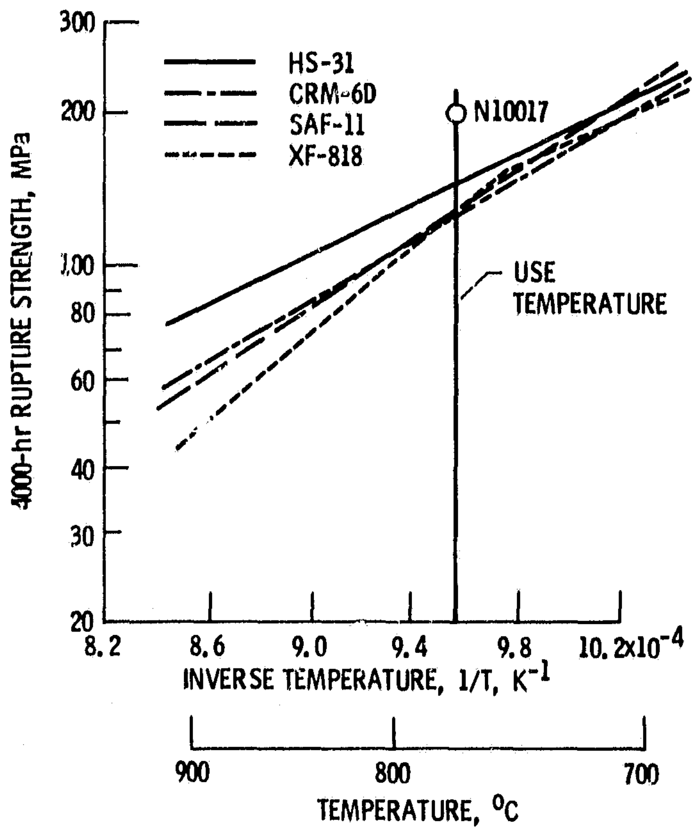

Figure 4. - 4000 hr stress-rupture strength of candidate cylinder and regenerator housing alloys.

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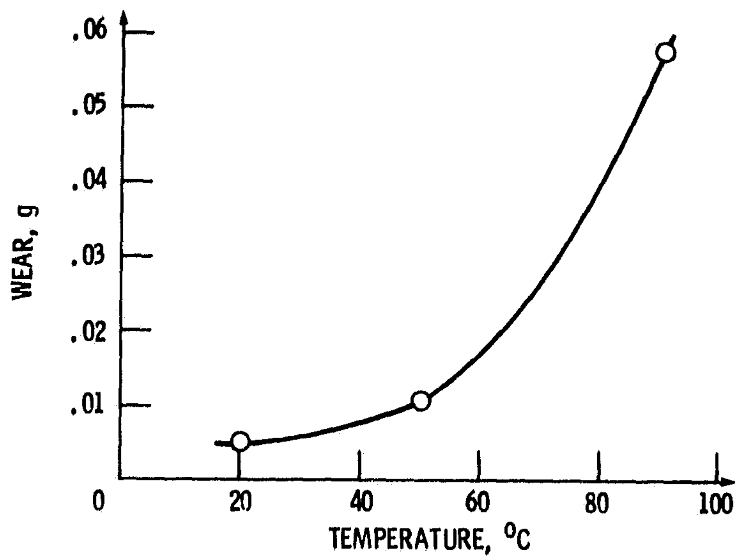

Figure 5. - Piston ring wear as a function of temperature.

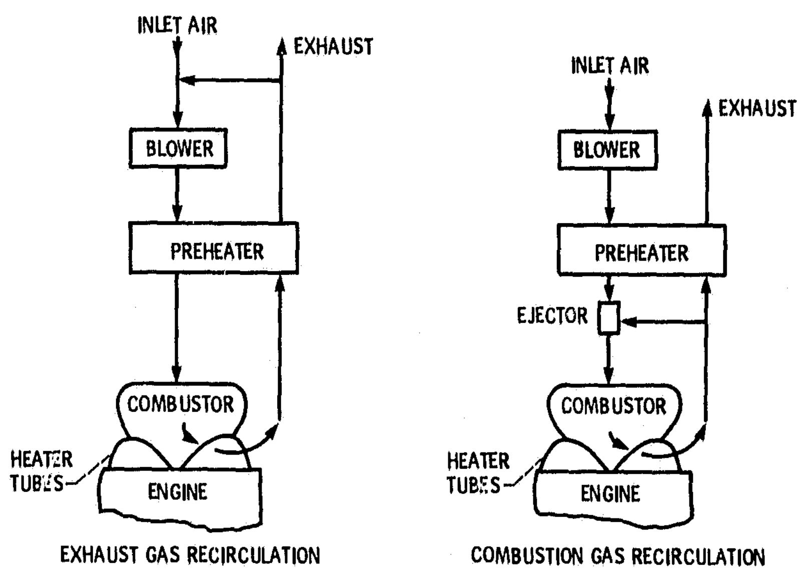

Figure 6. - Emission control approaches.

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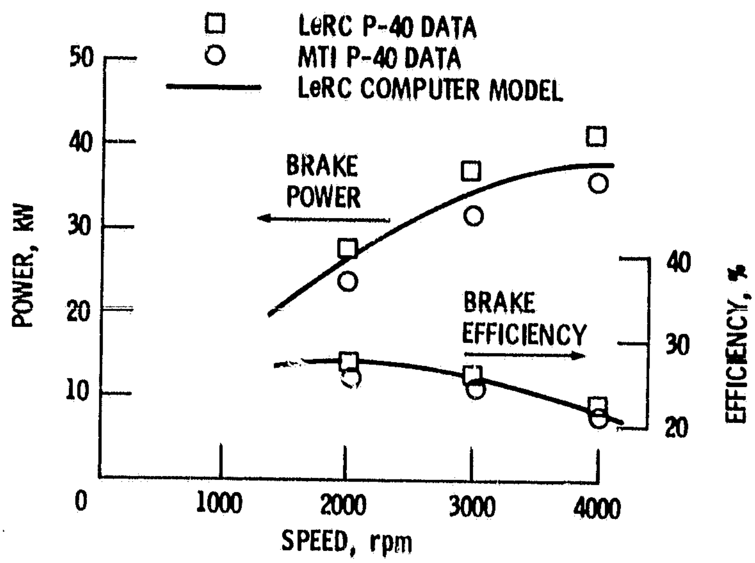

Figure 7. - Comparison of test data with LeRC code predictions; 15 MPa mean pressure; hydrogen working fluid.