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CERAMIC APPLICATIONS IN THE ADVANCED STIRLING AUTOMOTIVE ENGINE

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INTRODUCTION

In the past several years, there has been a rising national concern in two areas - pollution and energy. The concern with pollution as a problem led to the Clean Air Act which, with its various amendments, established stringent emissions standards for automobiles. The problem of dwindling energy supplies, particularly petroleum, was dramatically brought out by the 1973 Arab oil embargo. The need to confront these problems has led to examination of alternative automotive engine which may reduce both emissions and petroleum usage.

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The ERDA Heat Engine High Vehicle Systems Program is directed towards reducing demand for petroleum-based fuels in highway vehicles (automobiles, trucks, and buses). The emphasis is on the passenger automobile, the largest single consumer of petroleum. The Stirling engine is one of two continuous combustion engines now being developed because of their potential for high fuel economy, low emissions, and multi-fuel capability. The gas turbine engine is, of course, the other. Project management for research and development on continuous combustion engines has been assigned by the ERDA Office of Conservation, Division of Transportation Energy Conservation, to the NASA Lewis Research Center. This project will reside in the Energy Programs Directorate, Transportation Propulsion Division at LeRC.

This paper presents a discussion of the Stirling engine. I will describe the ideal cycle, its application to a practical machine, and the specific advantages of high efficiency, low emissions, multi-fuel capability, and low noise. Certain portions of the Stirling engine must operate continuously at high temperature. Although engines currently being developed use metal alloys for the hot components, ceramics offer the potential of cost reduction and efficiency improvement for advanced engine applications. I will describe potential applications for ceramics in Stirling engines, and some of the special problems pertinent to using ceramics in the Stirling engine. I will also describe briefly the research and technology program in ceramics which is planned to support the development of advanced Stirling engines.

THE STIRLING CYCLE ENGINE

Ideal Cycle

The Stirling engine is a thermal regenerative engine with a completely sealed gaseous working fluid. Heat is added and rejected as required across the engine walls. The combustion gas or other heating medium does not itself enter into the cycle except to provide heat. The ideal Stirling cycle is shown in figure 1. The pressure-volume and temperature-

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entropy diagrams are shown on the right. The ideal cycle consists of heat addition at constant volume (1 to 2), expansion at constant temperature (2 to 3), heat rejection at constant volume (3 to 4), and compression at constant temperature (4 to 1). A simple mechanical system to achieve the cycle is shown on the left. It consists primarily of a cylinder which is kept hot at one end (H) and cold at the other (C). The cylinder contains a power piston (P) which compresses the working fluid and takes work out, and a displacer piston (D) which moves the working fluid between the hot end and the cold end. External to the cylinder is a connecting passage between the hot and cold ends. This passage contains a regenerator (R) whose function is to abstract heat from the working fluid when it travels from the hot end to the cold end and return that heat when the working fluid goes from the cold end to the hot end.

The cycle starts with the displacer and power pistons positioned as shown in position 1. The engine internal pressure is at P_1; the pressure on the opposite side of the power piston (the external pressure) is also at P_1 and remains at P_1 throughout the cycle. In going from point 1 to point 2, the displacer is moved toward the power piston. This causes the working fluid to flow from the cold end to the hot end. On its way, it passes through the regenerator and picks up the heat which has been stored from the previous cycle. The gas pressure rises to a maximum cycle value at point 2 as a result of constant volume heating.

The pressure difference ($P_2 - P_1$) across the power piston results in a force which tends to push the power piston out of the cylinder. The power piston and displacer are now allowed to move together which expands the working fluid from P_2 to P_3 (which is equal to P_1). Heat is added to the working fluid during the expansion to maintain constant temperature.

After the expansion is complete, the displacer is moved away from the power piston (point 3 to point 4). This causes the working fluid to flow from the hot end to the cold end, giving up heat to the regenerator on its way. This results in a constant volume cooling process in going from point 3 to point 4. The working fluid pressure is now at P_4 which is the minimum for the cycle. The external pressure is now greater than the internal pressure and the resultant force on the piston tends to move it back into the cylinder.

The power piston is allowed to move towards the left, compressing the working fluid. Heat is simultaneously removed from the working fluid so that the compression from P_4 to P_1 is isothermal. Both the power piston and displacer are now back to their original positions and the cycle is complete.

The ideal cycle has the same thermal efficiency between any two temperature limits as the Carnot cycle. Hence, it is the most efficient heat engine cycle theoretically possible. Figure 2 shows ideal Stirling engine thermal efficiency as a function of hot end temperature for several cold end temperatures. The efficiency is equal to one minus the ratio of cold end temperature to hot end temperature.

Real Engines

Unfortunately, it is not feasible to construct a practical engine which follows the ideal Stirling cycle because to do so would require discontinuous motion for both the power piston and displacer. This would, of course, result in excessive mechanical forces and high fluid friction losses because infinite accelerations would be required. In addition, it is difficult to transfer heat effectively as is required to maintain constant temperature during expansion and compression. Real engines are constrained to essentially harmonic motion for the pistons. The heater and cooler are external to the cylinder at the hot and cold ends respectively, in series with the regenerator. Heat losses and less than perfect heat transfer cause the compression and expansion processes to be more nearly isentropic than isothermal. The net effect of these and other differences is that the discrete processes of the ideal cycle can no longer be distinguished. Because of the practical difficulties involved, modern Stirling engines do not operate on a true Stirling cycle, but rather on an amalgam of thermodynamic processes which results in a roughly elliptical indicator diagram.

The requirements of the ideal Stirling cycle, however, do serve as a basis for establishing the requisite elements of a real engine. In order to approach the desired cycle, the working fluid must be heated, it must be cooled, it must transfer energy to and remove energy from a regenerator, and it must be expanded and compressed at the proper times. These requirements define the five essential components of the Stirling engine as shown in figure 3 - the engine heater and a means for keeping it hot; the regenerator; the engine cooler and a means for keeping it cool; a displacer piston to control the movement of the working fluid through the heater, regenerator, and cooler; and the power piston to compress and expand the gas. And, in addition to the basic components, some sort of drive system is required to coordinate piston-displacer motion.

There are two basic types of practical Stirling engines - the displacer type and the double-acting type. The displacer type has a discrete displacer which has the sole function of causing the gas to flow alternately to the hot end and the cold end. In addition, it has a piston to compress and expand the gas and provide power. It may have one or more cylinders, but each is independent, i.e., the cycle is carried out completely within that cylinder and its inclusive components. The engine shown schematically in figure 4 uses a rhombic drive which is a unique mechanism for providing the required piston - displacer motion, for achieving dynamic balance, and for minimizing piston-cylinder side loads. Other mechanical systems are possible, but this has proven the most acceptable for displacer-type engines. The double-acting engine, on the other hand, must have multiple cylinders to function - generally three or more. In this type of engine, the upper face of the piston in one cylinder bounds an expansion space that is connected via a heater, a regenerator, and a cooler to a compression space bounded by the lower face of the piston in an adjacent cylinder. Normally, four cylinders are coupled together in a typical double-acting engine as shown in figure 5. This provides a 90° phase relationship between pistons which causes the required volume variation in the hot and cold spaces in order to achieve a practical cycle. Several mechanical drive systems have been used. The Ford-Philips engine (fig. 6) uses a swashplate to convert reciprocating motion to rotary and to maintain the necessary phase relationship. United Stirling uses a crosshead and crank arrangement which is somewhat more conventional (fig. 7).

The working fluid used in the Stirling engine is of critical importance in determining the efficiency and specific power output. Stirling engine performance is uniquely dependent on efficient heat transfer and on low friction, low inertia fluid movement. Therefore, the working fluid must have high thermal conductivity, high specific heat, low absolute viscosity, and low molecular weight. Obvious choices, based on theoretical considerations, are hydrogen and helium. Experimental data corroborate this. Figure 8 shows engine efficiency as a function of specific power output for several working fluids. Hydrogen shows a definite advantage, even over helium, particularly at high specific powers. The high output regime is the only one of interest for automotive application since, in that case, the Stirling engine is competing with the Otto cycle engine, which has an inherently high specific power. Therefore high operating pressures and speeds will be required to make Stirling engines attractive for automotive applications. Unfortunately, hydrogen also introduces several problems, such as the possibility of hydrogen embrittlement of the engine components and hydrogen loss through leakage or diffusion.

The Stirling engine for automotive applications offers four potential advantages over current engines. The first is energy efficiency. Improvement in fuel economy of 20 to 30 percent over current spark ignition engines while offering the same vehicle performance is projected for an "improved" Stirling metallic engine. Advanced Stirling engines operating at higher heater head temperatures indicate substantially greater fuel economy improvements. Intrinsically low emission is a second advantage of the Stirling engine. Continuous combustion allows low emissions without significant compromise in performance or expensive add-on cleanup systems. Emissions substantially below Clean Air Act ultimate standards should be achievable. Third, the Stirling engine uses external combustion to heat the working fluid and the combustion gas is not part of the working fluid. Special fuel requirements like octane or cetane rating are not imposed and contamination of the working fluid by the products of combustion and their effects on many system components is eliminated. This allows a wide range of potential fuels. The fourth Stirling engine advantage is that it has a very small variation in torque through the cycle. The engine therefore has very low vibration and noise compared to an internal combustion engine with the same number of cylinders.

In order to make a practical high efficiency Stirling engine for automotive application, additional components beyond the five essential components shown in figure 3 must be used. Figure 9 shows the basic Stirling cycle with the additional components needed for an automotive engine. As we see now, a practical engine would be double-acting, however, we have shown a single-acting system schematically. This is simply for ease of illustration and does not affect the basic concepts. The additional components are, 1) a burner to convert fuel energy to heat, 2) a blower to provide air to the burner, 3) an air preheater to heat the combustion air by recovering waste heat from the exhaust, 4) a radiator to dump waste heat from the cooler, 5) a drive system to convert cycle work to useful form, 6) a temperature control to control heater head temperature, and 7) a power control to adjust output to vehicle demands. The operating conditions shown are those which pertain to current systems. As mentioned previously, the ratio of cold end to hot end temperature is a key factor in determining performance. This engine operates at approx 1380° F at the hot end and approx 175° F at the cold end. Even at this relatively modest hot end temperature, expensive high temperature alloys are required. Note that I mean expensive when compared to cast iron or mild steel which are the major construction materials for internal combustion engines. Unlike internal combustion engines, the Stirling must operate at its maximum cycle temperature continuously. The hot end is also continuously at high pressure, varying from about 2300 to 3600 psi over the cycle at maximum power. Furthermore, the heater head is exposed to oxidizing hot gases from the outside, as well as hot high pressure hydrogen from the inside. And, in order to achieve high cycle efficiency, heat must be transferred rapidly and efficiently through the heater head from the combustion gases to the working fluid. We see the heater head as being the most critical component in the Stirling engine in terms of performance, durability, and cost. It is here that advancements in material and fabrication technology will have the biggest payoff.

The regenerator is also a key component in determining the efficiency of a Stirling engine. Robert Stirling's original patent in 1816 defined a regenerator and an air engine which incorporated the regenerator. The importance of the regenerator is in the fact that it conserves heat during the cycle. It abstracts heat from the working fluid as it passes from the hot end to the cold end and returns the heat to the working fluid as it returns to the hot end. Since the heat involved in this operation is of the order of eight times the amount of heat added at the heater head, the importance of the regenerator is apparent.

The Stirling engine is criticall, dependent on efficient heat transfer for its performance. In addition to the heater head and the regenerator - the cooler, the radiator, and the air preheater all must be carefully considered in developing the Stirling engine. Reducing the working fluid cold end temperature by 15° would have the same effect on efficiency as raising the hot end temperature by 60° - without increasing the high temperature problems.

THE POTENTIAL FOR CERAMIC COMPONENTS

Stirling engines currently being developed primarily use alloy metals in their construction. Ceramics are used in only two areas, the air preheater and insulating tiles between the burner and the heater head. For the advanced Stirling engine to achieve its objectives of high efficiency and low cost, the principal components are expected to be made from ceramic materials. In fact, it is unlikely that the advanced engine, as now conceived, is a viable concept without ceramic components. Metal components would be severely limited in temperature capability and would result in an engine too costly to be mass-produced. Hopefully, ceramics - with enough development effort - will allow substantially reduced component costs. This hope is based on the low cost and broad availability of basic ceramic materials as compared to the more exotic metals required for high temperature operation. Also, the use of ceramic components should permit the use of even higher cycle temperatures and hence higher efficiencies. We recognize that considerable research and technology effort will be required before these hopes can be realized, but we feel the potential is there and should be exploited.

Figure 10 shows the Stirling engine schematic again with our estimates of the operating parameters for an advanced engine. The principal change from the current engine is in higher operating temperatures. We are hoping to achieve heater head temperatures of 2000° F or higher. The increased cycle temperature will also be reflected in the air preheater where maximum temperatures will be 2700° F or more. The regenerator will see higher inlet temperatures and a higher differential since coolant temperatures should remain about the same. Burner temperatures should remain about the same. The specific components we see as potential candidates for ceramic construction are the heater head, the air preheater, the regenerator, the burner, and the power piston.

Figure 11 shows the metallic heater head for a four-cylinder double-acting engine currently being developed. The heater head is essentially a multi-tube heat exchanger. Its function is to provide for the transfer of heat from the combustion gases to the hydrogen working fluid. Combustion gas flows from the burner - which is mounted above the heater head-outward between the tubes, and then out through the preheater core to the exhaust pipe. The combustion side resistance is the determining factor in the overall heat transfer to the working fluid. The large number of tubes is necessary to obtain the required heat transfer surface. However, the tube length must be kept relatively short to minimize internal dead volume which has a deleterious effect on performance. Fins are used over part of the tube length to increase heat transfer. The tubes are manifolded to allow hydrogen to flow from the top of one cylinder (in the center) to the bottom of the adjacent cylinder through the regenerator modules (two per cylinder arranged around the periphery). For the heater head shown, at least 176 brazed connections are required to provide the proper flow paths. This particular heater head uses N-155 tubes and operates at 1300° to 1400° F. The mean hydrogen working pressure is 3000 psi. For advanced engines, working pressures may be higher to reduce specific weight.

A ceramic heater head offers the greatest payoff and presents the greatest challenge of any of the Stirling engine components. It operates under the most severe combination of temperature, pressure, and chemical environment. For a practical automobile engine, it must be trouble free over 3500 hours of operation. In order to fulfill their essential heat transfer function, metal heater heads are complex structures. Within the limits of fabrication techniques, ceramic heater heads must also transfer heat effectively without incorporating excessive dead volume. Reliable, leak-free connections must be made to the cylinder block - both at the cylinder head and at the regenerator. The ceramic structure must resist attack from the combustion gases and be impervious to the hot (2000° F or more), high pressure (3000 psi or more) hydrogen. The overall problem of effective hydrogen containment at high temperature and pressure may be the most difficult one to be faced. As stated previously, the ceramic heater head will probably not be built of tubes. The development of a new configuration, specifically adapted to ceramic properties, will be a key part of the ceramics program.

Current Stirling engines employ a rotary preheater with a ceramic core (aluminum silicate). This is a direct carryover from the regenerative gas turbine experience. Efforts are also underway to develop an effective stationary air preheater. This would be highly desirable in terms of simplicity and hopefully cost, if the required effectiveness can be achieved. Inlet temperature for the exhaust gas is approximately 2100° F for current engines. Combustion air enters the preheater at 150° F and leaves at 1800° F. At the higher temperatures expected for the advanced engine, aluminum silicate will not be adequate and higher temperature ceramic material will be required. An effective, low cost stationary air preheater would be highly desirable.

Burner flame temperatures for the advanced Stirling engine should be close to those for current engines. However, incoming air temperature will be higher - approximately 2450° F. Using ceramic construction throughout should allow a more uniform distribution of temperature, particularly near the walls since there would be less need to cool them. It may be possible to integrate the burner directly with the heater head, probably simplifying the engine and improving efficiency.

The regenerator in current engines is generally composed of a number of separate modules each of which consists of a container with a large number of tightly stacked, specifically oriented fine metal screens placed inside. The hydrogen inlet temperature is essentially that of the heater head (1300° to 1400° F). The regenerator is connected directly to the cooler where the hydrogen drops to approximately 150° F before going into the compression section of the engine. Advanced engines will operate at a regenerator inlet temperature of about 2000° F. It may be desirable to use stacked porous ceramic disks or possibly a single unit ceramic insert for advanced engine regenerators.

Foamed ceramic materials have been proposed for use in the power piston to withstand the high operating temperatures of advanced engines and to provide an insulating structure to minimize conduction heat losses across the piston from the hot end to the cold end of the cylinder.

System studies will be initiated in FY 1978 to examine the advanced Stirling engine and to develop conceptual designs for potential advanced automotive Stirling engines. These studies will be contracted with industry and are intended to clearly define the salient characteristics of advanced Stirling engines, predict their potential performance, determine the operating parameters throughout the engine, and delineate the technology advances required to achieve the projected engine capabilities. We expect ceramics technology to be a key part of the effort in developing an advanced Stirling engine.

SUPPORTING RESEARCH AND TECHNOLOGY PROGRAM IN CERAMICS

A broad-based ceramics technology program is planned to support the advanced Stirling engine program. This program will include an in-depth characterization of ceramic materials, development of improved ceramic materials and processes, and design, fabrication, and testing of ceramic components. As results are obtained from the advanced Stirling engine study contracts and ceramic component configurations and problems are defined, specific ceramic technology projects will be undertaken to attack these problems. The major portion of this program will be accomplished by industry and universities through ERDA-funded, NASA contracted programs. Some of the specific work planned to be done in each of the three portions of the ceramic technology program is described briefly in the following sections.

Characterization of Ceramic Materials

Mechanical and physical properties of current and emerging structural ceramics that have potential for engine applications will be characterized in depth. A design data base will be established to provide input to the advanced engine design activities. The durability of ceramics in terms of the effects of long-term exposure to engine operating conditions on mechanical properties and stability will be evaluated. Other phases of the overall material characterization effect will include nondestructive evaluation, fracture mechanics, life prediction methodology, and reliability analysis.

Improved Ceramic Materials

Improved ceramic materials will be developed to better meet advanced automotive engine requirements. For example, higher-density reaction-sintered silicon nitride is desirable for both improved strength and oxidation resistance. A project to achieve this would include optimization of the silicon powder particle size and distribution, refinement of the molding process, and improvement of the understanding and control of the nitradation step. Similar technology projects can be identified for other candidate materials such as silicon carbide and the oxide ceramics. While improved material properties will be emphasized, the applicability and economic viability of the related fabrication technology for the improved ceramic material will receive appropriate attention. Approaches to achieving improved materials involving fabrication processes with potential for low cost and high volume production will be of primary interest.

Component Design, Fabrication, and Testing

A strong ceramic technology base will be obtained through iterative experience in component design, fabrication, and testing. Insofar as possible, information on component design characteristics and operating parameters will be derived from the advanced engine characterization studies. Although the actual components tested may not be derived from specific engine designs, they will be used to address key issues such as verification of ceramic design concepts and component reliability under engine operating conditions. Component rig testing will be used as appropriate. Where feasible, component concepts will be evaluated in an appropriate laboratory test engine. Ceramics fabrication processes will be developed along with the new component designs. The objective is to develop ceramic components that can be manufactured at reasonable cost and that demonstrate high reliability.

CONCLUDING REMARKS

The Stirling engine is an alternative automotive engine concept which offers considerable promise for increased energy efficiency, reduced emissions, and broad fuel capability. One of the engine characteristics is that it must operate at high temperatures continuously (as opposed to the intermittent high temperature operation of the internal combustion engine). This presents the need for materials that can maintain their design properties over long periods of time at high temperature. Metals to do this job are relatively costly and scarce. Ceramics appear to offer an attractive potential for both reduced cost and increased performance. It is NASA's intent to evaluate this potential fully and exploit it for use in advanced automotive engines. Considerable work has already been done in evaluating ceramics for high performance gas turbine engines. Much more is required. The special problems of ceramics for Stirling engines have yet to be completely evaluated. At this time, hydrogen containment at high temperature and pressure and high heat exchanger effectiveness appear to be the key problems for Stirling engine ceramic components. And, for automotive applications, cost effectiveness and reliability are overriding considerations. These and the other pertinent problems will be addressed in ceramics programs now being planned and initiated.

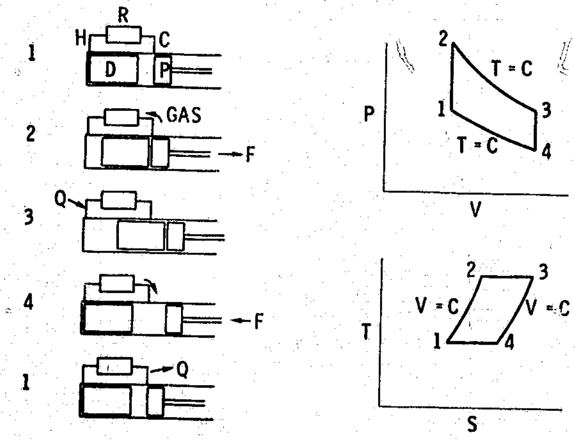

Figure 1. - Ideal Stirling cycle.

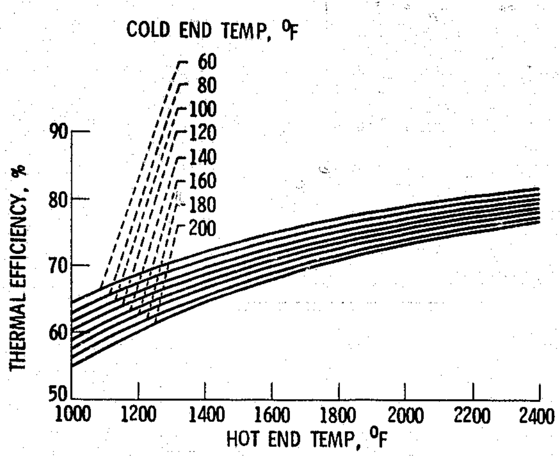

Figure 2. - Ideal Stirling engine thermal efficiency. As function of hot end temperature for various cold end temperatures.

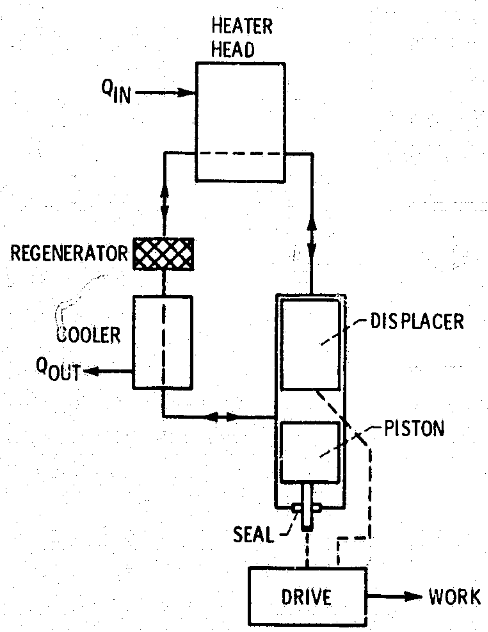

Figure 3. - Stirling cycle essential components.

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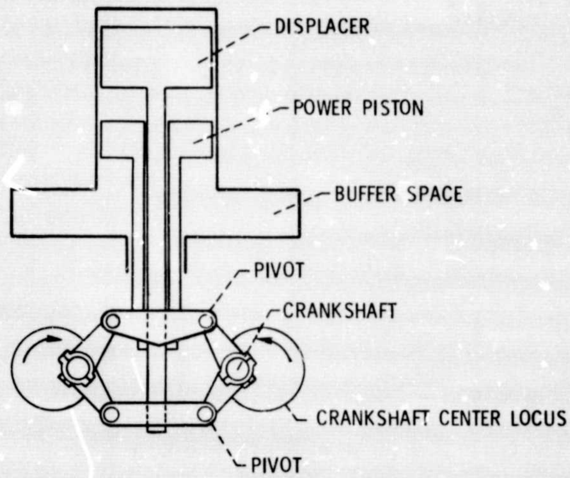

Figure 4. - Displacer Stirling.

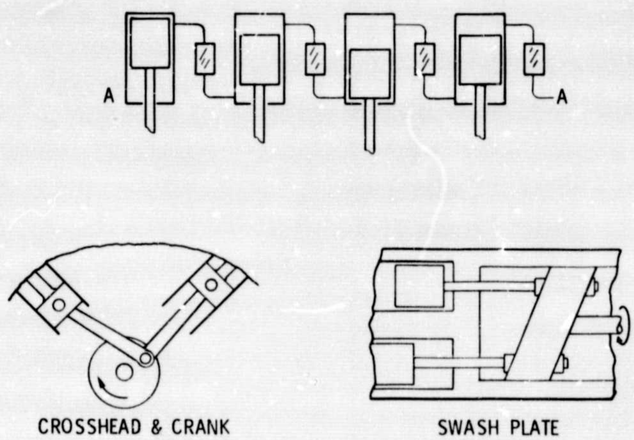

Figure 5. - Double acting Stirling.

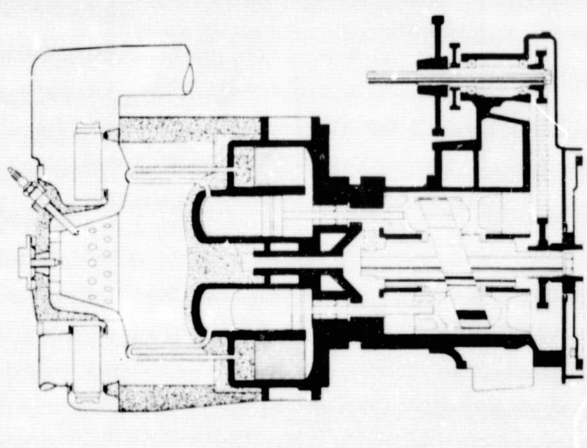

Figure 6. - Cross section of Ford Philips 170 hp Model 4-215 double acting swash plate engine.

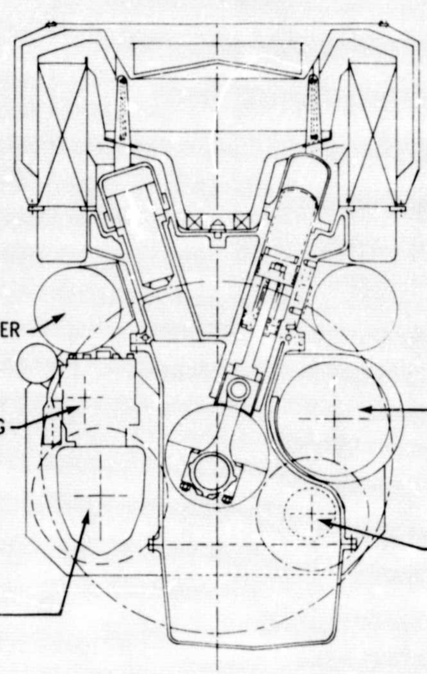

Figure 7. - Cross section of United Stirling's P-75 double acting V-4 engine.

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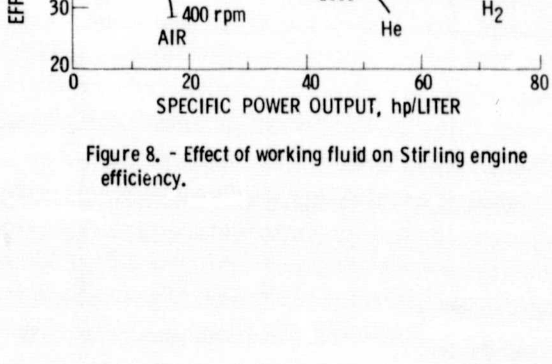

Figure 8. - Effect of working fluid on Stirling engine efficiency.

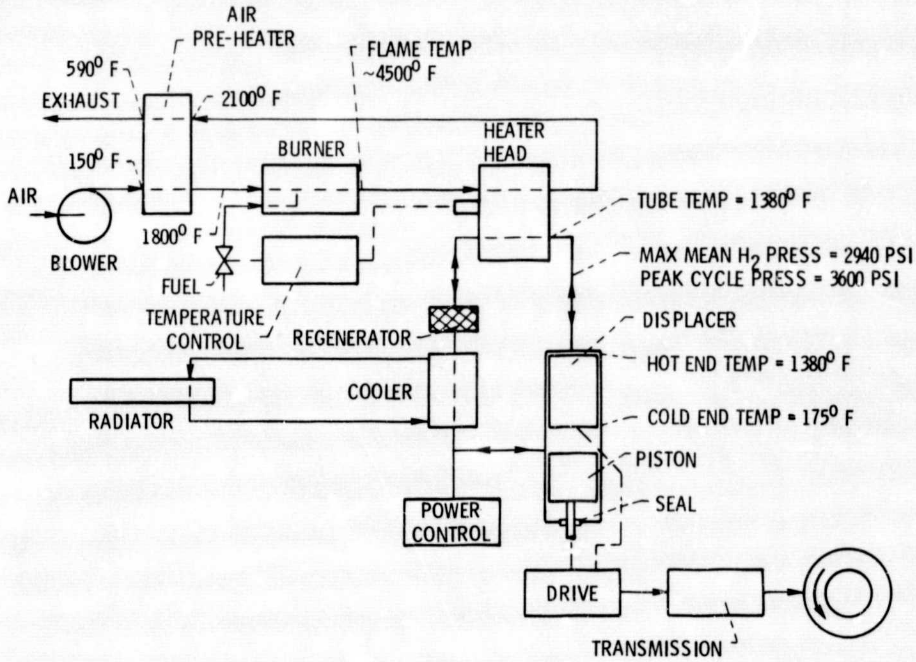

Figure 9. - Current automotive Stirling operating conditions.

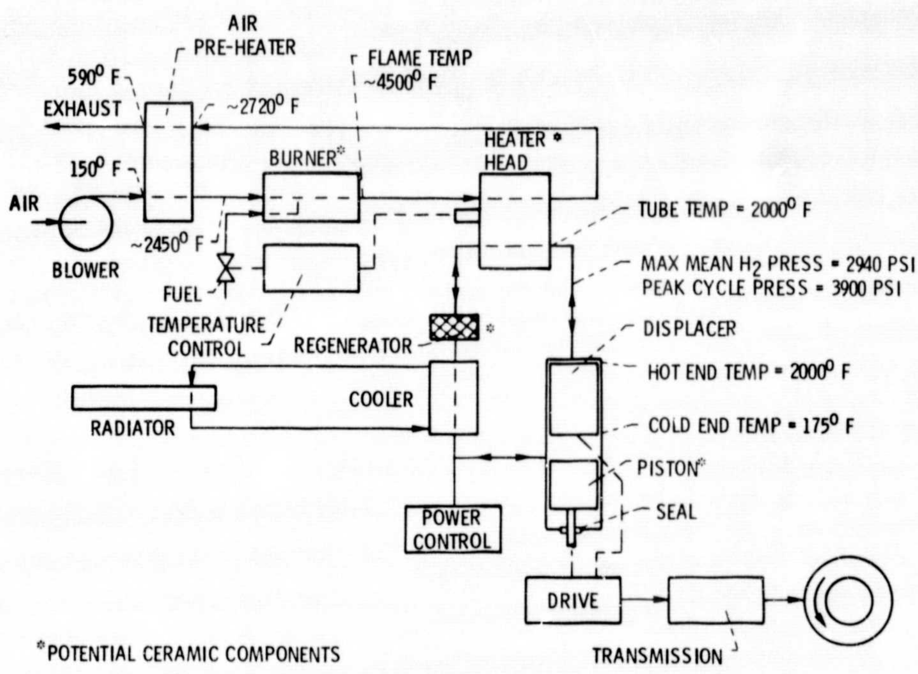

Figure 10. - Advanced automotive Stirling operating conditions.

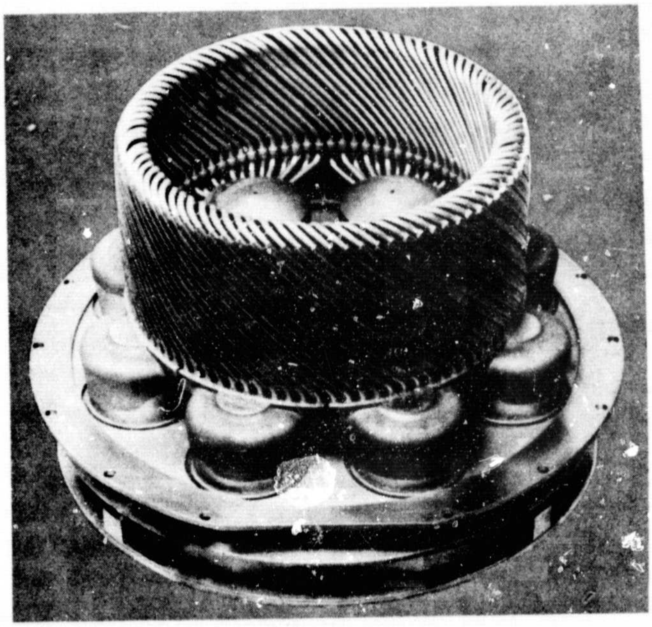

Figure 11. - Stirling engine heater head.