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Stirling Engine Supporting Research and Technology

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U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D



Prepared for
Twenty-third Automotive Technology Development
Contractors' Coordination Meeting
sponsored by U.S. Department of Energy
Dearborn, Michigan, October 21-24, 1985

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ABSTRACT

The supporting research and technology effort is intended to provide technical support to the current engine program and also to investigate advanced concepts for the next generation of Stirling engines. Technical areas represented are: seals, materials, engine experiments, combustion, system analysis, ceramics, and tribology. This paper presents a collage of more recent work in each area. Under seals, analysis and some experimental data on the effect of wear on rod seal performance is presented. The material work described concerns the effect of water content on hydrogen permeation. Results of experiments with the Philips' Advenco engine are presented. A comparison is made of two combustor nozzles, an air-atomizing and an ultrasonic atomizing nozzle. A new venture in systems analysis to provide more rigorous Stirling engine simulation is discussed. The results of hydrogen corrosion tests on silicon carbide are presented. Friction and wear tests on candidate materials for engine "hot ring" tests are discussed.

INTRODUCTION

Supporting research and technology is an effort which has gone on in parallel with the engine development since the beginning of the program. Its primary objective has been to provide support to the engine program by examining alternative approaches in key, high risk areas such as seals and materials. In addition, it has been concerned with investigation of advanced system and component technologies which could lead to reduced engine cost, improved reliability, greater fuel flexibility, and increased fuel efficiency in the next generation of Stirling engines. Figure 1 shows the areas in which we are currently working.

My intent in this paper is to provide brief views of some of the more recent work done in each area. In some cases, the work is still in progress. In others, the work is complete and reports are being written. What I am presenting is a sampling, not an exhaustive treatment. In each area, I will name some of the key people doing the work. Should you wish to know more about any given area, I suggest you contact the people actually involved.

RESEARCH AND TECHNOLOGY AREAS

SEALS - Work on the effects of wear on a conventional rod seal and the behavior of a new seal configuration was done at MTI by Martin Eusepi and Jed Walowit.

A typical pumping Leningrader (PL) rod seal (Fig. 2) has a cylindrical portion with trapezoidal cross section which serves as a static seal. Normally, the ring is designed to have about 75 μm radial interference with the rod. The conical portion provides the pumping action which assures that any oil which travels up the rod is pumped back down and does not enter the engine cycle. The analysis looked at this configuration in some detail - particularly at the inlet which is at the juncture of the conical and cylindrical portions of the seal. The analysis shows that a rather unusual condition exists at the inlet when the seal geometry and its interference with the rod are considered (Fig. 3). The seal is distorted such that, while the leading edge is in contact with the rod, several millimeters directly behind the edge are not touching the rod. This results in a very high contact pressure at the inlet edge. The calculated film thickness for this configuration is virtually nothing - substantially less than 1 μm . All this indicates that the inlet edge would wear and round off until the contact pressures had leveled out over the inlet length. When fully worn in, the pumping action of the inlet is greatly enhanced and a film thickness greater than 3 μm is calculated.

This calculated phenomenon seems to explain some of the things we have seen in actual seal testing. The apparent case of a seal wearing in can be seen in the next two Figs. 4 and 5. Hydrogen leakage rate is erratic and generally high during the first 100 hr of testing. Later, the leakage drops to a low value where it remains consistently for the rest of the testing. The same sort of change can be seen in the average friction force, which is significantly reduced after what seems to be a break-in period.

Another way of forming the inlet was examined (Fig. 6). In this case, an initially cylindrical seal is forced outward at one end with a steel ring to form a somewhat S-shaped inlet. We call this a ring-formed seal. Because of this inlet shape, the film thickness is much greater initially than for the conical inlet and is much less affected by wear. Analysis indicates a 6 μm film thickness unworn and an 8 μm thickness when worn to equilibrium. Experiments with this type of seal configuration have shown that this behavior is realistic.

MATERIALS - The primary objective of the material work has been to find or create low cost, nonstrategic alloys which can meet the demanding requirements of the Stirling engine application. To a large extent, this has been done. Later this afternoon you will hear some of the latest results of this work. Joe Stephens, Bob Titran, and Coulson Scheuermann have been the principals in this work at NASA Lewis.

Another area of materials research has been the problem of hydrogen permeation. The technique of doping the hydrogen with CO or CO₂ to form an oxide permeation barrier inside the engine was developed at NASA Lewis. Although doping worked well, we found that under certain circumstances, the protective oxide layer could be reduced by the hydrogen in the engine. Looking at this in more detail, we found that some oxygen was required in the hydrogen to avoid reduction. Eventually, all the oxygen in the hydrogen gas - whatever its source - shows up as water. This is the result of hydrogen reducing the CO, CO₂, or the protective surface oxides. This water, of course, can condense under the right conditions and reduce the amount of oxygen available in the hydrogen. We encountered this in engine testing. It was necessary to determine exactly how much water was required to prevent the oxide stripping reaction. This work was done at NASA Lewis by David Hulligan of Sverdrup Technology.

Experiments were carried out to define the effect of water content on hydrogen permeability, and by inference, the effect on the oxide coating. CG-27 tubes which had been fully oxidized internally to minimize permeability were exposed to various low oxygen content hydrogen mixtures at engine operating temperature and pressure. Total test durations were approximately 100 hr. Figure 7 shows the results in terms of permeability versus water

content. At water content above about 750 ppm, permeability is not affected. Below, permeability rises. I have assumed a boundary line at this point. The hydrogen must contain more than 750 ppm of water to maintain low hydrogen permeation. Figure 8 shows saturation concentration of water as a function of temperature. This figure indicates that enough water can be maintained in the engine under normal operating conditions to prevent oxide stripping. However, water could condense out in the hydrogen storage bottle to bring the concentration well below 750 ppm. This would eventually deplete the water in the engine and lead to oxide stripping. To be safe, it would appear that the hydrogen storage bottle would have to be maintained at about 50 °C (122 °F) or higher whenever the engine is operating.

ENGINE EXPERIMENTS - At NASA Lewis we have been testing both the Mod I engine developed on the automotive program and the Advenco engine which was developed by Philips as a means for examining advanced engine concepts. The Mod I engine testing has just begun, so I have nothing to report now. I will discuss Advenco testing briefly. Lanny Thieme is responsible for this work.

A cross section of the engine is shown in Fig. 9. The salient feature of the engine is the variable angle swashplate drive which is designed to provide power control by varying stroke. Our primary objective in these tests (Fig. 10) was to evaluate the potential benefits of stroke variation for power control and compare it with pressure control. And, in company with this, we intended to evaluate the variable angle swashplate as a means for obtaining variable stroke. In all, we wanted to provide information to Stirling R&D companies who were interested in developing engines with variable swashplate drive. Of course, as with all our engine testing, the data will be used in validating our Stirling engine computer model.

One of the results obtained in testing so far is a comparison of varying stroke and varying pressure controls at low power. Figure 11 shows brake efficiency as a function of brake power at 2000 and 3500 rpm engine speed. At 2000 rpm, there is no apparent difference between varying stroke and varying pressure. At 3500 rpm, the varying stroke approach shows some advantage at very low power. However, low power at high engine speed is not a significant operating point for the automotive application. Admittedly, this is a very small amount of data and no definitive conclusions as to the relative merit of the two control systems can be drawn. Following these tests, another drive system failure occurred while increasing stroke to 34 mm at 7 MPa and 1500 rpm. As you may know, a severe drive system failure was experienced during the last test series. Extensive repair was required. This failure was much less severe and involved basically only one crosshead, which hung up in its bore. Both failures occurred well below the design power level of 40 kW.

The engine has not been run beyond 10 kW. It is not clear whether the difficulties we have encountered may be intrinsic to the concept or are only a function of our particular design.

COMBUSTION - Several candidate combustor nozzles were tested in a special high temperature combustion facility at NASA Lewis by Jim Rollbuhler. One nozzle (Fig. 12) was a conical fuel spray type built by MTI which used atomizing air to produce a fine spray. The other (Fig. 13) was an ultrasonic nozzle built by Sono-Tek Company, which used resonating piezoelectric crystals to atomize the fuel. Both nozzles were tested at several values of inlet air temperature. I will show data for ambient temperature and for 250 °F. Figure 14 shows the difference in temperature between the combustion gas and the incoming air (an indication of the heat added by combustion) as a function of lambda. Performance of the conical nozzle is improved dramatically by the increase in inlet air temperature from ambient to 250 °F. On the other hand, performance of the ultrasonic nozzle is slightly degraded at the higher inlet temperature. This is apparently the effect of combustion heat soakback to the nozzle and the piezoelectric crystals inside. Their function is impaired at higher temperatures and they no longer provide the necessary vibration level to break up the fuel flow sufficiently. In fact, at higher temperatures the crystals can be destroyed. Although the concept is an interesting one and may offer overall system performance advantages, it is impractical for Stirling use in its present form.

SYSTEMS ANALYSIS - The primary objective of this work is to develop a more rigorous Stirling engine model. Current models tend to be very engine specific and depend heavily on "fudge factors" developed through engine testing. In general, the "fudge factors" are a way of accounting for cycle loss mechanisms and heat transfer and flow phenomena we really do not understand. A meeting was held in Washington on August 29, 1985 to discuss these problems and to develop an approach to solving them. The meeting was sponsored by DOE - in particular by the people at Oak Ridge National Laboratory. The attendees (Fig. 16) were largely from government labs with strong interest in Stirling engines - primarily for energy conservation. They were able to agree on the areas (Fig. 17) where research was most sorely needed to provide information for development of a more rigorous code. The effects pertinent to oscillating flow led the list. Other concerns were flow nonuniformities, gas spring and hysteresis effects, appendix gap losses, leakage effects, and all the complexities of regenerator behavior.

A response to some of the concerns voiced at this meeting had begun long before the meeting. Work is now in progress or will begin soon at Argonne National Laboratory, Sunpower, MTI, University of Minnesota, and Case Western Reserve University to investigate the key areas

of ignorance. A prime target is understanding of oscillating flow effects.

CERAMICS - Considering the experience with hydrogen permeation and recognizing the reduction potential of hydrogen, it seemed prudent to investigate possible hydrogen corrosion effects on structural ceramics which might be used for Stirling engines. This work is being done at NASA Lewis by Gary Hallum and Tom Herbell. Tests are being done to determine the effect of a high temperature dry hydrogen atmosphere on silicon carbide. Figure 18 shows some of the results obtained. Samples of sintered alpha silicon carbide (99.5 percent dense) were exposed to dry hydrogen at atmospheric pressure and 1300 °C for up to 500 hr. Twelve samples were tested for each data point shown and the results averaged. After 500 hr exposure, an average weight loss of 2.25 percent was experienced. Strength, in terms of modulus of rupture, dropped from over 70 ksi to under 50 ksi. Figure 19 shows the silicon carbide surface as received. It is a smooth, polished surface with pits, porosities, etc., up to about 5 µm in size. Figure 20 shows the surface after 500 hr exposure to hydrogen at 1300 °C. The grain boundaries are attacked first, with free carbon being reduced initially. Reduction of the silicon carbide grains follows. A similar result was obtained in testing at 1100 °C (Fig. 21). Of course, reaction rates and weight loss were lower (1.36 percent) at the lower temperature. Strength tests have not yet been made on these samples. I would expect some proportionate decrement in strength. Unfortunately, it was not possible to run these tests at the high pressures characteristic of automotive Stirling operation (5 to 15 MPa). Results obtained at ambient pressure must be extrapolated to operating pressures, which can be expected to result in higher erosion rates. Some preliminary tests with mullite ($3Al_2O_3 \cdot 2SiO_2$) indicate similar results. More definitive tests are planned.

The implications of these test results for ceramic Stirling engines using hydrogen are not good. Some tests will be made with wet hydrogen (1000 ppm H_2O or more). We expect this may inhibit reaction, as was the experience in the permeation barrier work. However, retention of water vapor in the system poses a potential problem and unlike the case of hydrogen permeability, hydrogen corrosion poses the potential of catastrophic failure. It is not unlikely that practical ceramic Stirling engines will have to use helium as a working fluid.

TRIBOLOGY - We are planning Mod I engine tests with specially-designed pistons using a "hot ring" (Fig. 22) to seal the appendix gap. Losses generated in the appendix gap (the volume between the piston and cylinder above the top ring) are estimated theoretically to make a substantial impact on overall engine performance. Results from tests of this configuration will be compared with those generated using a standard engine, and the benefits assessed.

A crucial aspect of the design of the "hot ring" was the identification of ring and cylinder wall materials which would have acceptable friction and wear properties in the hot area of a Stirling engine cylinder. At this time we are not trying to achieve full life capability of 3500 hr. The "hot ring" must operate effectively only long enough to obtain the necessary performance data. Friction and wear experiments on several candidate material combinations were carried out at NASA Lewis by Harold Sliney. In particular, a low friction, low wear high temperature coating developed by Sliney was evaluated as a cylinder coating. The coating is

designated PS-200 and its composition is shown in Fig. 23. Preliminary tests in helium at 25, 350, and 760 °C established the desirability of PS-200 for this application (Fig. 24). Also, Stellite 6B was then evaluated in hydrogen at the same temperatures (Fig. 25). It performed well. No thermal or chemical degradation occurred. Friction and wear were very low - of the order of magnitude that occurs for sliding surfaces that are boundary lubricated with formulated oils. PS-200 and Stellite 6B were selected for fabrication of the "hot ring" test components.

- SEALS
- MATERIALS
- ENGINE EXPERIMENTS
- COMBUSTION
- SYSTEM ANALYSIS
- CERAMICS
- TRIBOLOGY

Figure 1. - Stirling Engine supporting research and technology.

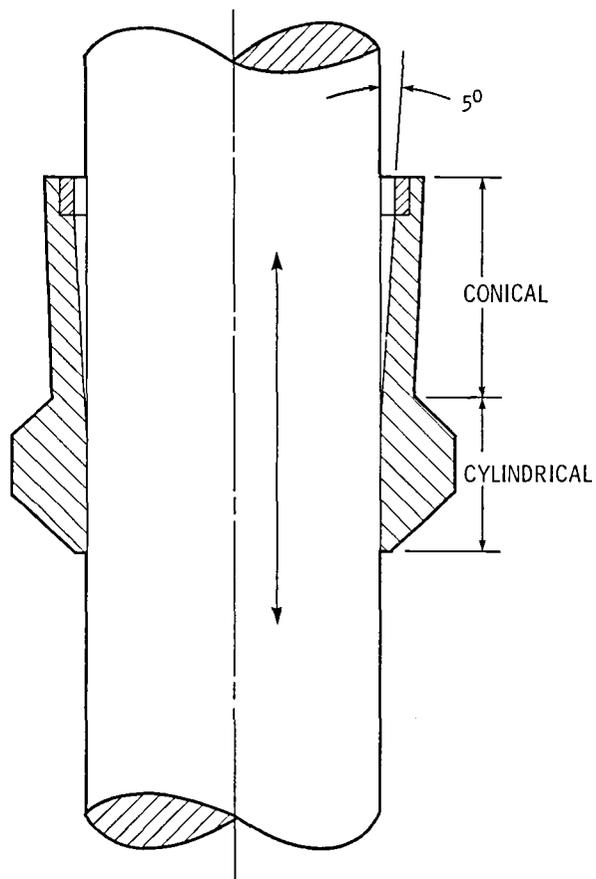


Figure 2. - Pumping Leningrader seal.

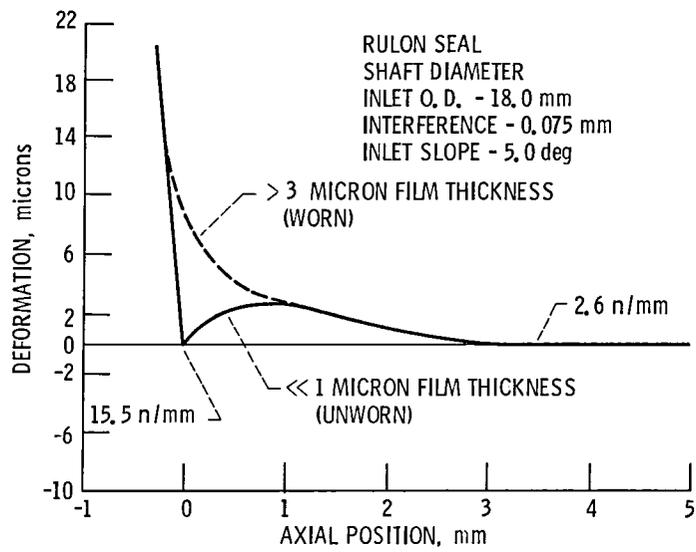


Figure 3. - Enlarged view of elastically deformed PL inlet.

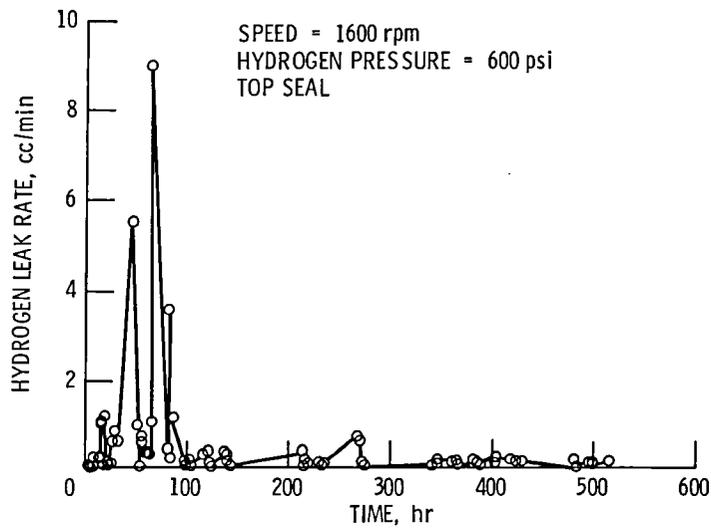


Figure 4. - Seal set no. 23.

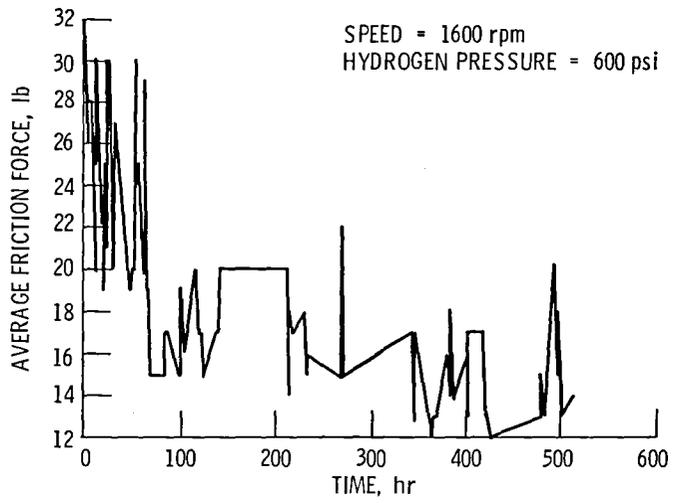
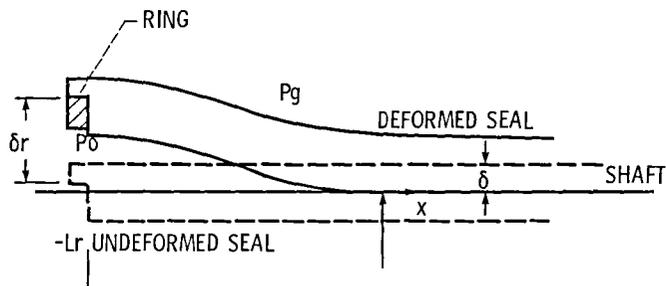


Figure 5. - Seal set no. 23.



FILM THICKNESS (UNWORN) ~6 MICRONS

FILM THICKNESS (WORN) ~8 MICRONS

Figure 6. - Ring-formed seal.

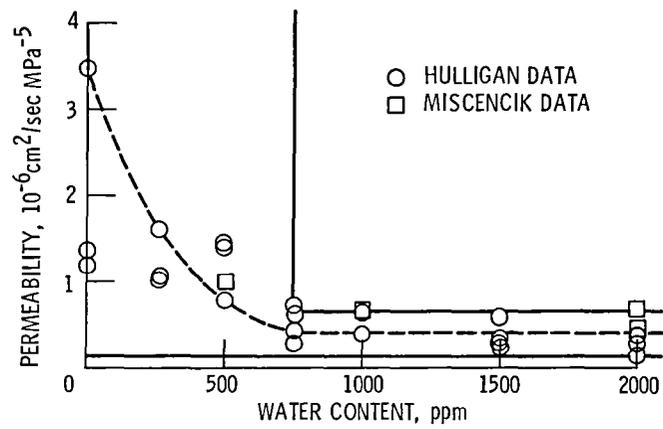


Figure 7. - Permeability vs water content.

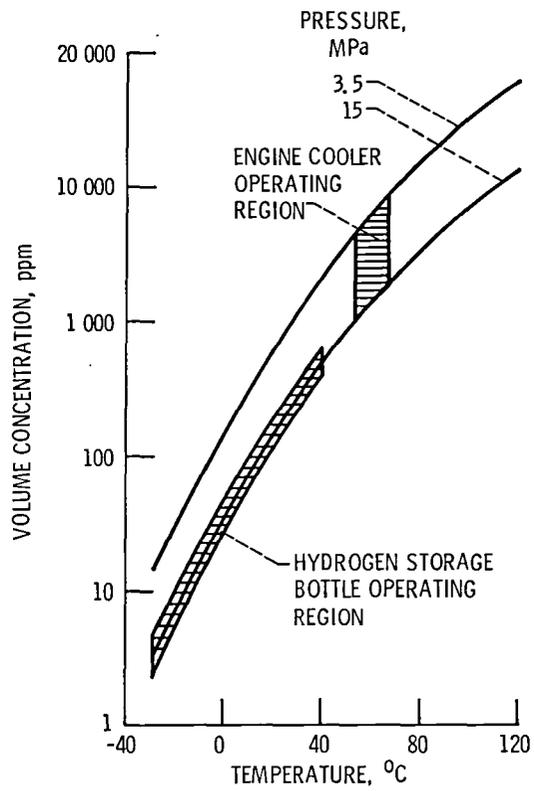


Figure 8. - Saturation concentration of water.

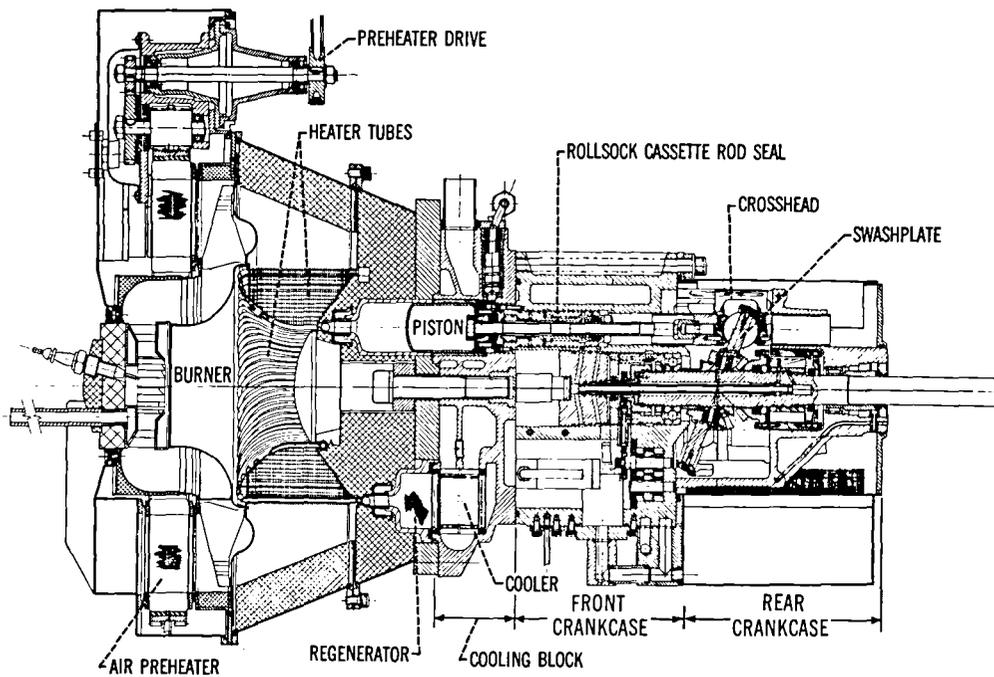


Figure 9. - Advenco Stirling-engine assembly.

- EVALUATE THE BENEFITS OF VARIABLE-STROKE CONTROL
- EVALUATE VARIABLE-ANGLE SWASHPLATE DRIVE AS A MEANS FOR OBTAINING VARIABLE STROKE
- PROVIDE INFORMATION TO STIRLING ENGINE R & D COMPANIES FOR DEVELOPMENT OF VARIABLE-ANGLE SWASHPLATE DRIVE
- OBTAIN TEST DATA OVER RANGE OF STROKES TO AID IN VALIDATION OF COMPUTER SIMULATION

Figure 10. - Advenco engine test objectives.

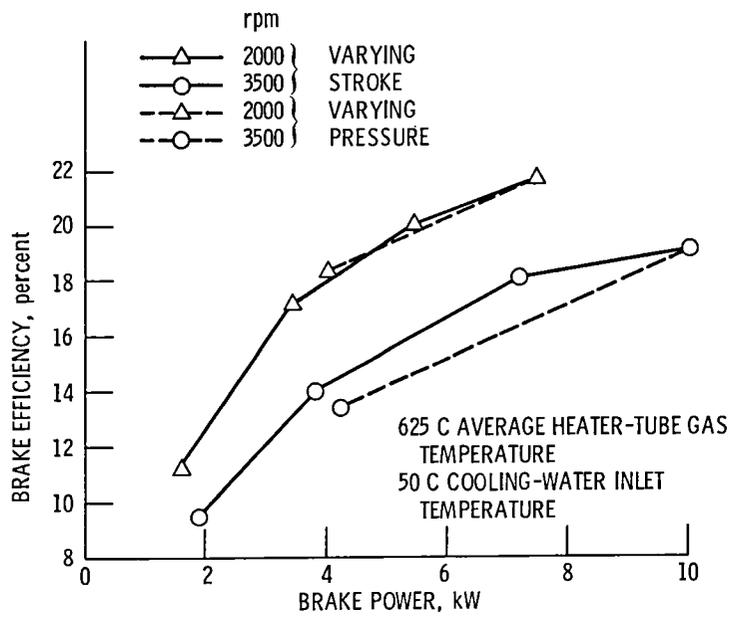


Figure 11. - Part load efficiencies-Advenco Stirling, varying stroke vs varying pressure, H₂ working fluid.

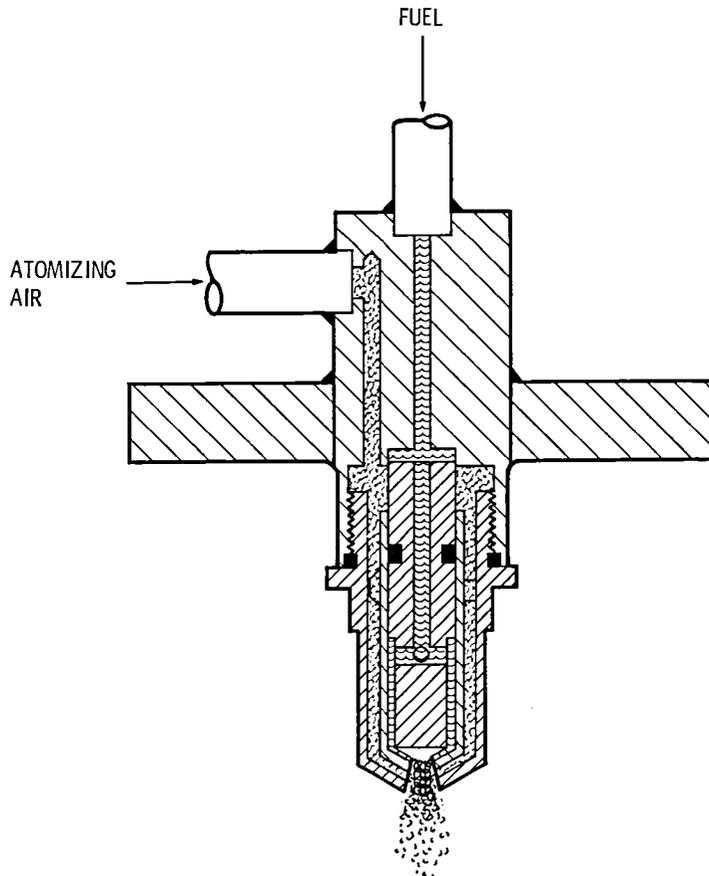


Figure 12. - Conical fuel spray nozzle.

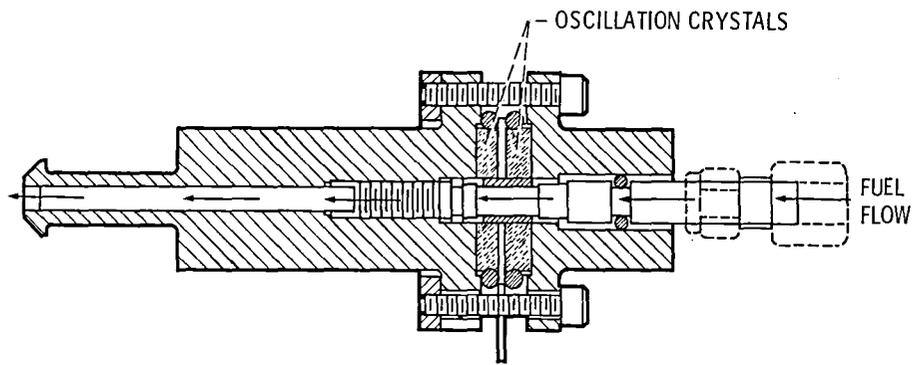


Figure 13. - Ultrasonic nozzle.

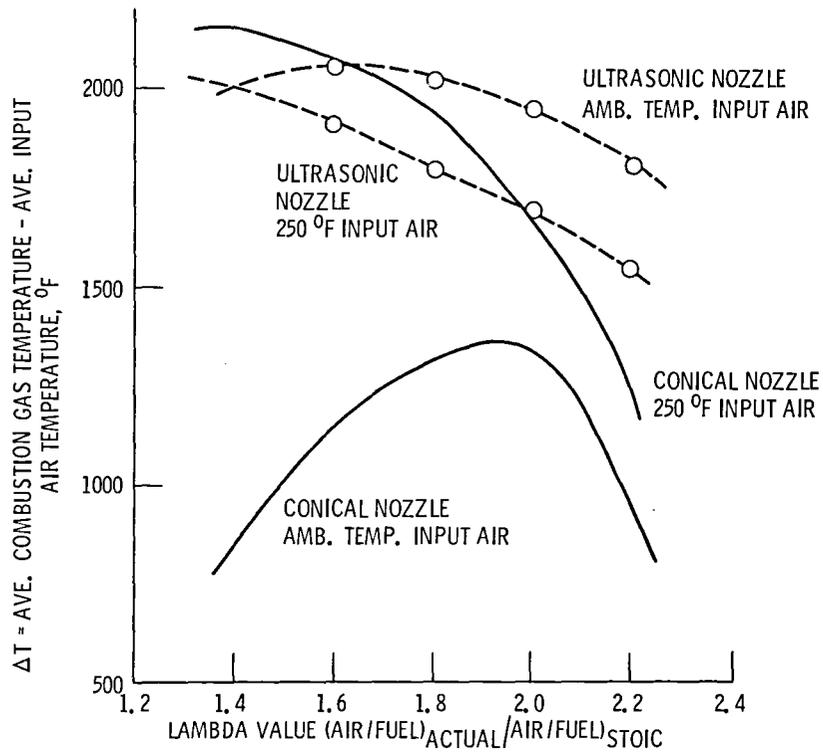


Figure 14. - Nozzle performance comparison.

- IN GENERAL, A CODE CALIBRATED FOR ONE ENGINE DOESN'T PREDICT PERFORMANCE WELL FOR ANOTHER ENGINE
- A CODE CALIBRATED TO PREDICT PERFORMANCE WELL FOR SEVERAL ENGINES CAN'T RELIABLY BE EXTRAPOLATED TO AN ENGINE WITH SIGNIFICANTLY DIFFERENT GEOMETRY
- WE DON'T HAVE A GOOD UNDERSTANDING OF THE LOSS MECHANISMS OR HEAT TRANSFER AND FLUID PHENOMENA INSIDE THE ENGINE

Figure 15. - Conclusions from attempted code validations.

ATTENDEES

MIKE KULIASHA	ORNL
FRED GRIFFIN	ORNL
NORBERTO DOMINGO	ORNL
FANG CHEN	ORNL
FRED CRESWICK	ORNL
RON FISKUM	DOE
JOHN RYAN	DOE
BOB HOLTZ	ANL
JIM DALY	ANL
ISRAEL URIELLI	UNIV. OF OHIO
JOE SMITH	MIT
BILL MARTINI	MARTINI ENGINEERING
JIM DUDENHOEFER	NASA/LeRC
ROY TEW	NASA/LeRC
JEFF SCHRIEBER	NASA/LeRC

Figure 16. - Analytical meeting sponsored by DOE/ ORNL, Washington, D. C., August 29, 1985.

- OSCILLATING FLOW EFFECTS ON ΔP AND HEAT TRANSFER IN TUBES, MATRICES AND AREA TRANSITIONS
- FLOW NON-UNIFORMITIES -- TUBE TO TUBE, REGENERATOR CROSS-SECTION, AREA TRANSITIONS
- GAS SPRING AND WORKING SPACE HYSTERESIS EFFECTS -- LOSSES DUE TO OSCILLATING PRESSURE LEVEL - AND FLOW
- APPENDIX GAP LOSSES
- LEAKAGE EFFECTS
- REGENERATOR BEHAVIOR

Figure 17. - Phenomena which need R & D for better understanding.

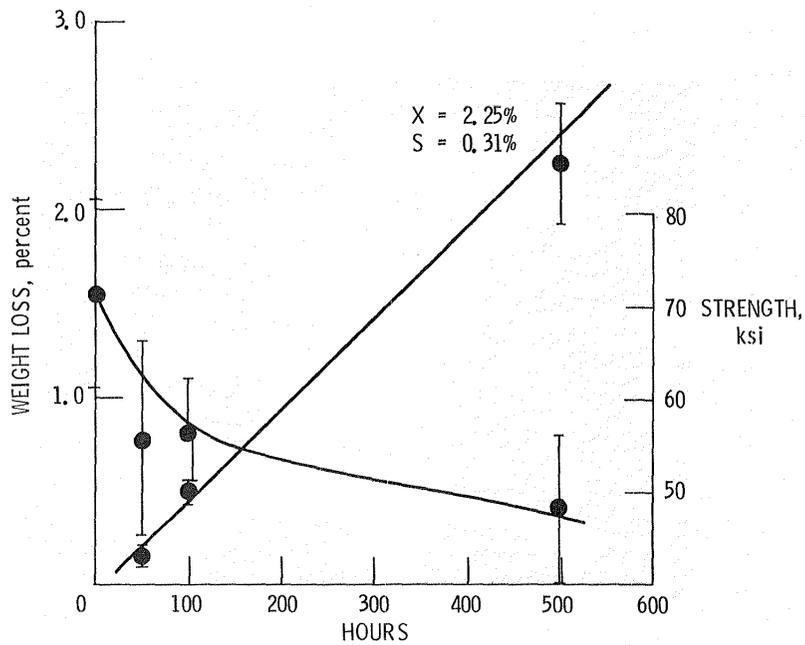


Figure 18. - Percent weight loss vs hours at 1300 °C
 Sintered alpha silicon carbide-99.5% dense in dry
 hydrogen - ~ 70 ppm water.

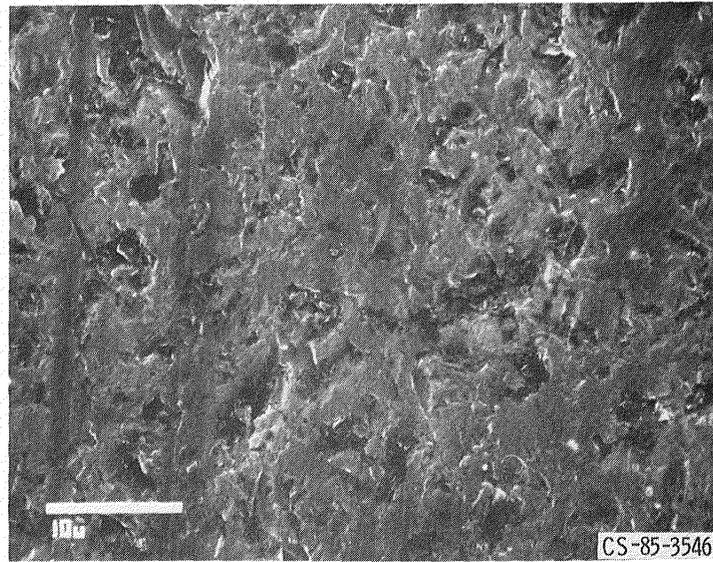


Figure 19. - Silicon carbide surface as received.

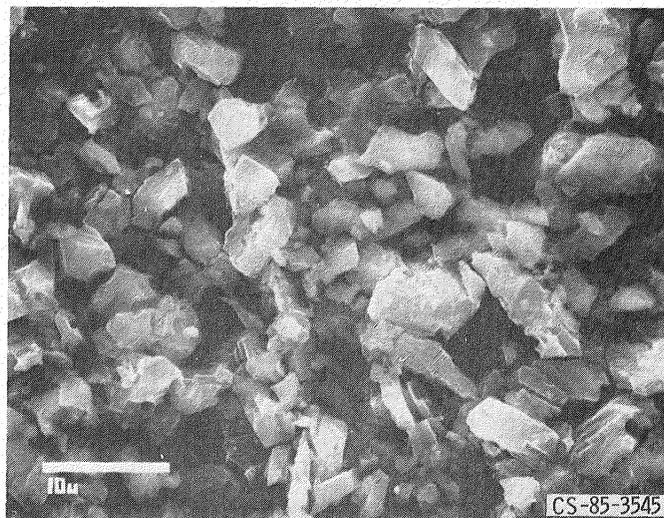


Figure 20. - Silicon carbide surface after 500 hr exposure to hydrogen at 1300 °C.

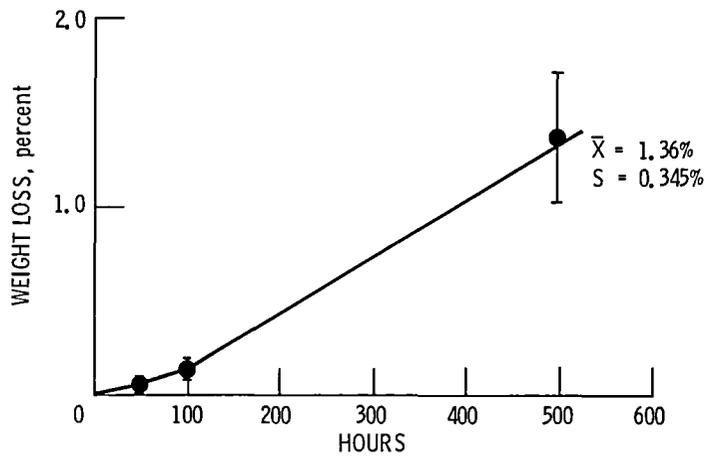


Figure 21. - Percent weight loss vs hours at 1100 °C. Sintered alpha silicon carbide - 99.5% dense in dry hydrogen - ~70 ppm water.

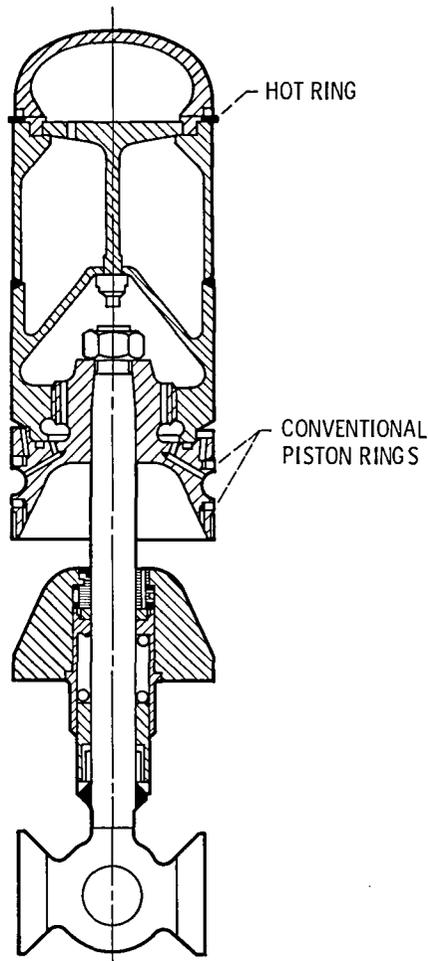


Figure 22. - Mod 1 engine piston with hot ring.

COMPONENT	COMPOSITION wt%
Cr ₃ C ₂	48
Ni Al	32
Baf ₂ /Caf ₂ EUTECTIC	10
SILVER	10

Figure 23. - Low wear coating - PS 200.

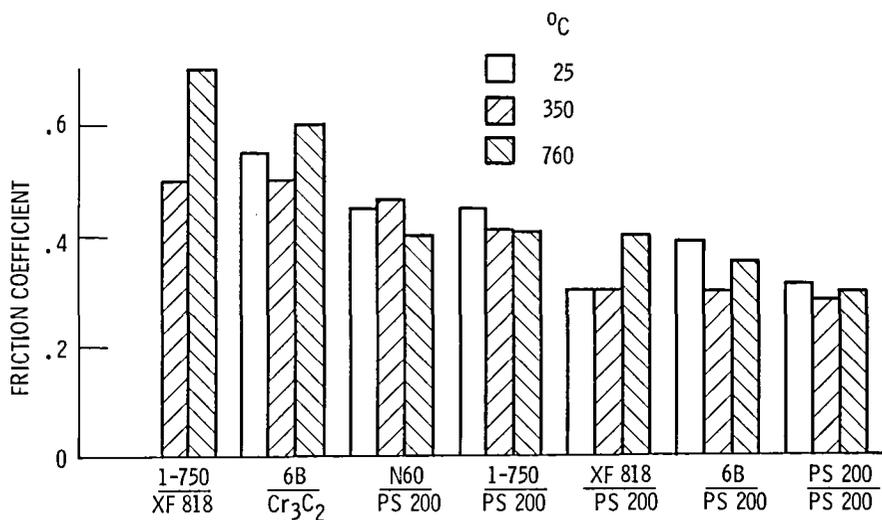


Figure 24. - Summary of friction coefficients in Helium atmosphere.

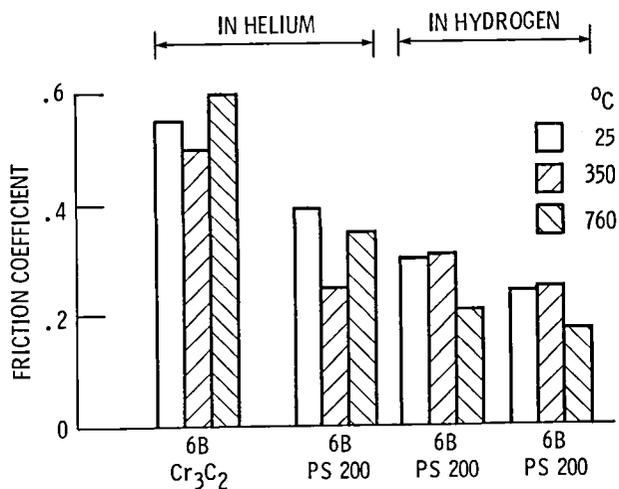


Figure 25. - Friction of stellite 6B sliding on bonded chromium carbide and on PS 200.

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