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Work performed for
U.S. DEPARTMENT OF ENERGY
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SUMMARY

A United Stirling 4-95 Stirling engine was tested without auxiliaries at the NASA Lewis Research Center. Three different regenerator configurations were tested with hydrogen. The test objectives were: (1) to obtain steady-state and dynamic engine data, including indicated power, for validation of an existing NASA Lewis computer model for that engine; and (2) to evaluate structurally the use of silicon carbide regenerators.

This paper presents comparisons of the measured brake performance, indicated mean effective pressure (IMEP), and cyclic pressure variations, with those predicted by the code.

The measured data tended to be lower than the computer code predictions. The silicon carbide foam regenerators appear to be structurally suitable but the foam matrix tested severely reduced performance.

INTRODUCTION

The work described in this paper was conducted as part of the supporting research and technology activities under the DOE/NASA Stirling Engine Highway Vehicle Systems program.

In an attempt to verify the Stirling engine computer code developed at NASA Lewis, testing was performed at NASA Lewis using a United Stirling 4-95 (P-40) engine. The primary objective of these tests was to obtain steady-state and dynamic engine data, including indicated power, for validation of this code. A secondary objective was to evaluate, structurally, the use of silicon carbide foam regenerators in a Stirling engine.

A brief description of the computer code, along with the results of the testing is included. The comparisons with the computer code include brake power and efficiency, indicated mean effective pressure (IMEP), and dynamic pressures. The structural and thermodynamic performance of the silicon carbide regenerators is also discussed.

DESCRIPTION OF COMPUTER CODE

The computer code used to model the P-40 Stirling engine was developed at NASA Lewis (ref. 1). The code is of the third-order type and calculates engine performance, pressures, and temperatures by using actual engine data input as boundary conditions. Inputs include mean cycle pressure, heater tube and cylinder metal temperatures, cooling water inlet temperature and flow, along with engine speed.

Friction factor and Nusselt number correlations used for the heater and cooler tubes are those from Kayes and London (ref. 2). Regenerator pressure drop data was obtained in the NASA Lewis steady-state flow rig with nitrogen. Regenerator heat transfer characteristics were measured in the single blow heat transfer rig at Mechanical Technology Inc. (MTI). The friction factor and heat transfer coefficients were calculated as a function of Reynolds number and input into the code (figs. 1 and 2). The code assumes that heat transfer and flow losses in the ducts connecting the heat exchangers are negligible. The code does not include the external heating system. Therefore, the measured brake efficiency was based on the energy flow into the heater head.

TEST APPARATUS AND PROCEDURE

The United Stirling 4-95 engine and test facility are the same as those used for previous testing at NASA Lewis (ref. 3). The engine is a double-acting four cylinder with U-drive. The engine with auxiliaries is rated at about 40 kW. For these tests the auxiliaries were removed from the engine and driven by electric motors. Only the lube oil pump and hydrogen compressor were powered by the engine. The engine and test facility are described in some detail in reference 3.

A NASA-designed modular electronic instrumentation system (MEIS), was used for "on-line" calculation of the indicated mean effective pressure (IMEP) in the compression space and expansion space for each thermodynamic cycle in the engine. The MEIS system was originally designed for use with internal combustion engines (ref. 4). This device was modified by adding a scanner to allow sampling of all eight working spaces with only two IMEP modules. There are several parameters available as outputs from the MEIS system. These include the average for 100 revolutions and per revolution IMEP values for each working space; real-time pressure and working space volumes for each working space; crankshaft position; and a marker indicating which thermodynamic cycle is being sampled. These outputs were recorded using the digital and analog central data systems as appropriate.

Three different regenerator configurations were tested: standard sintered stainless steel wire mesh screens, sintered wire mesh screens optimized for part-power conditions, and a combination of standard wire mesh and silicon carbide regenerators. All testing was done with hydrogen as the working fluid, an average heater tube thermocouple temperature of 720 °C and a cooling water inlet temperature of 50 °C. The engine performance was measured with each regenerator configuration over a range of mean cycle pressure from 5 to 15 MPa and speeds from 1000 to 4000 rpm. Steady-state data (speeds, pressures, temperatures, etc.) and dynamic data (engine crank angle and working space pressures) were recorded. Computer code predictions were made to compare with the test data using the measured steady-state data and regenerator test rig data as inputs.

Steady-state flow characteristics for each type of regenerator were measured with nitrogen in the NASA Lewis flow rig. For each series of engine tests, the regenerators were installed in pairs with matching flow characteristics.

STANDARD AND PART-POWER REGENERATOR TESTS

The standard regenerator test data was used as a baseline to compare the performance of the engine with the part-power regenerator test results, along with code predictions for each. The main purpose of testing the part-power regenerators was to investigate how well the code, with the appropriate modifications, was able to predict the performance for a different regenerator design. These part-power regenerators were optimized for maximum efficiency at 1500 rpm.

Brake Power

Brake power results for the standard and part-power regenerators are shown in figures 3(a) and (b) respectively. The results were close to the NASA Lewis code predictions in both cases. The highest value for the standard regenerators was 43.21 kW for the engine and 43.43 kW for that predicted from the code. Measured values were 0.1 to 7 percent lower than the predicted values. The measured power for the part-power regenerators fell slightly farther below the predicted values. The maximum measured brake power for the part-power regenerators was 42.95 kW, compared to the predicted maximum of 44.17 kW. For each of the data points tested, the measured brake power was 3 to 10 percent lower than the predicted values. The shapes of these curves are nearly identical for the measured and predicted power.

Brake Efficiency

Brake efficiency for the standard and part-power regenerators are shown in figures 4(a) and (b). The measured brake efficiency is close to, but generally tends to fall slightly below the predicted values. The measured data seems to form a distinct family of curves with the corresponding predicted data. In both cases, the measured values fell within 0.1 to 2.3 percentage points of the predicted efficiency.

IMEP

The digital and analog IMEP data agreed. The average compression space IMEP's relative to the predicted values are shown in figures 5(a) and (b). IMEP values for the expansion space are shown in figures 6(a) and (b). The IMEP values from the MEIS system followed the same trends for both sets of regenerator data. The ratios of the actual to predicted values for the various pressures and speeds are relatively consistent for both types of regenerators. The measured compression and expansion space IMEP decreased with increasing speed. Measured data for both the compression space and expansion space IMEP's were lower than predicted.

Very low IMEP values for the expansion space with the standard regenerators were observed at 15 MPa. These were not consistent with data at 5 and 10 MPa or with data from the part-power regenerators. The low values were most likely due to a malfunction of the MEIS system.

Dynamic Pressure Measurements

The measured and predicted dynamic pressures for the compression and expansion space in cycle 4 versus crank angle are shown in figures 7(a) and (b) respectively. The corresponding P-V diagrams for these pressures are also shown in figures 8(a) and (b). This data is for the part-power regenerators at 15 MPa and 2000 rpm.

The measured pressures appear to have a smaller amplitude than the predicted. By normalizing the measured pressure data to have the same amplitude and mean value as the predicted curve, it was possible to compare waveforms as well as phase relationship. The waveforms are close, but the measured data tend to have slightly lower maximum and minimum values than predicted, indicating that there is a small difference in the overall shape of the curves. A phase shift of about two crankshaft degrees is also present. The reduced amplitudes of the measured data indicate that there was some leakage in the engine possibly due to the piston rings. This is being investigated in more depth.

SILICON CARBIDE REGENERATOR TESTS

The silicon carbide regenerators were supplied by Energy Research and Generation Inc. (ERG). Because of the large variation in the silicon carbide flow characteristics, all eight regenerators could not be tested in the engine at the same time. Therefore, the regenerator configuration for the silicon carbide tests consisted of five wire screen type and three of the SiC type.

One pair of ceramic regenerators was installed in the first thermodynamic cycle. The third ceramic regenerator was paired with a standard stainless steel wire mesh screen regenerator with similar flow characteristics in the third thermodynamic cycle. Standard screen regenerators were installed in the remaining two cycles.

Although it was not possible to test with a complete matched set of ceramic regenerators in the engine, it was felt that some useful information would be gained by the tests: (1) the structural and chemical stability of the material could be evaluated in an engine environment; (2) data from the individual cycles could be compared with code predictions; and (3) the effect of using unmatched components in the engine could be observed.

Prior to testing, one regenerator was cyclic flow tested with nitrogen for 8 hr at 3 Hz to minimize the risk to the engine. The maximum pressure drop across the regenerator for this test was the same as the maximum drop expected in the engine. The material was also statically tested for 88 hr in a hydrogen environment; the apparent weight loss was small, approximately 0.03 percent

Computer code predictions were made on an individual cycle basis for one cycle having a matched pair of SiC regenerators. Due to the nature of the code, predictions could not be made for the cycle having nonhomogeneous regenerators. Therefore, brake power and brake efficiencies for this regenerator configuration could not be predicted accurately.

With mixed regenerators in the engine, the average measured heater tube temperature varied greatly between heater quadrants (fig. 9). The back row heater head temperatures corresponding to quadrant 3 with one SiC and one screen regenerator indicated the differences in the heat transfer characteristics of the materials. The back row heater tube temperature in the flow path with the silicon carbide regenerator was 652 °C compared to 721 °C for the flow path with the wire screen regenerator. Also, the silicon carbide cold connecting duct gas temperature for this cycle was about 5 °C higher than that for the wire screen duct. The SiC material was not as effective as the wire screens in transferring the heat to and from the working fluid because it was not optimized for this engine. The cycles with the SiC regenerators tended to have greater heat flow through the regenerators from the expansion space to the compression space.

The measured expansion space IMEP values at 15 MPa did follow the same trend as the code (fig. 10). In contrast with the standard and part-power regenerator tests, the measured IMEP was higher than the predicted values. The data for the cycle with the two paired silicon carbide regenerators shows a significant decrease in expansion space IMEP at the higher speeds because of the reduced heat transfer capability and the nonuniformity of the silicon carbide material.

The SiC regenerators appeared to survive engine testing with a 5 percent decrease in flow characteristics across the regenerator and a very small weight change, approximately 0.3 percent. This weight loss may have been due to a small amount of glass binder reacting with the hydrogen.

SUMMARY AND CONCLUDING REMARKS

The results of these NASA Lewis P-40 Stirling engine tests can be summarized with the following:

1. The computer code developed at NASA Lewis did predict, with reasonable accuracy, the performance of the engine throughout the range of operating points tested. In particular, the predicted brake power and brake efficiency agreed quite well with the standard and part-power regenerator data.

2. IMEP trends for the code followed the actual measured curves as observed from the MEIS system. The measured IMEP data was consistently lower than the predicted values.

3. Measured dynamic pressures are similar to those predicted but have smaller amplitude and an apparent phase shift.

4. Structurally, the silicon carbide material was capable of withstanding the varying pressure forces within the engine. However, there appears to have been a slight chemical reaction with the hydrogen working gas.

The work of verifying the NASA Lewis Stirling code is just beginning. Future testing with the Advenco (variable stroke, swashplate drive), and Mod I Stirling engines at NASA Lewis will provide further test data for code validation. The efforts with the P-40 tests has aided to establish techniques and procedures that may be used in measuring IMEP and recording dynamic data for these engines. Although the P-40 engine testing has been terminated, component flow tests and dimensional checks are in progress to ensure the accuracy of the information input to the computer code.

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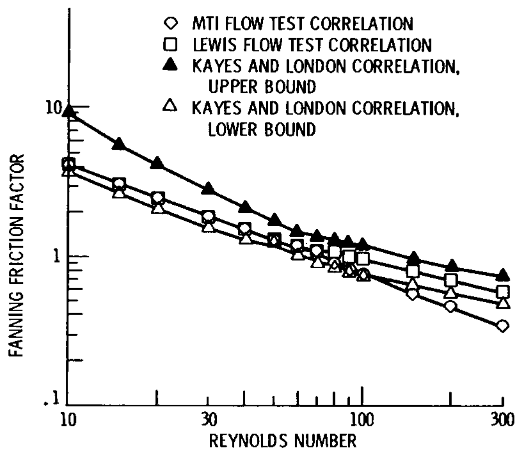


FIGURE 1. - FRICTION FACTOR VERSUS REYNOLDS NUMBER FOR STANDARD WIRE SCREEN REGENERATORS.

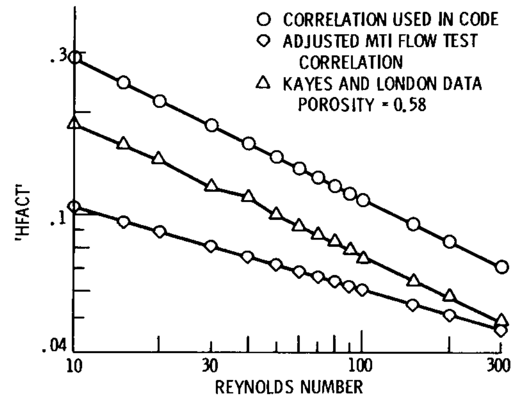
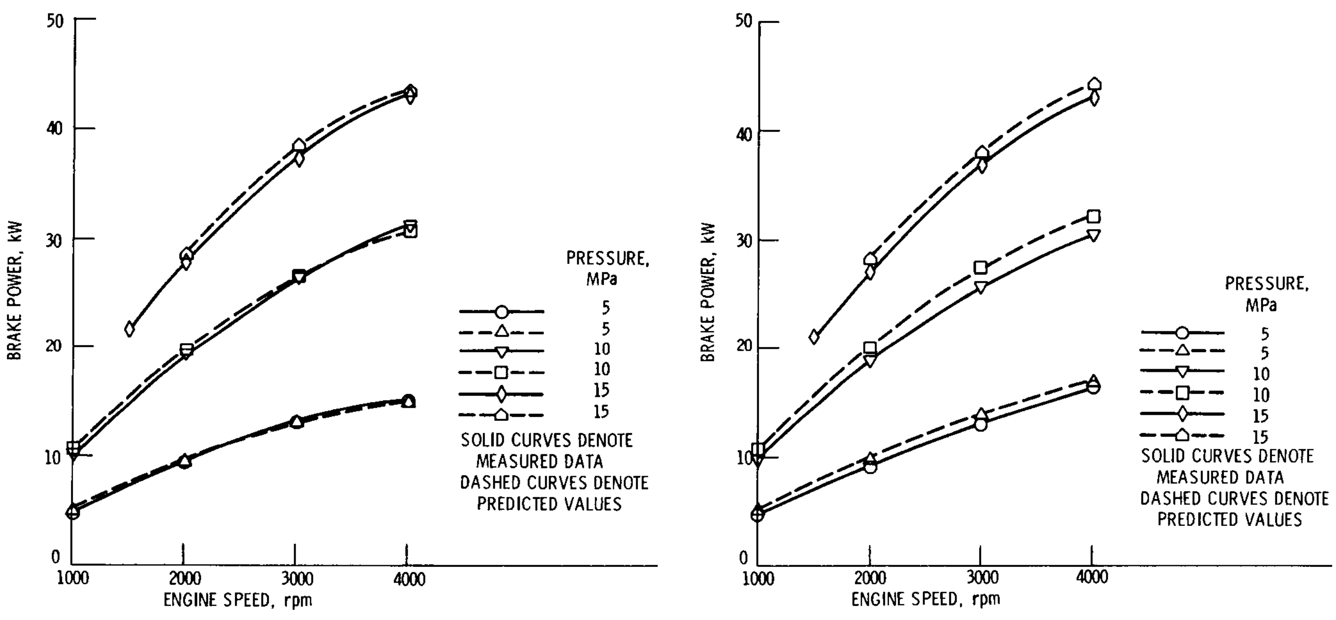


FIGURE 2. - HEAT TRANSFER COEFFICIENT.



(A) STANDARD REGENERATORS.

(B) PART-POWER REGENERATORS.

FIGURE 3. - BRAKE POWER VERSUS ENGINE SPEED.

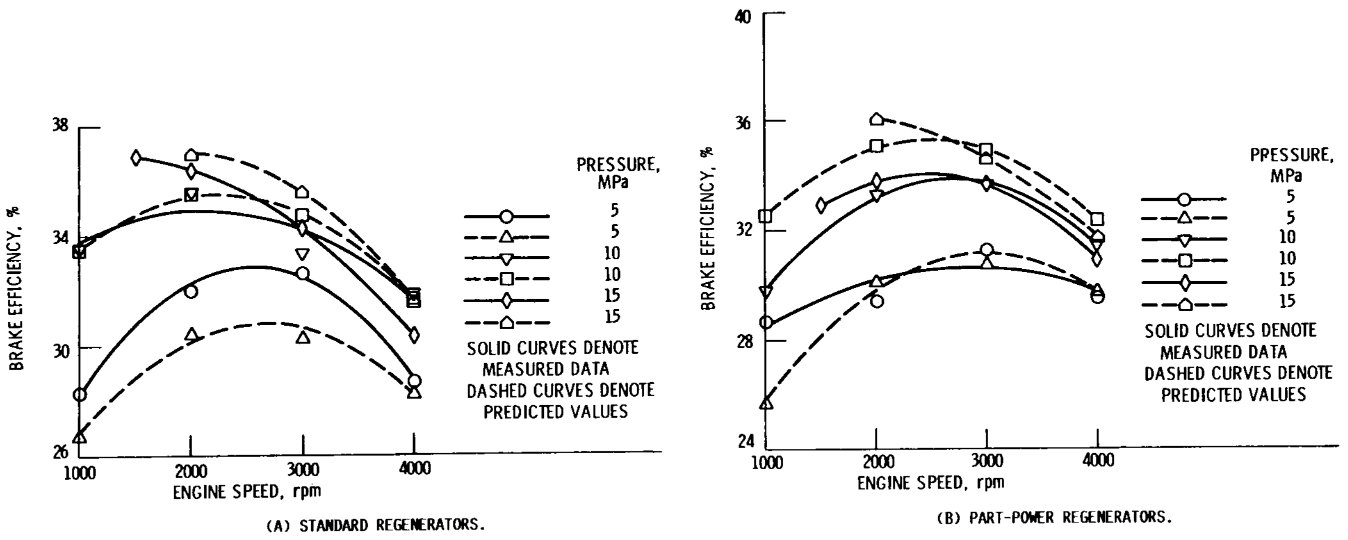


FIGURE 4. - BRAKE EFFICIENCY VERSUS ENGINE SPEED.

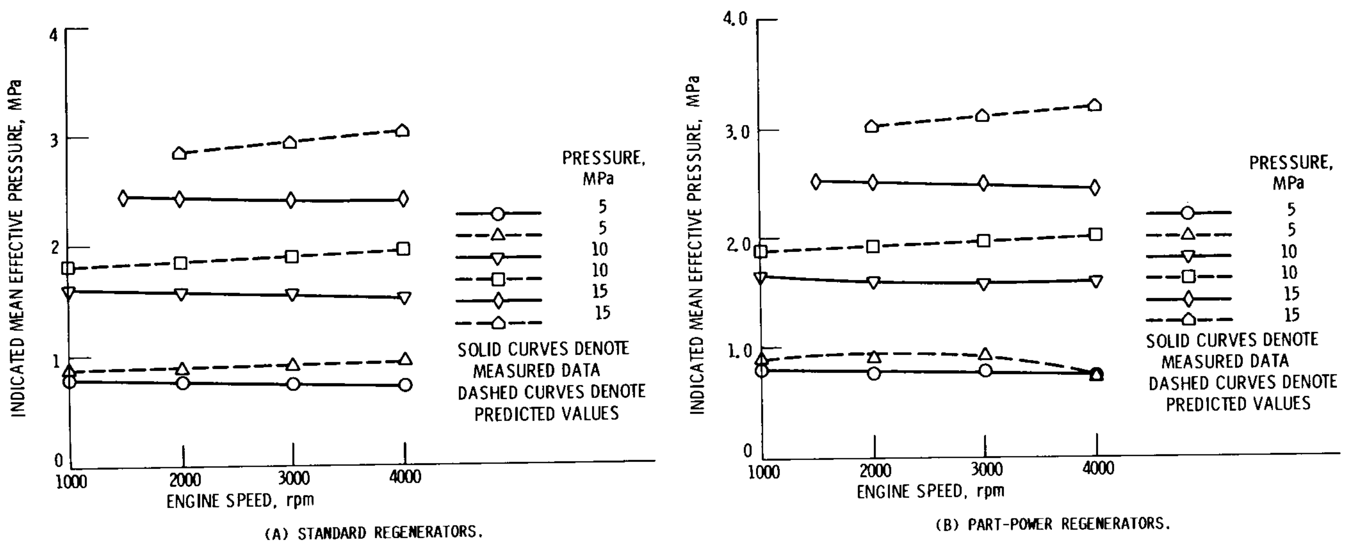
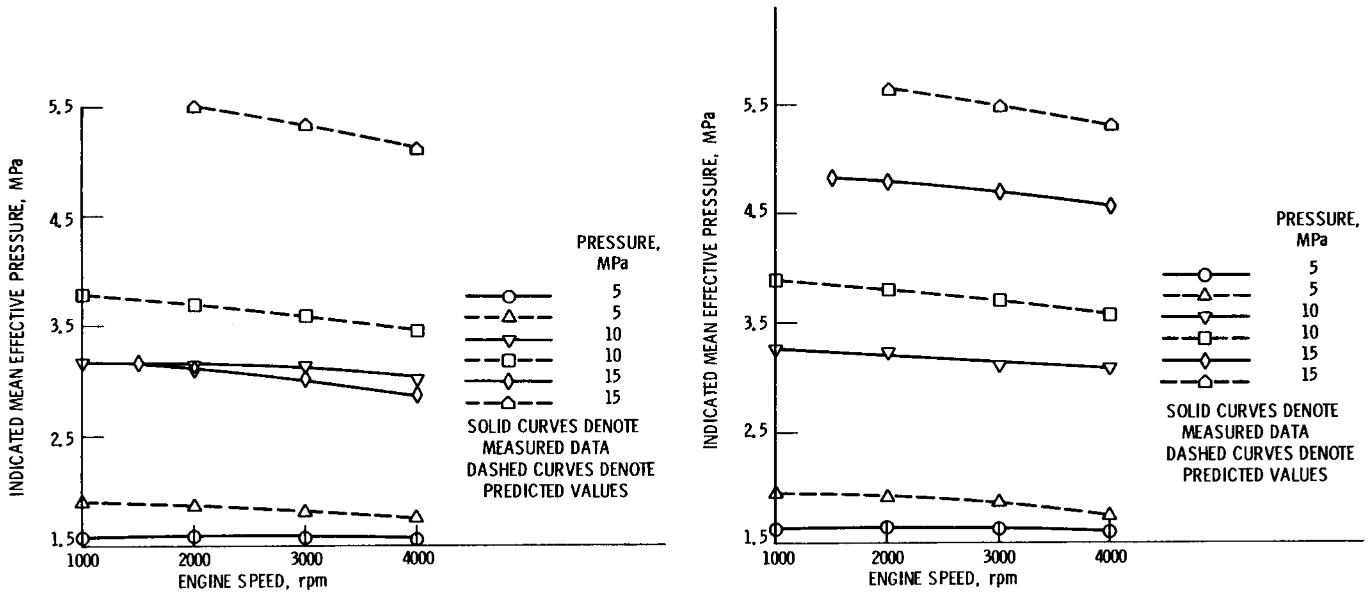


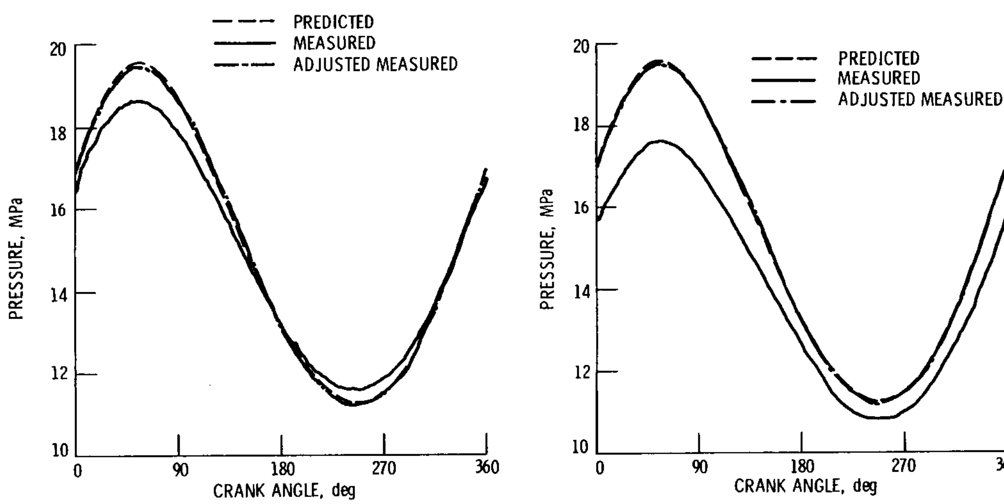
FIGURE 5. - COMPRESSION SPACE IMEP VERSUS ENGINE SPEED.



(A) STANDARD REGENERATORS.

(B) PART-POWER REGENERATORS.

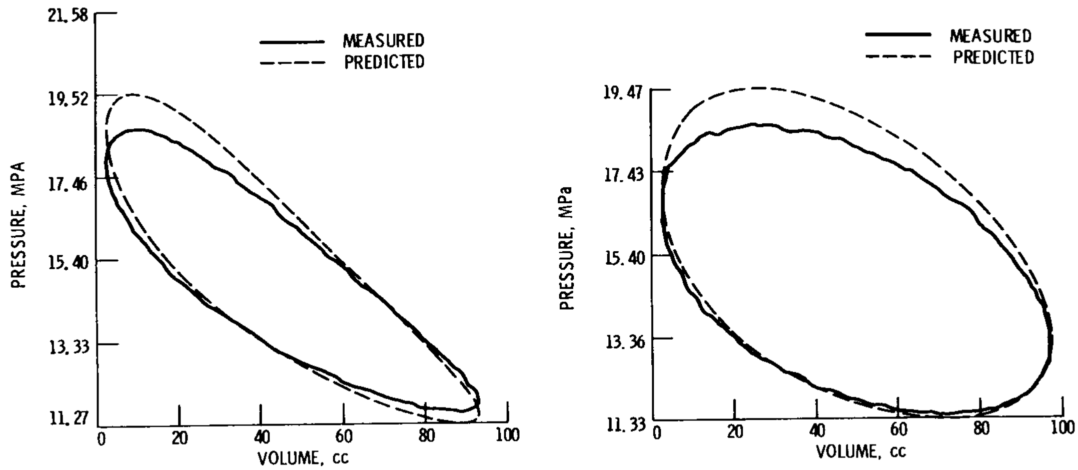
FIGURE 6. - EXPANSION SPACE IMEP VERSUS ENGINE SPEED.



(A) COMPRESSION SPACE.

(B) EXPANSION SPACE.

FIGURE 7. - CYCLE 4 DYNAMIC PRESSURES AT 15 MPA, 2000 RPM.



(A) COMPRESSION SPACE.

(B) EXPANSION SPACE.

FIGURE 8. - CYCLE 4 P-V DIAGRAM AT 15 MPA, 2000 RPM.

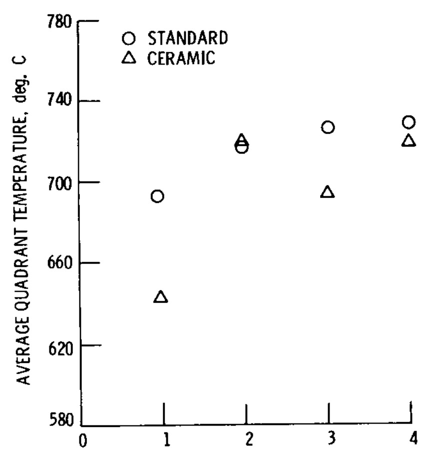


FIGURE 9. - AVERAGE SECOND ROW HEATER TUBE TEMPERATURES BY QUADRANT AT 15 MPA, 2000 RPM.

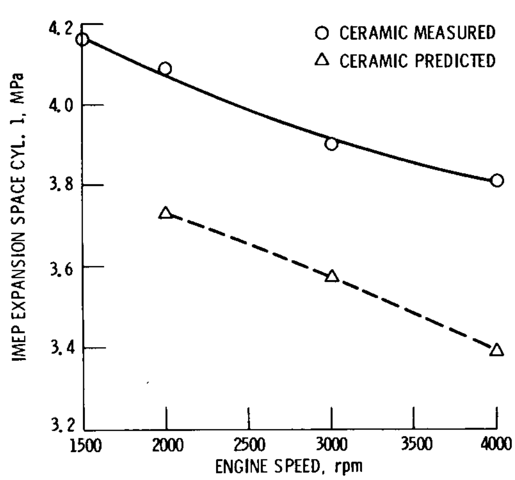


FIGURE 10. - EXPANSION SPACE IMEP FOR CYCLE 1 VERSUS ENGINE SPEED.

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