N89-12913

HIGH TEMPERATURE STRESS-STRAIN ANALYSIS

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The objectives of the high-temperature structures program are threefold: to assist in the development of analytical tools needed to improve design analyses and procedures for the efficient and accurate prediction of the nonlinear structural response of hot-section components; to aid in the calibration. validation, and evaluation of the analytical tools by comparing predictions with experimental data; and to evaluate existing as well as advanced temperature and strain measurement instrumentation. As the analytical tools, test methods, tests, instrumentation, as well as data acquisition, management, and analysis methods are developed and evaluated, a proven, integrated analysis and experiment method will result in a more accurate prediction of the cyclic life of hot section components.

TEST FACILITIES

The two test facilities at Lewis which support the development of the analytical tools and the evaluation of advanced instrumentation are the high-temperature structures laboratory and the structural component response test facility. Both of these facilities have the capability to conduct controlled thermomechanical cyclic experiments under computer control. Small cylindrical bar and tubular specimens are tested in the high-temperature structures laboratory (see fig. 1) using uniaxial and biaxial test machines. Larger specimens such as flat plates, cylinders, and combustor liner segments are tested in the structural component response test facility, which consists of two rigs that operate at atmospheric pressures. Flat-plate specimens (5 by 8 in.) are tested in the bench-top quartz lamp rig (see fig. 2); large, cylindrical (20 in. diam.) and combustor liner specimens are tested in the annular quartz lamp rig (see fig. 3). The high-temperature structures laboratory, the bench-top quartz lamp rig, and the annular quartz lamp rig are operational.

High Temperature Structures Laboratory

Two uniaxial test machines (load capacity, ±20-kip) and two recently installed biaxial test machines (±55-kip load in tension/compression and 25-kip in torsional capacity) are used in the high-temperature structures laboratory for deformation testing. Two new uniaxial test machines have been purchased to replace the existing uniaxial machines. Each of these machines is computer controlled by an S20 Data General computer. A larger Data General computer (MV/4000) is used for data storage, management, reduction, and analysis. Five-kilowatt radiofrequency induction heaters are used with the uniaxial machines, and 50-kW audiofrequency induction heaters are used with the tension/torsion test machines. Instrumentation includes high-temperature water-cooled uniaxial extensometers for measuring strains on the uniaxial test machines. Two high temperature biaxial extensometers will be tested and evaluated on the biaxial test machines. A third high-temperature biaxial extensometer has been evaluated as part of an interagency agreement with the Oak Ridge National Laboratory.

High-Temperature Laboratory Test Results and Constitutive Model Verification

One of the concerns about viscoplastic constitutive models, which for the most part are based on uniaxial isothermal test data, is their ability to accurately predict stresses and strains for cyclic thermomechanical conditions. To begin to assess this effects both in-phase and out-of-phase (temperature and strain) uniaxial nonisothermal tests have been conducted at NASA Lewis.

For illustration purposes, a comparison of out-of-phase uniaxial nonisothermal (TMD) experimental data with predictions from four unified models is shown in figure 4. The strain and temperature variations are linear (saw tooth) and 180° out-of-phase. The strain rate is 0.000046 in./in.-sec., the total strain range is ±0.3 percent, and the temperature range is 395 to 606 °C (743 to 1123 °F). The period is 295.3 sec/cycle. The temperature range selected is representative of a location on a combustor liner near the cooling holes, one of the several critical failure locations on a combustor liner. Qualitatively, the Walker and Bodner models predict reasonably well the uniaxial out-of-phase nonisothermal hysteresis response compared with the experimental data, but quantitatively, to accurately predict the shape and levels of the cyclic response, further refinements to the models are required. Additional tests are underway to expand the data base.

Bench-Top Rig

The major components of the bench-top quartz lamp rig are shown in figure 2. Four quartz lamps (6 kVA) are used to heat the plate specimens. The lamps are air cooled, and the test fixture is water cooled. A manifold provides cooling air to the top surface of the test plate. The cooling air to the plate can be preheated to 400 °F. A lamp-out detection system determines when a lamp has burned out.

A dual-loop programmable controller, a microprocessor, is used to control the power to the lamps. A specified power-time history is programmed into the microprocessor, and the cooling air temperature and flow rate are appropriately set so that when combined, the desired thermal cycle is imposed on the test plate.

Thermocouples and an infrared thermovision system are used to obtain surface temperatures on the plate. There are provisions for taking 30 thermocouple measurements. A viewport, consisting of a 5-in.-diameter quartz window, provides access for obtaining an infrared thermal image. Both thermocouple and thermal image data are obtained on the cool side of the test plate. Only thermocouple data are obtained on the hot side (facing the four quartz lamps) of the test plate. The thermocouple data provide temperatures at discrete points, while the infrared system provides detailed maps of thermal information about the test specimen.

During a test run both the facilities data (pressures. flows, power, etc) and the research data (primarily temperature) are acquired for each thermal cycle using the ESCORT II data acquisition system at Lewis. These data can be stored automatically once every second on the Amdahl computer. The software, however, does allow for varying the time at which data are taken during a thermal cycle. These data can be displayed on CRT's in the control room with about a 4-sec delay time.

To obtain real time readings of pertinent data, a strip chart recorder with nine channels is used.

The raw thermal images obtained from the infrared camera are stored on a VHS tape recorder, with the clock time superimposed on each image. Images of the test plate of from about 4 to about 1 in. in diameter (for finer resolution of temperatures) can be obtained with the zooming capability of the infrared system. Thirty thermal images are captured on tape every second. A computer system is then used to process, reduce, enhance, and analyze the transient temperature information. These data are also compared with the thermocouple data. Thermocouple data are used in the calibration of the infrared system.

Bench Top Rig Test Results

Some of the salient results of tests conducted on a Hastelloy-X flat plate, with dimensions of 8 by 5 by 0.05 in. are as follows: The plate temperatures are very repeatable from cycle to cycle. A 20-sec ramp time from low to peak temperature on the plate was achieved. The nominal life of the quartz lamps is 500 thermal cycles. Actual lamp life, however, varies depending on power settings (maximum or minimum, the hold times at those settings, and the ramp rates for a given thermal cycle. The infrared thermovision system provides a qualitative measure (maps) and, in some cases, a quantitative measure of transient surface temperatures. The experience, data, and other information obtained from the bench-top rig tests have benefited the tests conducted on the annular quartz lamp rig.

As an example of how the bench-top rig was used to evaluate a high-temperature strain measurement system for possible future use on the annular rig, a cooperative effort with UTRC and Lewis instrumentation personnel was undertaken to evaluate a laser specklegram system. The objective of the research program was to perform a demonstration test of laser speckle photographs by measuring strain on a flat plate. The demonstration test was a success; however, the inability to measure strain in some cases and accuracy of strain measurements in other cases were less than hoped for, but the system has potential. Preliminary temperature and structural analyses of the flat plate tested are underway and prediction of strains in the plate will be compared with the experimental data.

Another technique, high resolution photography, was employed to measure strain on plates in the bench rig. For this technique, a grid system of 0.5 in. squares was marked on the plate with a scribe or painted on with high temperature paint as shown in figure 5. The grid system is for the convenience of measuring strain, as strain can be measured between any two points which can be visually identified in the photograph. Technical Pan 2415 film was used which has a nominal resolution of 400 lines/mm. This would allow resolution of 0.0001 in. at 1X magnification. Photographs are made of the test plate in the original condition and at subsequent temperatures during the heating cycle.

In-plane displacements are determined by measuring the change in dimensions of the grid squares between two temperatures. A machinists microscope was used to measure these dimensions. The instrument used in this case reads out to 0.00005 in. With this system, measurements to 0.001 in. appear feasible and better accuracy is theoretically possible.

Out-of-plane distortion can be measured by placing boron fibers in front of the test plate (in the case on the quartz window) and using a single flash to illuminate the plate. A sharp shadow is cast on the plate from the boron fiber. Lateral displacement of the shadow from one test condition to another indicates out-of-plane displacement of the test plate. The displacement is a function of the tangent of the angle of illumination. It may be noted that a curved plate gives a curved shadow.

Preliminary results comparing measured and calculated strains are

Strain direction	Comparison
X	From the twice calculated value up to 1 order of magnitude larger
Y	Close to calculated value and up to same order of magnitude

These results are encouraging and with refinements in measuring and computer codes, closer results may be expected.

Annular Rig

Figure 3 shows the annular quartz lamp rig installation and its major components. This rig is being operated under a cooperative agreement with Pratt & Whitney Aircraft (P&WA). G. Pfeifer and D. Sullivan are the P&WA coinvestigators on this project.

The quartz lamp heating system used to cyclically heat a test liner is shown in figure 6. One-hundred-twelve 6-kVA lamps configured circumferentially in 16 sectors, each having 7 lamps, are used to heat a 20-in.-diameter test liner. This system, in addition to drawing up to 672 kVA of 480-V power, requires 3.5 lb/sec of ambient temperature air at 5 psig, 1.5 lb/sec of ambient temperature air at 1 psig. and 80 gal/min of specially treated water for cooling the rig.

A natural-gas and air mixture is burned in a combustor can upstream of the test section to provide preheated cooling air to the test liner. Cooling air temperatures of from 400 to 600 °F can be obtained by varying the fuel/air mixture ratio. The cooling airflow rate is variable from about 4.0 to 7.5 lb/sec at 35 psig. Both the cooling-air temperature and flow rate can be varied to obtain the desired cyclic temperatures on the test liner.

The annular rig has six 5-in.-diameter viewports, three of which are spaced at 120° apart and are used to view the middle section of the test liner. The other three, also spaced at 120° apart, are used to view the upstream portion of the liner and its attachment piece. These windows are rotated 45° from the liner windows. The quartz windows are air and water cooled. Through these windows television cameras and the infrared camera are used to monitor and take temperature measurements on the liner. There are also provisions for having 140 thermocouples on the test liner.

The dual loop programmable controller system, the ESCORT II data acquisition system, and the infrared thermovision system, described previously for the bench-top rig application, are the same systems used for the annular rig. However, a more sophisticated lamp out detection system is used on the annular rig. It consists of an IBM PC AT and other equipment to monitor voltages and current to each of the SCR's, as well as to the 16 lamp sectors. Results are displayed on the computer screen, and if an upper or lower limit is exceeded, an alarm is sounded.

Annular Rig Test Results

A power versus time curve was determined that simulated an actual engine mission thermal cycle on the test liner, a stacked-ring louver configuration fabricated from Hastelloy-X and supplied by P&WA.. The power history for the thermal cycle is shown in figure 7. The cyclic test conditions were a coolant flow rate of 5.5 lb/sec, a coolant flow temperature of 600 °F, a minimum power of 38 percent (actual), and a maximum power of 83 percent (actual). The total thermal cycle time was 2.2 minutes. The time was broken up into a 6-sec ramp up time from minimum to maximum power, a 60-sec hold time at maximum power, a 6-sec ramp down time. and a 60-sec hold time at minimum power. This power history was programmed into the dual-loop programmable controller. The controller was run in the set-point control mode.

Of the large quality thermocouple and IR temperature data base obtained, some typical thermocouple data are shown in figures 8 and 9. The data shown are the hot side and cool-side temperatures at maximum and minimum power. Figure 10 shows transient temperature response at three locations on louver 5 of the liner. For the 6-sec ramp up in power there was about a 25-sec time required for the liner temperature to reach equilibrium conditions, or about a 20-sec lag between the time to maximum power and stable peak liner temperatures. The 6-sec ram down-time results in an almost mirror image of the ramp up in terms of time for the liner to reach stable minimum temperatures. The ramp up and the ramp down times simulate the ascent and descent phases of an engine mission cycle, and the hold time represents cruise conditions, where the interaction of creep and plasticity occur simultaneously. These temperatures are used in the heat-transfer/structural analysis of the liner.

The infrared thermovision system is used to obtain a more detailed map of the cool-side liner temperatures. Figure 11 is an example of the IR data obtained. plotted are axial temperatures on the louver No. 4. Only the temperatures are shown for the maximum and minimum powers at steady-state conditions of the thermal cycle. Thermocouple data are also shown for comparison.With this system over 10^7 temperature measurements are obtained for each thermal cycle.

In addition to the temperature data obtained, dimensional measurements were made on the original liner and at several points during testing. Photographs were also taken which show the relative distortion of the liner as the test progressed. A plot of the relative radial displacement measurements on louver 5 at 300, 742, and 1800 cycles is shown in figure 12. Obtaining a set of these measurements is tedious and required several weeks of downtime for the test program. For this reason and to add to the overall information, photographs were made of the louvers between runs.

A composite photograph of the inside louvers of the liner after 1031 cycles is shown in figure 13. Very little distortion was evident and no cracks were found. Because of the minimal distortion of the liner, it was decided to increase the strain by increasing the maximum temperature reached in the test cycle. The maximum power setting for the test cycle was increased from 83% to 87%. This raised the overall thermocouple reading 70 to 1610 °F with one hot spot temperature jumping 180 to 1890 °F. As a result, the liner distortion was accelerated.

After 1603 cycles a crack developed in the liner as shown in figure 14. This crack occurred in a hot spot and was also in the vicinity of the weld on that louver. The hot spot developed because of closure of several cooling holes as shown in Figure 15. There was no thermocouple right at the hot spot but the maximum temperature was at least 1720 °F and could have been over 1890 °F.

A composite photograph of the liner after 1782 cycles is shown in Figure 16. This shows that most of the distortion occurs in louvers 4, 5, 6, and 7 in the 1 80° and 270° views. The top (0°) and 90° views show much less distortion.

The effect of this distortion on the air flow through the liner can be seen in figure 17. The distortion partially blocks the flow of air from the holes on the exterior of the liner. This results in hot spots and the attendant distortion.

The test program on this liner was terminated after 1782 cycles because the distortion of the louvers became severe enough to contact the frame of one of the quartz lamp banks. Measurements of the crack from the initial observation at 1603 cycles to 1728 cycles indicated 2% increase in length.

The distortion of the louvers is not atypical of liners run in service. The distortion shows some symmetry to the heat pattern of the lamps in that the peaks of distortion are at the longitudinal center of a lamp bank where the maximum heat flux occurred. It should be noted that a distortion peak was not formed at every bank of lamps.

Of the 112 original quartz lamps, only a few remained after the testing. Criteria for lamp replacement were excessive darkening of the glass envelope or sagging filaments. Based on the cumulative failures to date, a statistical analysis predicts a lamp half life of 65 hours.

TEST LINER ANALYSIS

The liner surface temperature measurements obtained from the thermocouples and the infrared thermovision system were used first to obtain the film coefficients on the cool and hot surfaces. Based on these coefficients, a heat-transfer analysis was performed using MARC, a general-purpose, nonlinear, finite-element heat-transfer and structural-analysis program. A two-dimensional. axisymmetric, transient, heat-transfer analysis of the louver was performed. Eight-node, heat-transfer finite elements were used in the analysis, and 107 elements and 522 nodes were used to model the louver. Comparisons between prediction and experimental data shows good agreement at the maximum power level, but at the lower power level the prediction was not quite as good.

The MARC program produces a tape which contains the temperature information The temperatures (or thermal loads) are then input to the structural-analysis program. The MARC program was also used to perform the structural analysis. A two-dimensional axisymmetric transient structural analysis of the louver was performed. Eight-node-structure finite elements were used in the analysis. The stress model was identical to the heat-transfer model. Symmetric boundary conditions were assumed at the ends of the louver. Walker's viscoplastic constitutive model was used in the analysis. This viscoplastic model, and others like it, accounts for the interaction between creep and plasticity, strain rate effects, time-independent and time-dependent effects, and other effects critical to a combustor-liner analysis and design.

Figure 18 shows hysteresis loops of hoop stress versus hoop strain for three locations on the liner: seam weld, lip, and knuckle. The data show a wide variation in strains, strain ranges, strain rates, as well as stresses and stress ranges. These data could be used to identify critical failure locations in a liner and provide for better damage or fatigue/failure predictions.

CONCLUSIONS

The high temperature structures laboratory is operational. A large quality data base on Hastelloy-X has been generated. The bench-top quartz lamp rig and the annular quartz lamp rig are also operational. Tests of a conventional sheet metal louver liner in the annular rig have been completed. Almost 1800 thermal cycles were accumulated on the liner before liner testing was terminated due to gross distortion on the liner. Liner temperatures were stable and repeatable not only for each thermal cycle but from test to test. Observed liner distortion simulated very well that of an in-service liner. By varying test conditions the distortion to the liner was accelerated. Cracking on the liner occurred at a seam weld between 1500 and 1600 thermal cycles. The cracks on the liner did not grow appreciably during the additional 200 or so thermal cycles. A large quality data base consisting of measured liner temperatures and displacements has been obtained. The temperature data obtained from thermocouples and the infrared camera are being analyzed and used in a preliminary heat-transfer analysis of the liner. Preliminary nonlinear, structural analyses are also being performed using as input the thermal loads obtained from the thermal analyses. A UTRC laser specklegram system and a high resolution camera system for measuring strain in a flat plate have been evaluated using the bench-top rig. The data are being reduced and analyzed. Preliminary 2-D thermal and nonlinear structural analyses of the test plate are being performed. In conclusion, both the annular and bench-top quartz lamp rigs are viable tools for high temperature cyclic structural testing of combustor liner segments and flat plates.

FUTURE RESEARCH

An advanced segmented combustor liner is being instrumented with 140 thermocouples. Testing of this liner in the annular rig should begin by December. Plans are also to test straight cylindrical specimens. Advanced, high-temperature strain gages and a high resolution camera system will continue to be evaluated on the bench-top rig. High-temperature torsional testing on a biaxial test machine is scheduled to begin in early November. A three-dimensional thermal/structural analysis of the conventional test liner will soon be underway.

HIGH-TEMPERATURE FATIGUE AND STRUCTURES LABORATORY

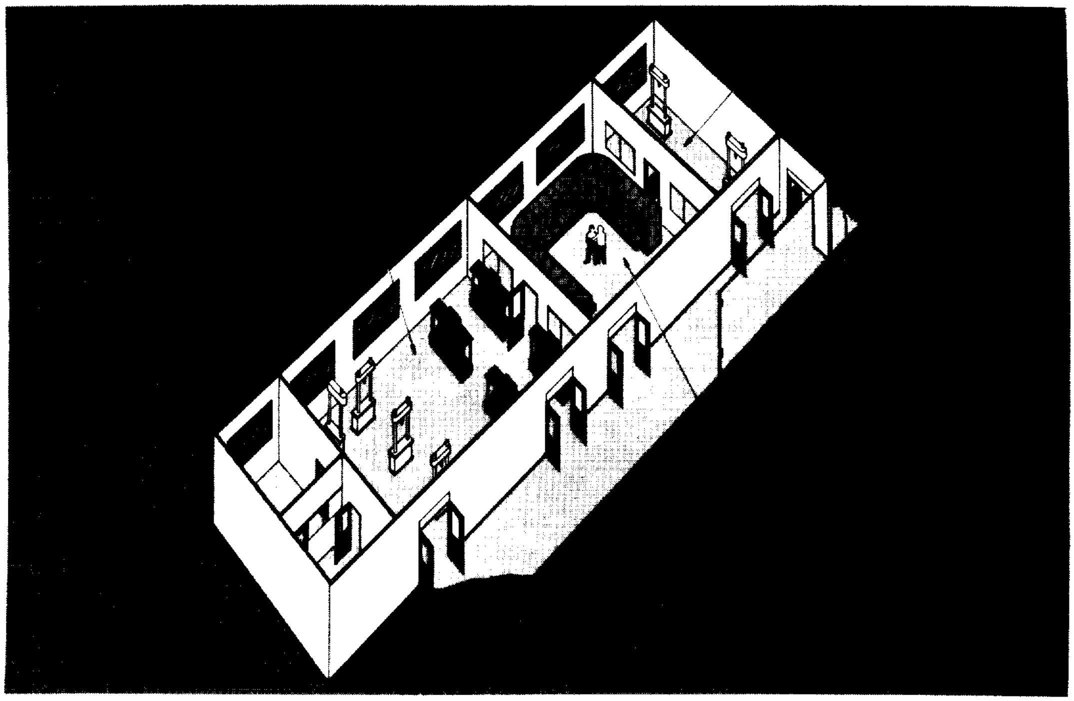

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Figure 1

BENCH-TOP QUARTZ LAMP RIG

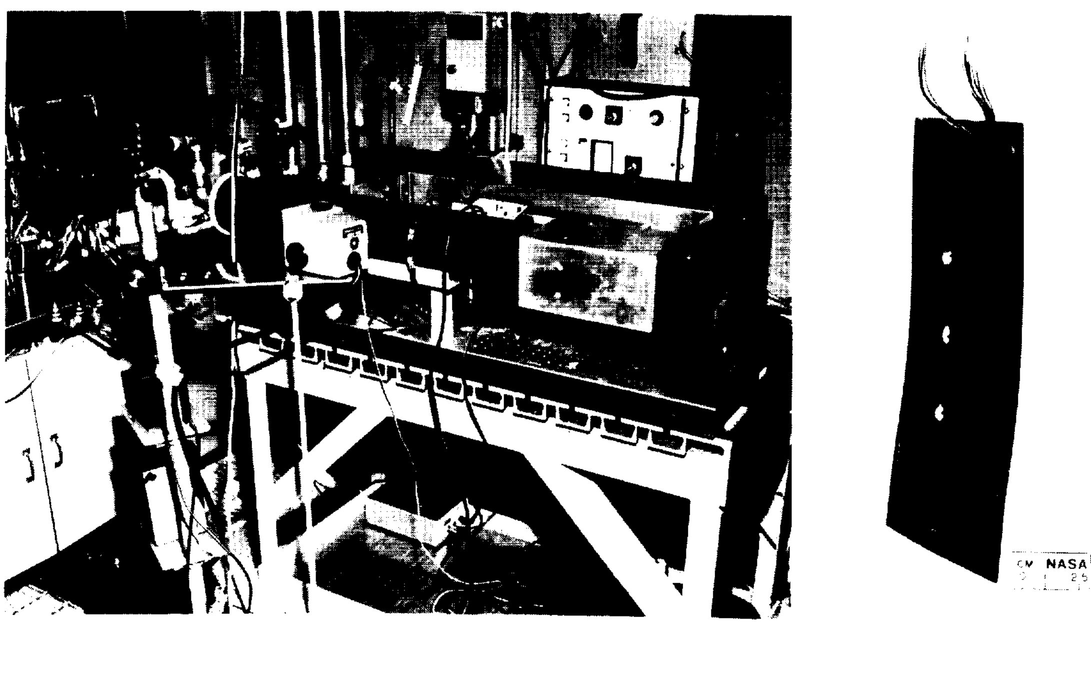
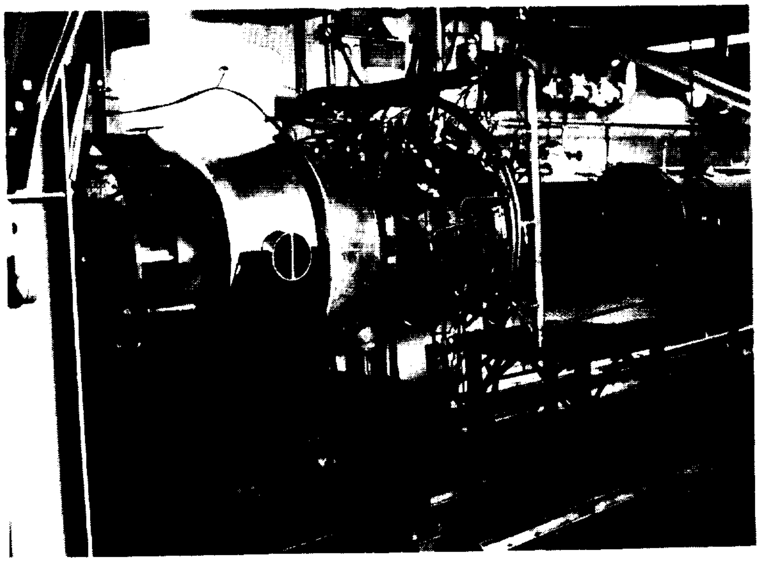
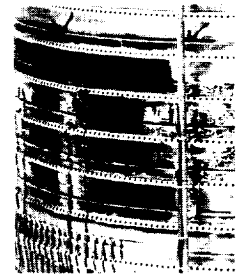


Figure 2

ANNULAR QUARTZ LAMP RIG





20-IN. DIAM CYLINDRICAL SPECIMEN

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Figure 3

COMPARISON OF OUT-OF-PHASE UNIAXIAL THERMOMECHANICAL EXPERIMENTAL DATA AND UNIFIED MODEL PREDICTIONS

HASTELLOY X FOR TEMPERATURE RANGE OF 400 - 600 °C (752 - 1112 °F); STRAIN RATE, 0.00005/SEC; 1 KSI = 5.9 MPA

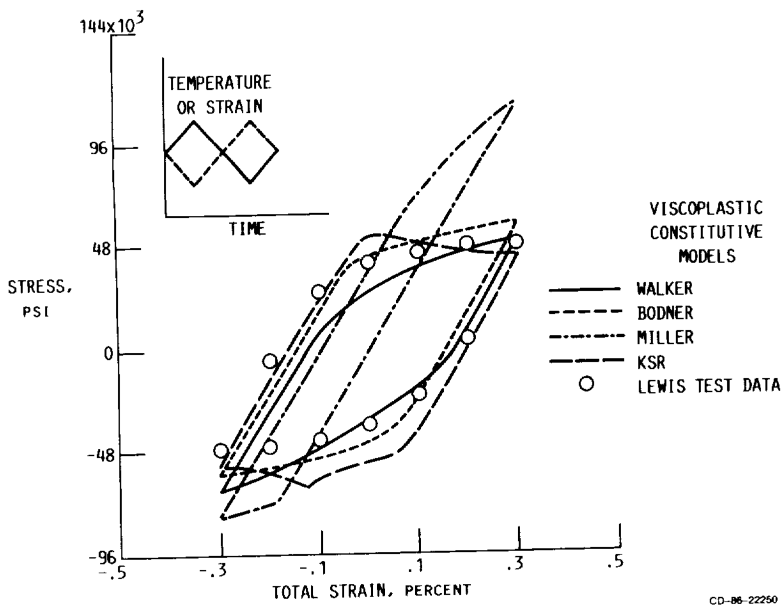

Figure 4

PLATE SHOWING GRID SYSTEM

NOTE BORON FIBERS AT 45^{0} WITH SHADOWS ON PLATE

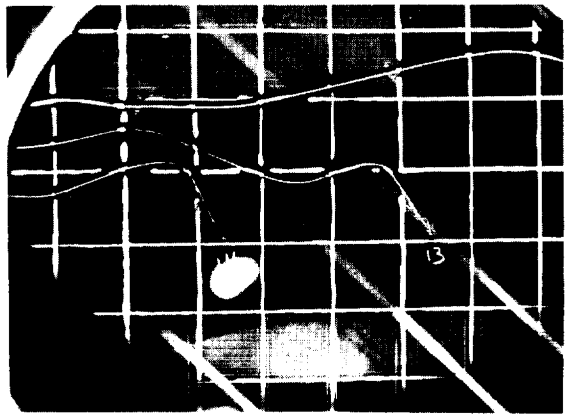

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Figure 5

QUARTZ LAMP HEATING SYSTEM

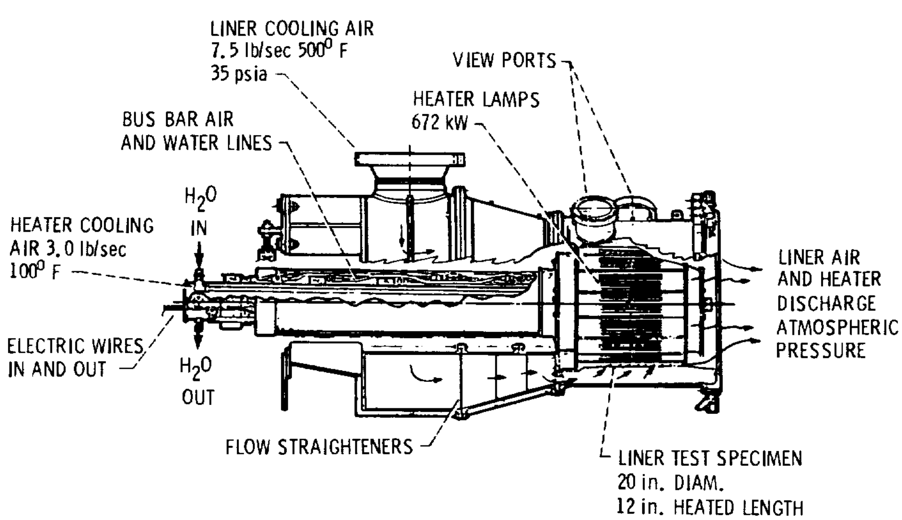

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Figure 6

POWER HISTORY FOR THERMAL CYCLE

COOLANT FLOW RATE, 5.5/SEC; COOLANT FLOW TEMPERATURE, 600 °F

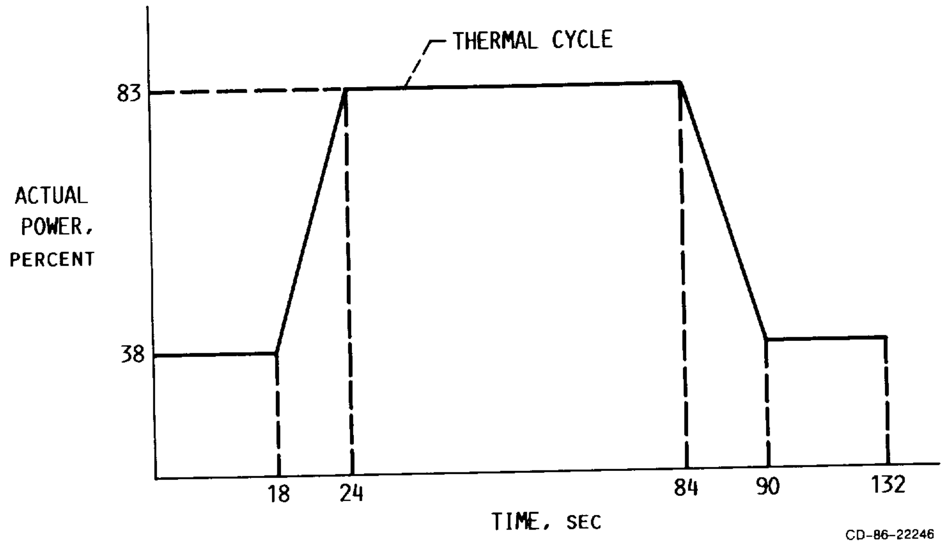

Figure 7

CYCLIC SURFACE LINER TEMPERATURES AT THREE LOCATIONS ON LOUVER 5

THERMOCOUPLE DATA

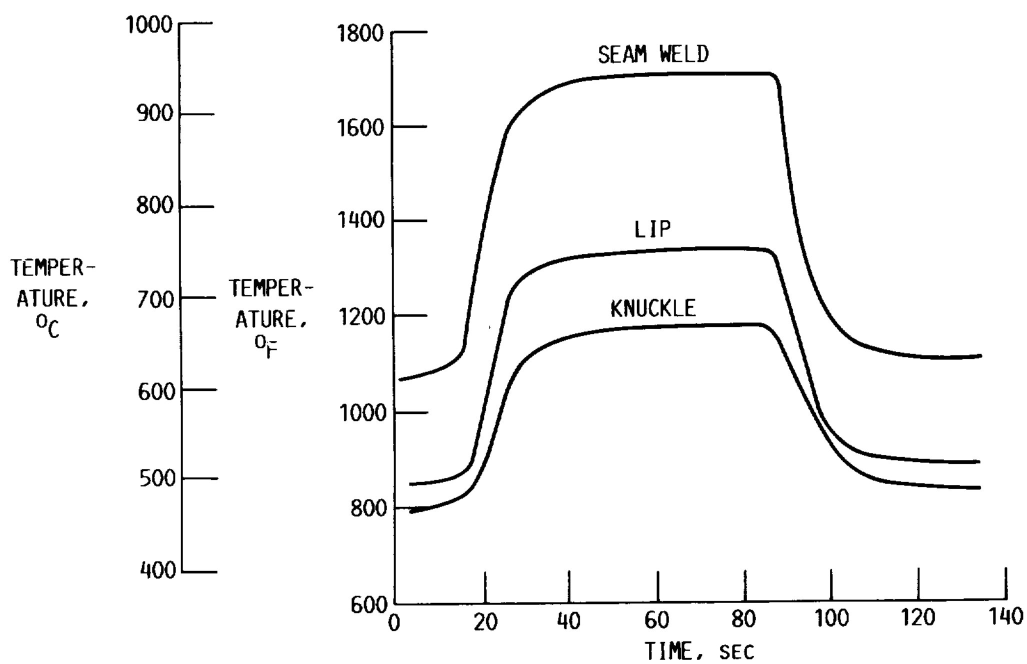

Figure 8

HOT SURFACE AXIAL LINER TEMPERATURES

LOUVERS 4 AND 5

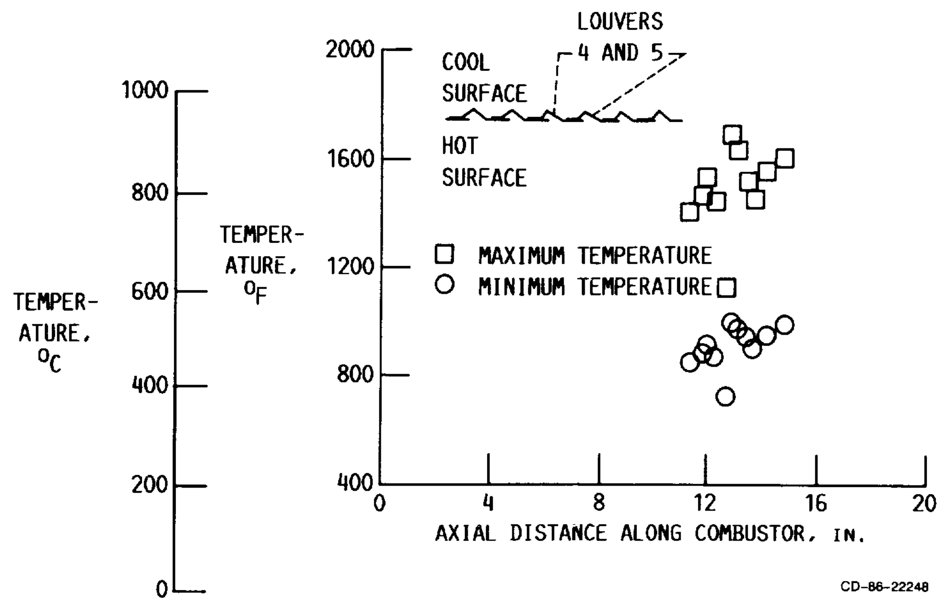

Figure 9

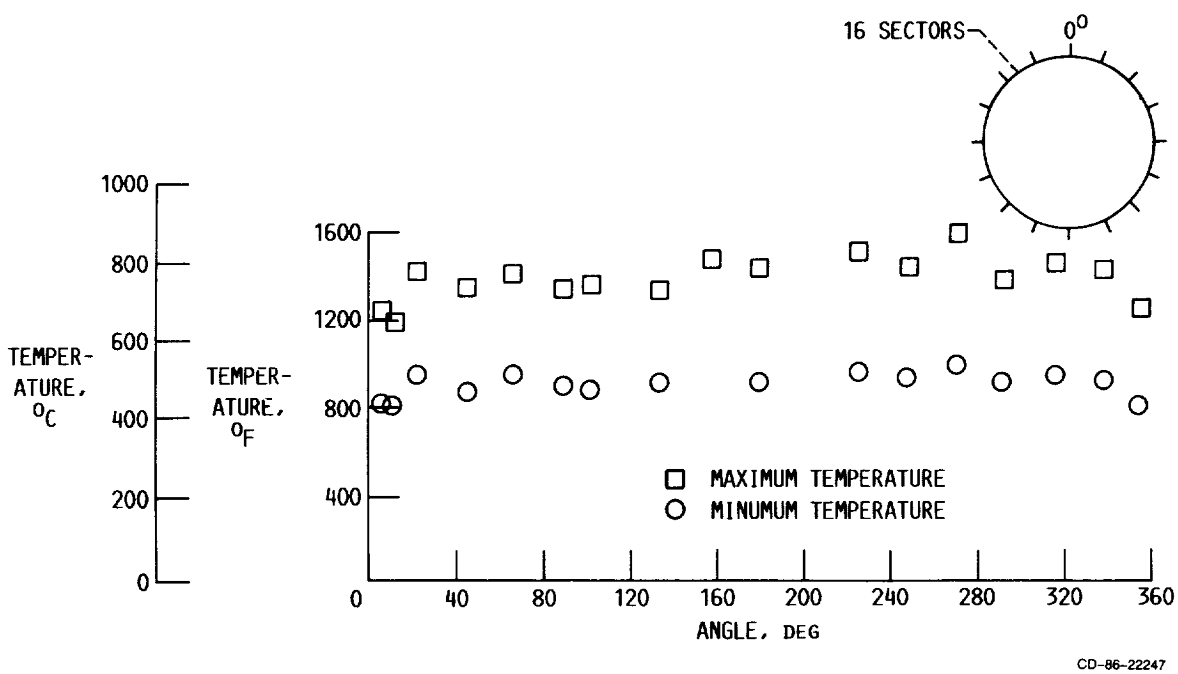

Figure 10

MEASURED COOL-SIDE LINER TEMPERATURES

COOLING AIR FLOW RATE, 5.5 lb/sec; COOLING AIR TEMPERATURE, 600 °F

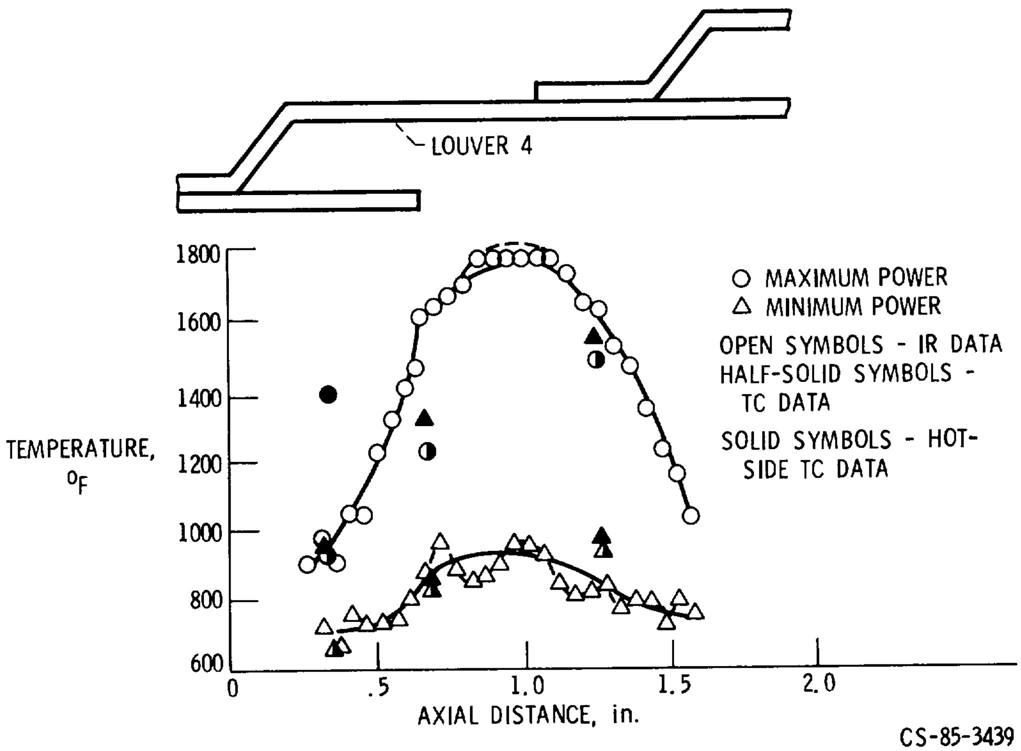

Figure 11

RADIAL DISPLACEMENT MEASUREMENTS AT THE LIP OF COMBUSTOR LINER LOUVER 5 AT 2.5° INCREMENTS

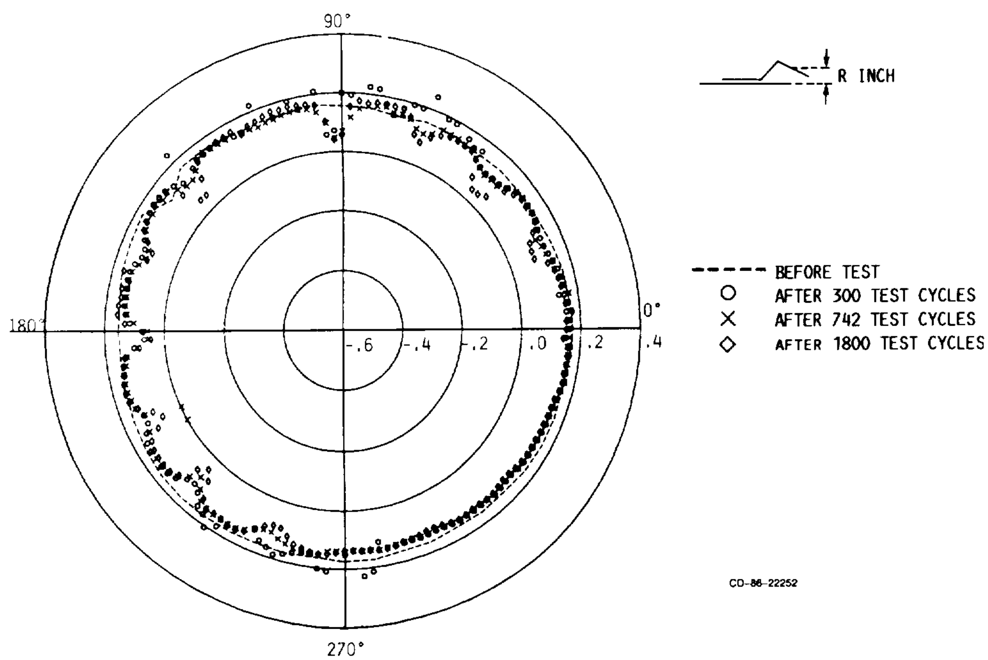

Figure 12

COMPOSITE PHOTOGRAPH OF LOUVERS INSIDE COMBUSTOR LINER AFTER 1031 CYCLES

NOTE THE RELATIVELY SMALL DISTORTION OF LOUVERS

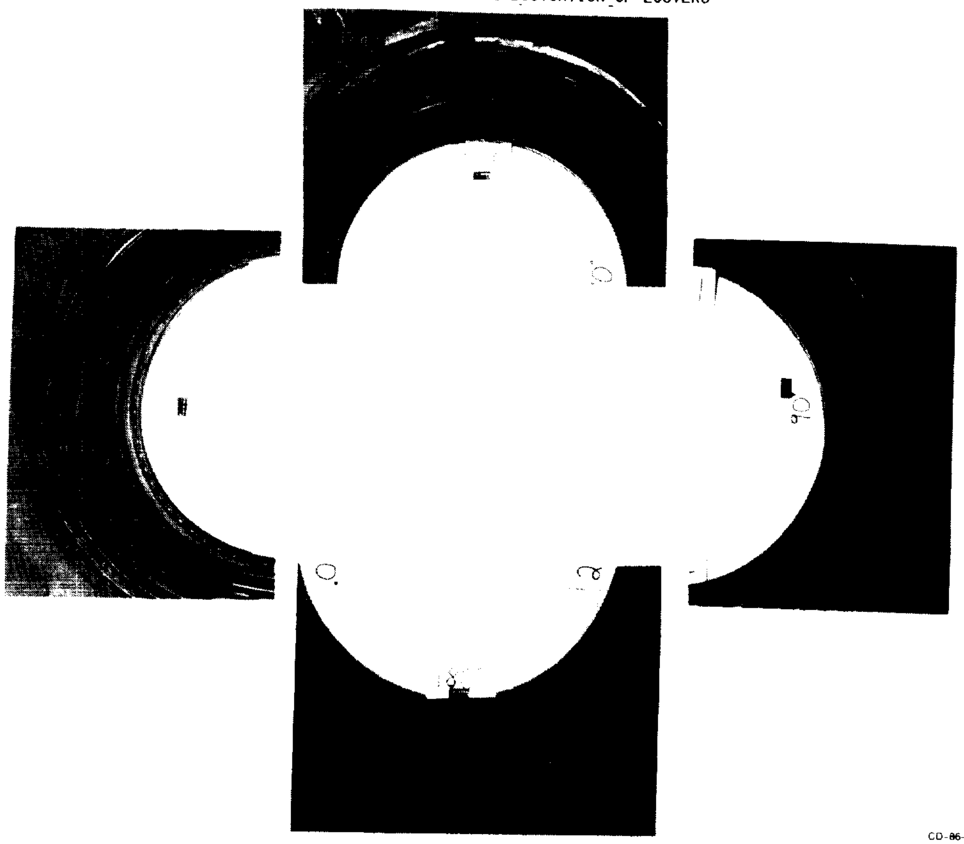

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Figure 13

CRACK WHICH INITIATED IN LOUVER 5 BEFORE THE 1603rd CYCLE

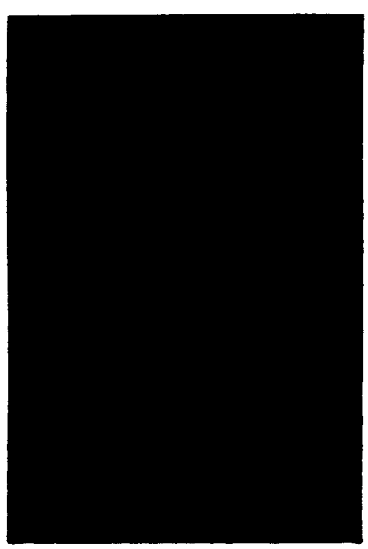

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Figure 14

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OF POOR QUALITY

CLOSURE OF COOLING HOLES WHICH CAUSED HOT SPOT AND CRACK IN INSIDE LOUVER

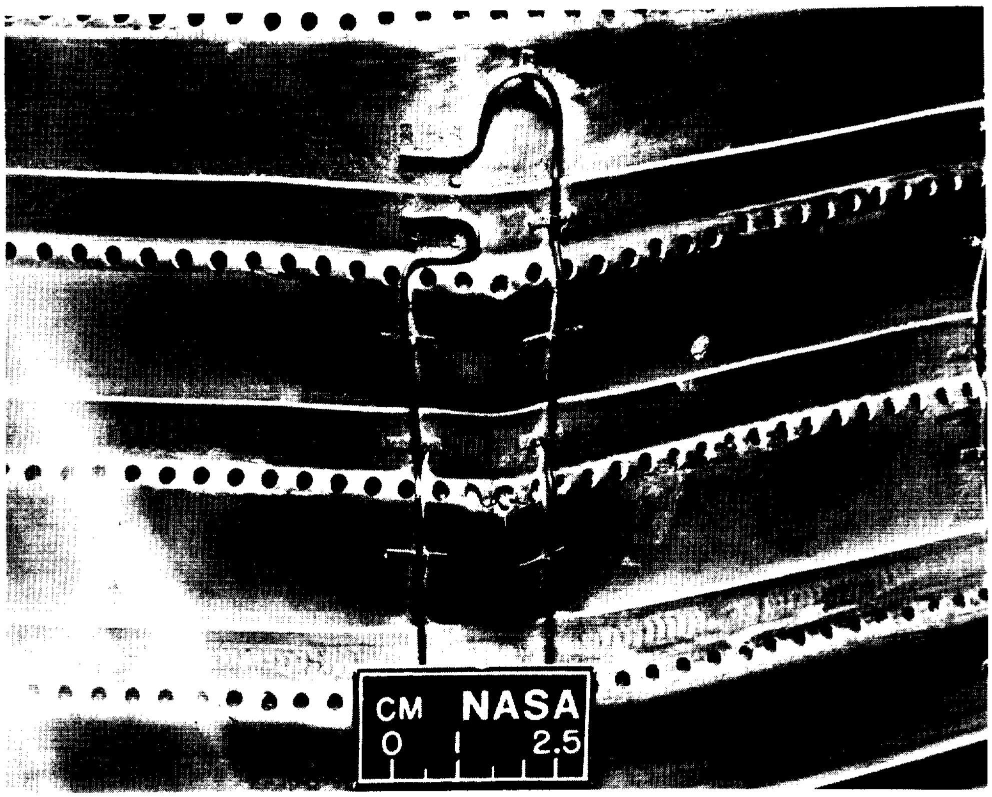

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Figure 15

COMPOSITE PHOTOGRAPH OF LOUVERS AFTER 1782 CYCLES

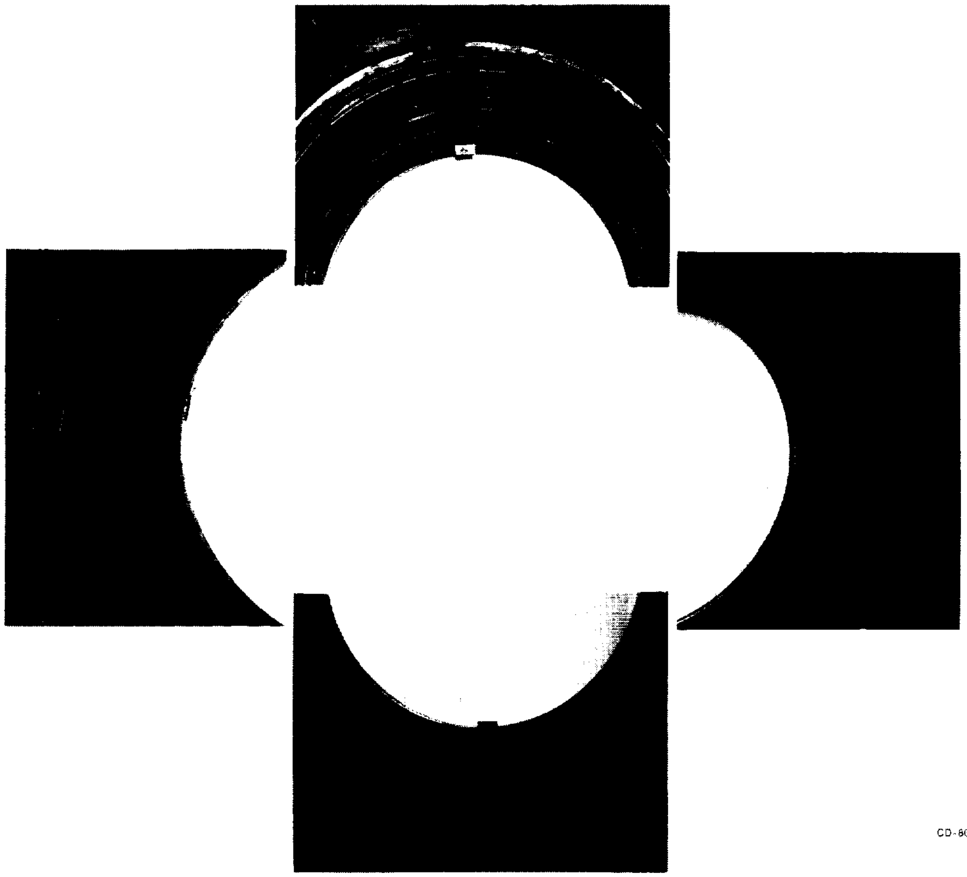

Figure 16

INSIDE OF COMBUSTOR

NOTE EFFECT OF DISTORTION OF LOUVERS ON AIR FLOW

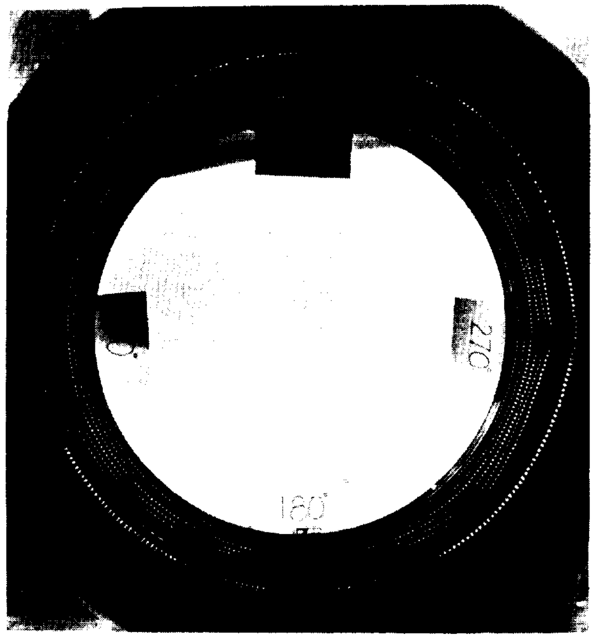

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Figure 17

REPRESENTATIVE 2-D COMBUSTOR LINER HYSTERESIS LOOP PREDICTIONS OF LOUVER 5 USING THE WALKER MODEL

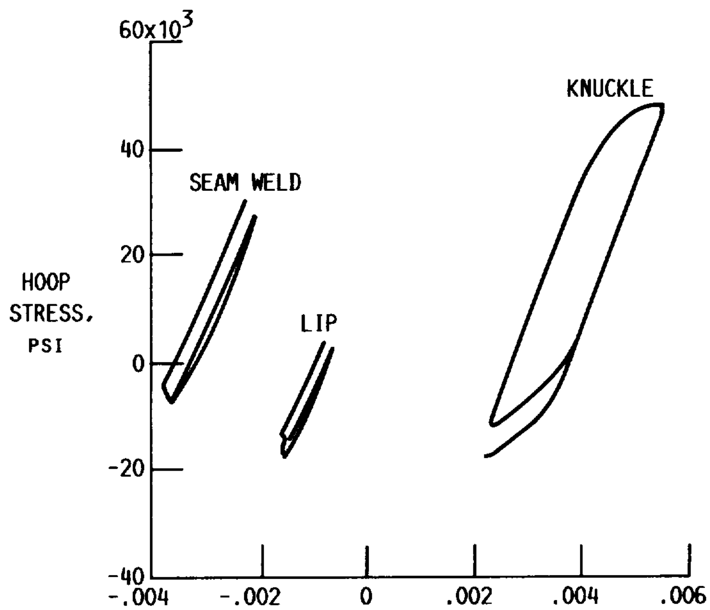

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Figure 18