VALIDATION OF STRUCTURAL ANALYSIS METHODS USING BURNER LINER CYCLIC RIG TEST DATA

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INTRODUCTION

The objectives of the HOST Burner Liner Cyclic Rig Test Program are basically threefold: (1) to assist in developing predictive tools needed to improve design analyses and procedures for the efficient and accurate prediction of burner liner structural response; (2) to calibrate, evaluate and validate these predictive tools by comparing the predicted results with the experimental data generated in the tests; and (3) to evaluate existing as well as advanced temperature and strain measurement instrumentation, both contact and non-contact, in a simulated engine cycle environment. The data generated will include measurements of the thermal environment (metal surface temperatures) as well as structural (strain) and life (fatigue) responses of simulated burner liners and specimens under controlled boundary and operating conditions. These data will be used to calibrate, compare and validate analytical theories, methodologies and design procedures, as well as improvements in them, for predicting liner temperatures, stress-strain responses and cycles to failure. Comparison of predicted results with experimental data will be used to show where the predictive theories, etc. need improvements. In addition, as the predictive tools, as well as the tests, test methods, and data acquisition and reduction techniques, are developed and validated, a proven, integrated analysis/experiment method will be developed to determine the cyclic life of a simulated burner liner.

TEST RIGS

Figure 1 includes a list of the test rigs under construction, with anticipated delivery dates and the basic specimens and burner liner components to be analyzed and tested in each rig. Flat plate specimens, with and without holes, will be tested in the Box Rig while tubular specimens, with and without holes, and subelements of burner liners will be tested in the Annular Rig. Each test will be increasingly more complex than the preceding one, both from the standpoint of geometry as well as the data acquisition and reduction requirements. Correspondingly, the structural analysis will become more complex in the progression of test configurations. For example, figure 2 shows the progression of flat plate specimens to be tested and structurally analyzed.

A schematic of the Box Rig, being fabricated in-house, is shown in figure 3. Four quartz lamps are used to heat the 8 x 5 x 0.05 inch flat plate specimens. Both water and air cooling are used. A viewing port provides for visual inspection of the specimen and data acquisition. Provisions for instrumentation include 30 thermocouples and 10 strain gage connections. Initially, the Box Rig will provide temperature and limited strain measurements using commercially available thermocouples and wire resistance strain gages. But as advanced temperature and strain measurement instrumentation is developed and becomes available under the HOST program and elsewhere, the Box Rig will serve to evaluate the advanced instrumentation, for example, infrared thermal imaging camera for temperature mapping, thinfilm thermocouples and strain gages, laser speckle strain measurements, etc. The instrumentation with the greatest potential will then be installed and used on the Annular Rig.

A schematic of the Annular Rig is shown in figure 4. The test section, being built by P&W as part of a cooperative effort between NASA Lewis and P&W, has 112 quartz lamps to heat the 21-inch annular test specimen. The length of the heated portion of the test specimen is 10 inches. Both water and air cooling are used. Three active viewing ports are provided for visual inspection of the specimen and data acquisition. Seven quick disconnect instrumentation panels are shown in the figure. These panels provide for 100 thermocouple, 28 strain gage and 21 pressure transducer connections. Both the Box Rig and Annular Rig Test Programs will be conducted at NASA Lewis in ECRL-1.

Test conditions and variables to be considered in each of the test rigs and test configurations, and also used in the structural analysis, for validation of the predictive theories and tools will include thermal and mechanical load histories (simulating an engine mission cycle), different boundary conditions (fixed, free, etc.) a variety of specimen and subelement geometries (including advanced burner liner structural design concepts), different materials (initially Hastelloy-X will be used), various cooling schemes and cooling hole configurations, and the simulation of hot streaks. Based on these test conditions and test variables, test matrices for each rig and configuration will be developed with the intent to verify the predictive tools over as wide a range as is feasible, using the simplest of possible tests. Table I is a sample test matrix for a flat plate without holes.

EXPERIMENTS

To verify the feasibility of the tests and test rig designs, and identify potential test problems and analysis/experiment complications, a limited number of preliminary experiments were conducted and structural analyses performed using 5 x 8 x 0.05 inch Hastelloy-X flat plate specimens. The specimens were tested in the box rig shown in figure 5. Three quartz lamps, placed about 2 inches apart, center-to-center, about 1-1/2 inches from the reflector and about 1-1/2 inches below the test specimen, were used to heat the specimen. The lamps were air cooled through a manifold located at the bottom of the box. Air pressure for cooling the lamps ranged from 4 psi at the lowest power setting (30 W) to 60 psi at the maximum power (18 000 W) setting. The power was controllable in steps from 30 to 18 000 watts. No water cooling was provided in this rig. The top of the plate could be viewed through a cut-out in the top cover. Some of the more salient results of these tests are presented below.

The test specimen was held fixed between two identical frames by tightening 10 bolts, as shown in figure 6. The frames and specimen were positioned horizontally above the lamps and were held in place by leg supports (long bolts) which rested on the bottom of the box.

Both the frame and test specimen were instrumented. A total of 22 thermocouples (0.032-in.-diam. Chromel-Alumel) were mounted on the frame. Ten thermocouples were mounted on the specimens; three on the outer face (cool side) and seven on the inner face (hot side) exposed to the quartz lamps. The thermocouples were mounted along the two center axes of the plate. High-temperature resistance strain gages, BLH Model HT-12/2-5A, were mounted on two specimens. The strain gage is made of platinum-tungsten alloy and works for temperatures up to 1200° F. The locations of the thermocouples and strain gages on the frame and test specimen are shown in figure 7.

Three flat plate specimens without holes were tested. The first series of tests were conducted to verify that the rig was working properly, to verify the rigs performance capability and durability, and to observe the failure mode of the plate (buckling). The frame was instrumented with thermocouples but the plate was not. Temperature measurements of the frame indicated that depending on the rate at which the power was increased, the temperature difference between the top and bottom half of the frame could vary from 0 to 100° F at temperatures below 500° F (maximum frame temperature) to a maximum variation of 0 to 400° F at 1000° F and above. By increasing the power slowly, this difference could be controlled and kept to a minimum. The conclusion reached is that control of the frame temperature is needed to prevent buckling of the plate for a fixed edge boundary condition.

In the second series of tests, both temperature and strain measurements were obtained. Temperature variations on the plate and frame were recorded for several power settings. For a single power setting, representative plots of the plate and frame temperatures are shown in figures 8 and 9. The power level was stepped up from 375 volts (12 100 W) to 435 volts (15 500 W) and held constant for about 7 minutes. The delta increase in frame temperature ranged from 50° to 100° F whereas the delta increase in plate temperature ranged from 100° to 230° F. The initial maximum/minimum temperatures for the frame and plate were 510° (TC 12)/260° F (TC 4) and 1270° (TC 4)/830° F (TC 1), respectively. The final maximum/minimum temperatures for the frame and plate were 600°/310° F and 1500°/1000° F respectively. The frame temperature increased almost linearly with time while the plate temperature reached almost steady state conditions at about 2 minutes into the step increase in power. Contrary to our expectations, a non-uniform plate temperature was observed for this and all tests in the longitudial direction, while a more uniform temperature was observed across the plate (see figs. 8 and 9) for all tests. Through the thickness temperatures varied widely, ranging from 20° to 200° F. Unexplainably, the data show that the front half of the plate was much hotter than the back half of the plate (by about 530° F for data shown in fig. 9), and the front half of the frame (both bottom and top) was hotter than the back half (by about 100° F for the data shown in fig. 8) for all tests. The most obvious reasons for this anomaly were ruled out, such as a slopping plate, distance between lamps and test specimen, cooling air flow patterns, plugged air holes, and misalignment of the cooling air manifold. These tests showed: it was possible to control the plate temperature, both transient and steady state, by varying power settings and air flows; it was possible to achieve desired maximum/minimum temperatures in the plate, approximately 1700° F temperature at a power setting of 440 volts and a 900° F temperature at a power setting of 300 volts; it was possible to control the frame temperature to a degree; it was possible to control strains by varying both frame and plate temperatures for fixed edge boundary conditions; it was not possible to achieve uniform surface temperatures in the plate either in the horizontal or longitudinal directions; it was not possible to achieve the desired or uniform through the thickness temperature gradients; and strain measurements were not obtained above 1200° F.

The primary objective of the third series of tests was to demonstrate whether or not a simulated engine mission cycle could be obtained. The test results showed that controlled complex, cyclic thermal cycles could be imposed on a flat plate specimen. Other than this, the test results obtained were similar to those obtained from the second series of tests.

ANALYSIS

A structural analysis of a flat plate specimen without holes was performed using MARC, a general purpose, nonlinear finite element structural analysis computer program. Walker's viscoplastic constitutive model was incorporated into MARC to account for the interaction between creep and plastic deformations.

The plate was analyzed using a four node plane stress element. The mesh configuration was set up so that direct comparisons could be made between models with a single hole and without a hole. The mesh configurations for these two models are shown in figure 10. The configurations are doubly symmetric, thus only a quarter of the plate is modelled.

A parametric study was conducted to examine different boundary conditions for a flat plate without holes. The results indicated that both the test specimen and frame would have to be analyzed together and that controlled, variable boundary conditions were necessary to reproduce the desired stress levels in the plate. Controlling the boundary conditions was done by providing truss members at the edges of the plate as shown in figure 11. By appropriately adjusting the temperature difference between the plate and the edge members, the stress levels can be varied in the plate. Thus, boundary conditions ranging from free edge (with the plate and edge bars at the same temperature) to fixed edge (with the edge bars kept at a reference temperature while the plate temperature is increased), as well as all intermediate conditions is possible. Further, depending on whether the edge bar temperatures lag behind the plate temperatures or vice versa, compression or tension may be produced in the plate. This reversal of stress would make it possible to trace hysteresis loops and thus study thermal ratcheting, compare experiment with predictions, etc.

A simulated engine mission cycle was studied assuming uniform temperatures in the plate and the edge bars, with a 5-percent temperature difference between the plate and frame as shown in figure 12. The initial temperature was set at 940° F and the cycle consisted of a 25-second ramp up to a maximum temperature of 1740° F, a 40 second hold time at this temperature level and a 30-second ramp down to a temperature of 940° F. Figure 12 shows the time variation of stress in element 18 (see fig. 10). The stress-strain variation for this element is plotted in figure 13. No direct comparisons could be made between this analysis and the experiments described earlier because of the nonuniformity of plate and frame temperatures obtained from the experiment.

CONCLUSIONS AND FUTURE RESEARCH

The preliminary experiments demonstrated the feasibility of the rig to achieve the desired plate temperatures, temperature gradients and cyclic thermal load histories, although uniform plate temperatures were not achieved. Finite element models of plates, with and without holes, and frames were generated and structural analyses were performed. However, a direct comparison between experiment and analysis could not be done because of the nonuniform plate temperatures obtained in the experiments.

The new Quartz Lamp Box Rig under construction has four quartz lamps, with a maximum power of 24 000 watts. This rig is expected to produce much more uniform plate temperatures than those obtained in the rig just described. In addition, computer controlled operation and data acquisition will allow for more accurate and extensive tests. The ESCORT II Data Acquisition System, available at Lewis, will be used for data acquisition and control of the experiment. The data obtained, both temperature and strain measurements, will be stored on tape for processing, reduction and analysis at a later date. Also, an infrared thermal video imaging system will be integrated into the system to obtain temperature maps of the plate.

The Annular Rig, as described earlier, under construction, will provide data on cylindrical shells and subelements of burner liners. The same features available for the Box Rig will be carried over to the Annular Rig. Preliminary structural analyses of plates and shells will be used to guide the direction of the experimentation in both the Box and Annular Rigs. Other analyses will be conducted to predict the material stress-strain response using the measured temperature distributions obtained from the tests. These analyses will provide a basis for comparing analytical predictions, for example, using several constitutive models, with the experimental data for validation and subsequent selection of improved analysis methods to predict, more efficiently and accurately, the structural response of burner liners.

TABLE I - SAMPLE TEST MATRIX FOR FLAT PLATE

TEST CONFIGURATION - FLAT PLATE WITHOUT HOLES

MATERIAL - HASTELLOY X

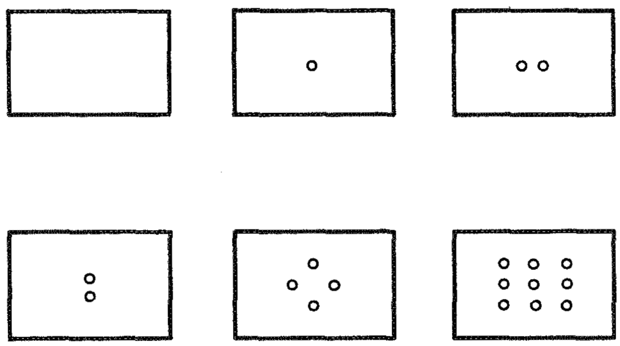
TEST NO.	TEMPERATURE STATE	TEMPERATURE HISTORY: RAMP UP TIME, sec.	RAMP UP TEMP., °F	HOLD TIME TIME, sec.	HOLD TIME TEMP., °F	RAMP DOWN TIME, sec.	RAMP DOWN TEMP., °F	BOUNDARY COND. FOR PLATE EDGES	NUMBER OF CYCLES (TIME BET. CYCLES, sec)
1	STEADY STATE-UNIFORM TEMP.	20	RT-600	300	600	--		FIXED EDGES	--
2	"	20	RT-800	300	800	--		"	--
3	"	20	RT-1000	300	1000	--		"	--
4	"	20	RT-1200	300	1200	--		"	--
5	"	20	RT-1400	300	1400	--		"	--
6	"	20	RT-1600	300	1600	--		"	--
7	"	20	RT-1800	300	1800	--		"	--
8	"	40	RT-1000	300	1000	--		"	--
9	"	40	RT-1400	300	1400	--		"	--
10	"	40	RT-1800	300	1800	--		"	--
11	"	60	RT-1000	300	1000	--		"	--
12	"	60	RT-1400	300	1400	--		"	--
13	"	60	RT-1800	300	1800	--		"	--
14	"	20	RT-1000	500	1000	--		"	--
15	"	40	RT-1000	500	1000	--		"	--
16	"	60	RT-1000	500	1000	--		"	--
17	"	20	RT-1400	500	1400	--		"	--
18	"	40	RT-1400	500	1400	--		"	--
19	"	60	RT-1400	500	1400	--		"	--
20	"	20	RT-1800	500	1800	--		"	--
21	"	40	RT-1800	500	1800	--		"	--
22	"	60	RT-1800	500	1800	--		"	--
23	CYCLE-	20	RT-1400	80	1400	20	1400-800	"	5
24	VARIABLE TEMP.	20	RT-1600	80	1600	20	1600-800	"	5
25	"	20	RT-1800	80	1800	20	1800-800	"	5
26	"	20	RT-1400	120	1400	20	1400-800	"	5 (60)
27	"	20	RT-1600	120	1600	20	1600-800	"	5 (60)
28	"	20	RT-1800	120	1800	20	1800-800	"	5 (60)
29	"	30	RT-1400	80	1400	30	1400-800	"	5 (60)
30	"	30	RT-1600	80	1600	30	1600-800	"	5 (60)
31	"	30	RT-1800	80	1800	30	1800-800	"	5 (60)
32	"	20	RT-1400	80	1400	20	1400-800	"	25 (60)
33	"	20	RT-1600	80	1600	20	1600-800	"	25 (60)
34	"	20	RT-1800	80	1800	20	1800-800	"	25 (60)
35	HOT STREAK (+50°F)					--			
36	UNIFORM TEMP.	20	RT-1000	300	1000	--		"	--
37	"	20	RT-1400	300	1400	--		"	--
38	"	20	RT-1800	300	1800	--		"	--
39	HOT STREAK (+50°F)								
40	CYCLIC TEMP.	20	RT-1400	80	1400	20	1400-800	"	5 (60)
41	"	20	RT-1600	80	1600	20	1600-800	"	5 (60)
42	"	20	RT-1800	80	1800	20	1800-800	"	5 (60)
43	HOT STREAK (+100° F)	20		80	1400	20	1400-800	"	5 (60)
44	CYCLIC TEMP.	20		80	1600	20	1600-800	"	5 (60)
45	"	20		80	1800	20	1800-800	"	5 (60)

COMPONENTS TO BE ANALYZED AND TESTED IN HOST BURNER LINER CYCLIC RIGS

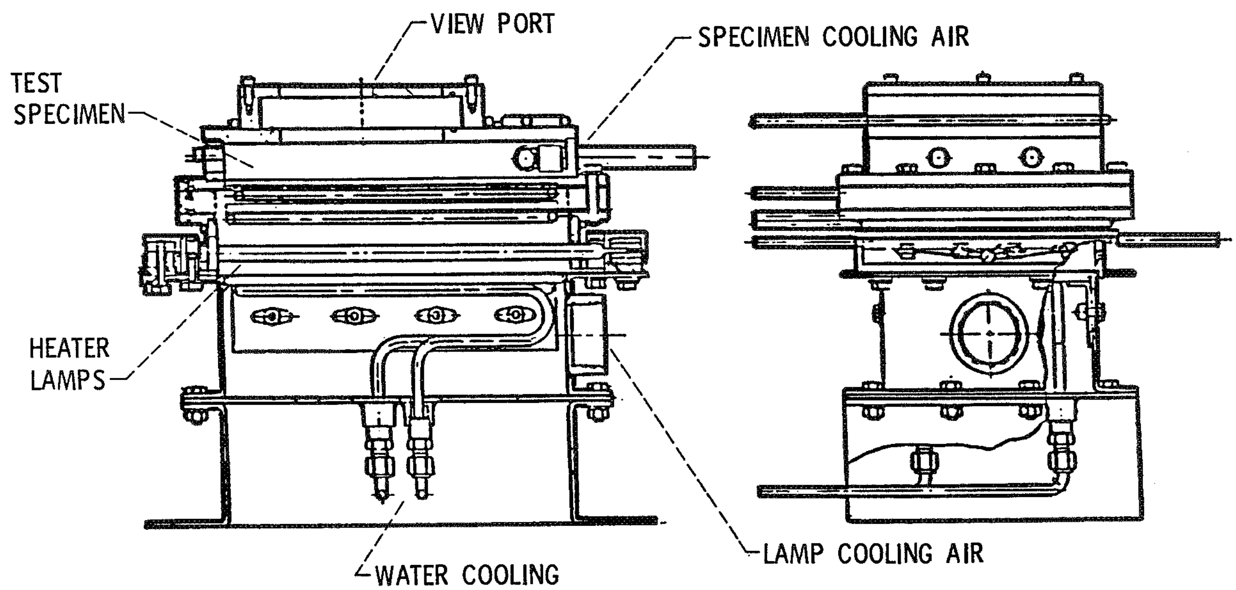
1. QUARTZ LAMP BOX RIG (DELIVERY DATE - SEPTEMBER '83)
   FLAT PLATES WITH AND WITHOUT HOLES

2. QUARTZ LAMP ANNULAR RIG (DELIVERY DATE - APRIL '84)
   CYLINDRICAL SHELLS WITH AND WITHOUT HOLES
   SUBELEMENTS OF COMBUSTOR LINERS

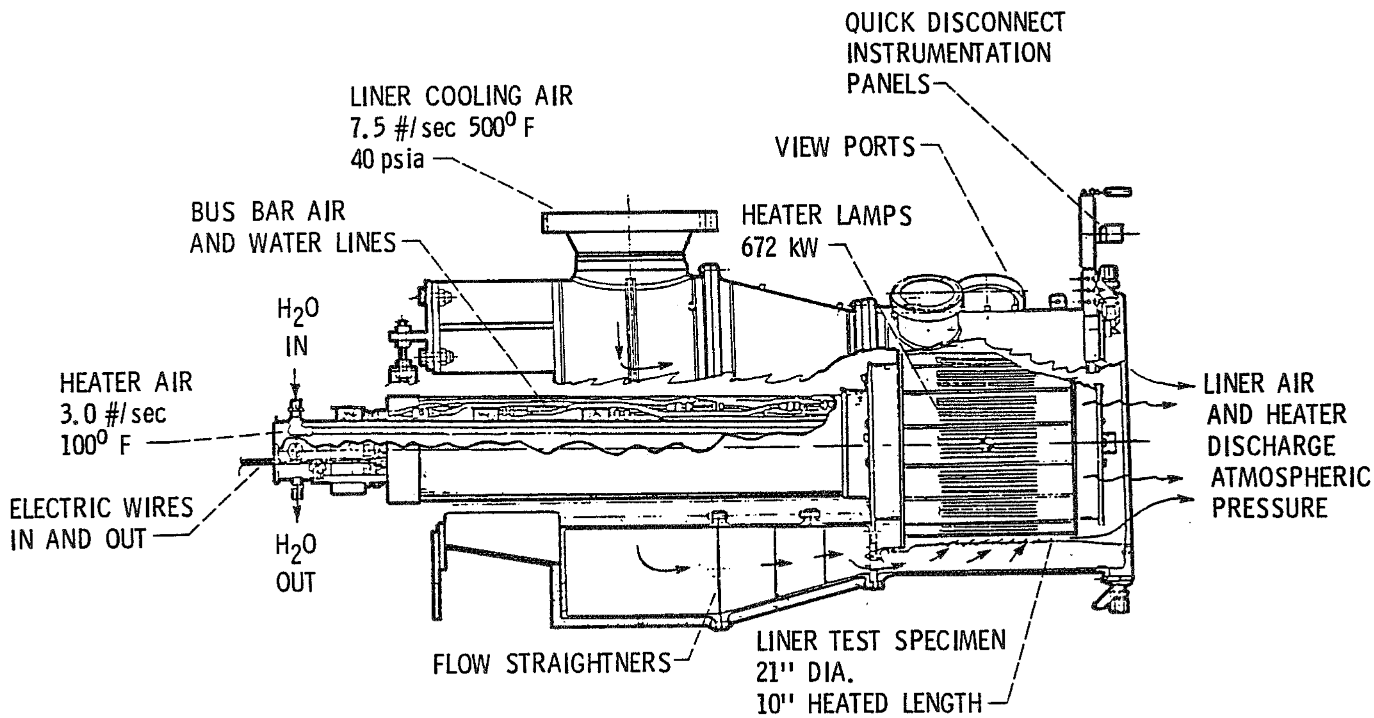
FLAT PLATE SPECIMEN CONFIGURATIONS TO BE ANALYZED AND TESTED



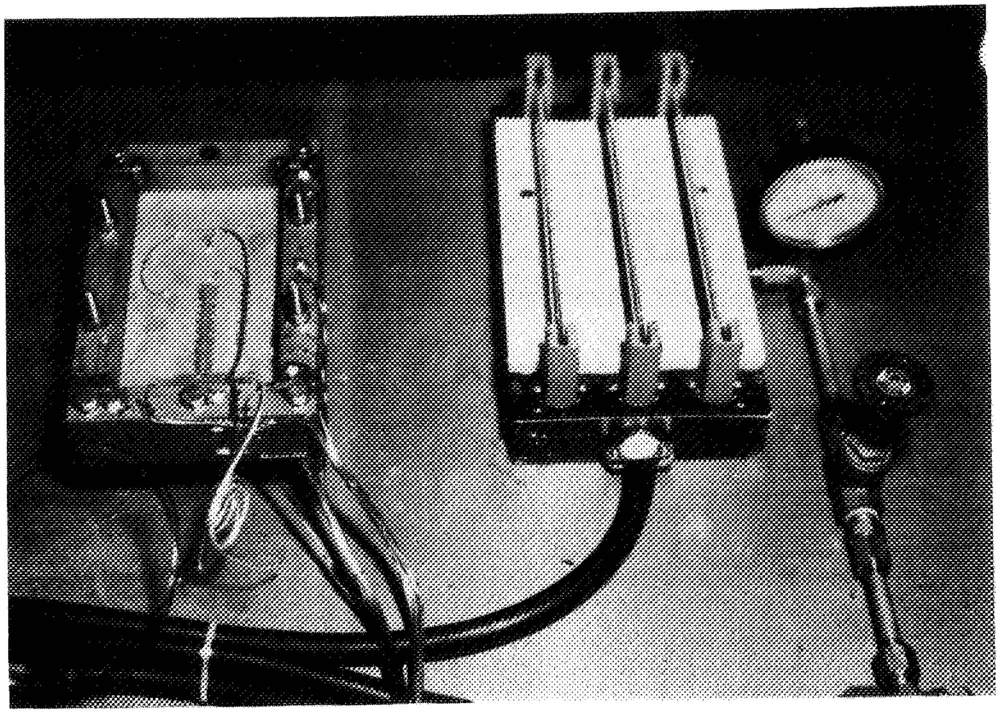
SCHEMATIC OF QUARTZ LAMP BOX RIG



SCHEMATIC OF QUARTZ LAMP ANNULAR RIG



BOX RIG TEST SET UP



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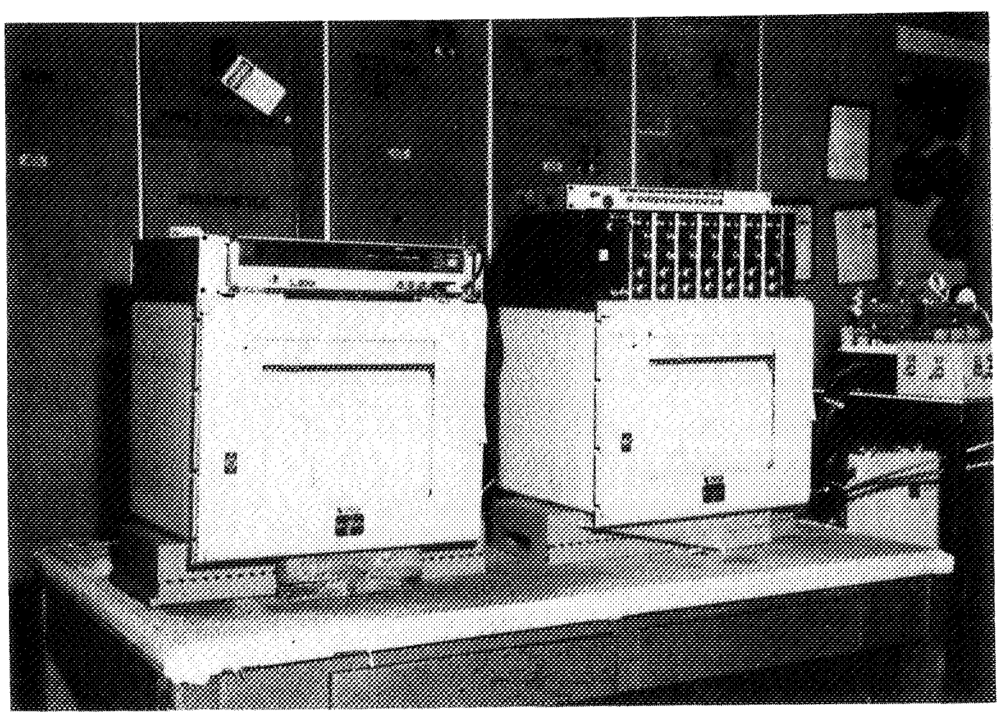
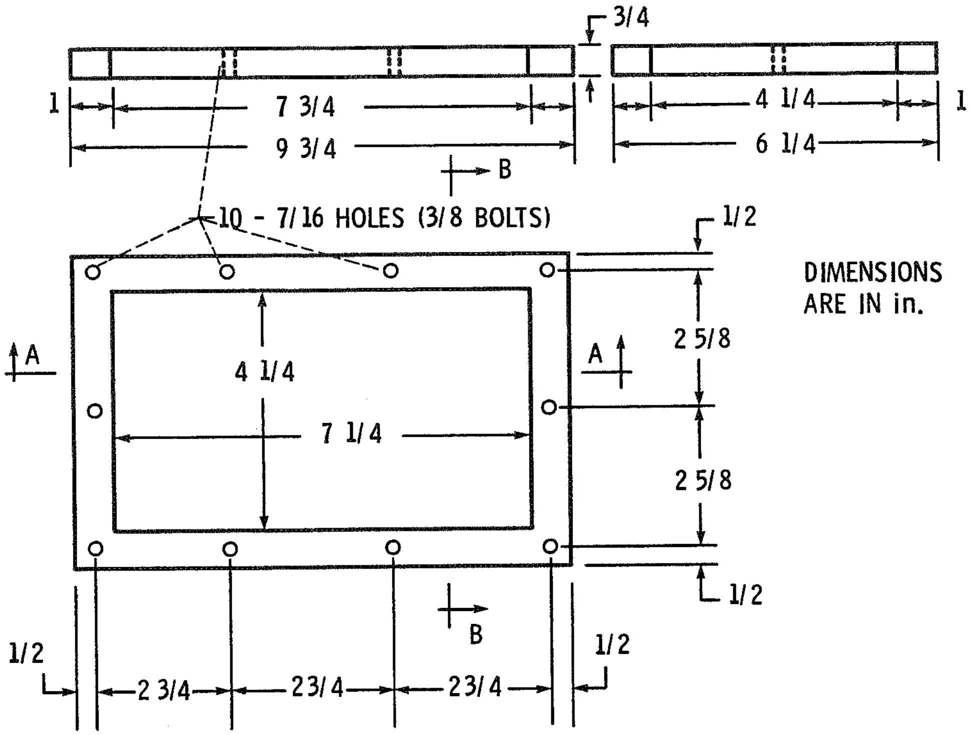
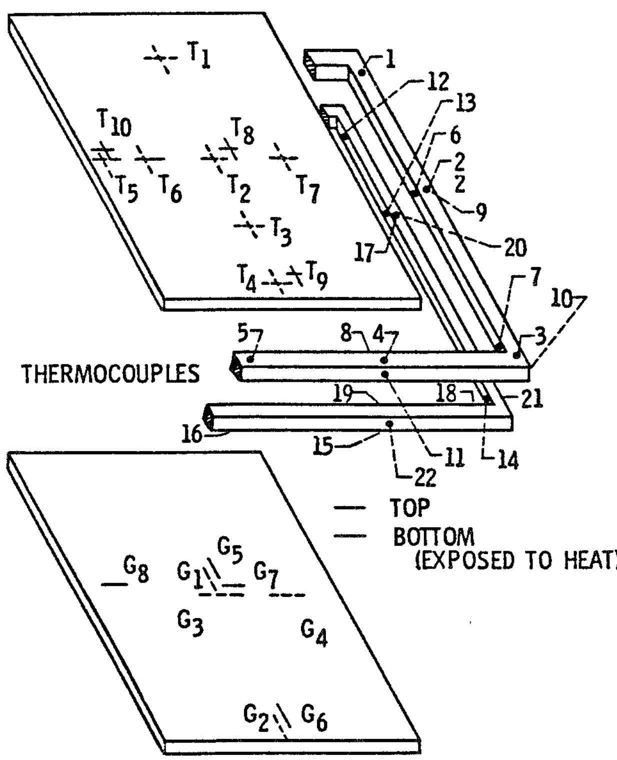


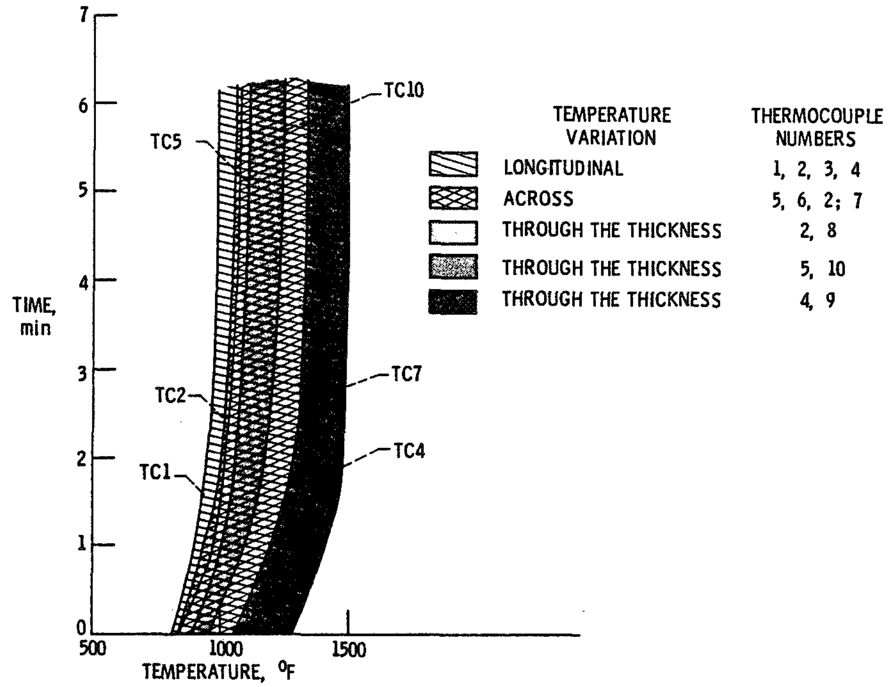
FRAME FOR HOLDING THE PLATE SPECIMENS



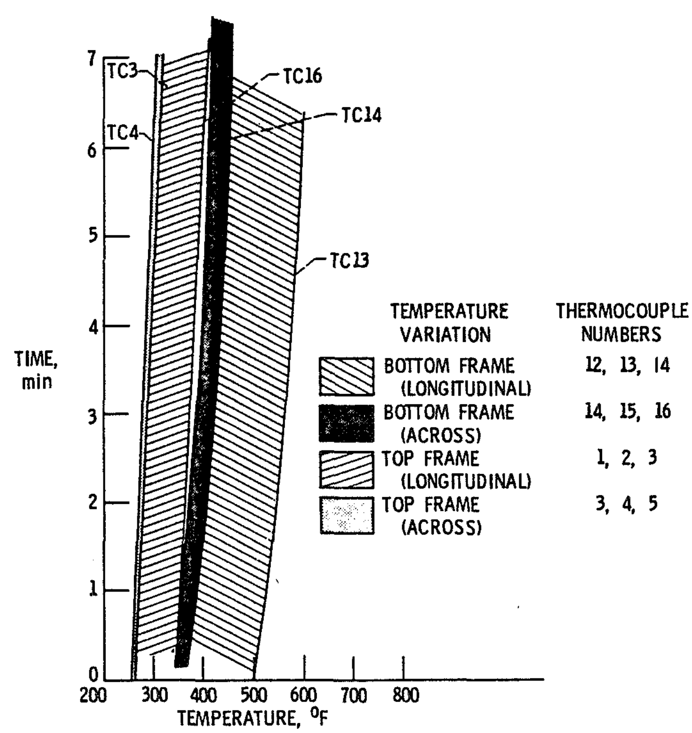
FRAME AND PLATE THERMOCOUPLE AND STRAIN GAGE LOCATIONS



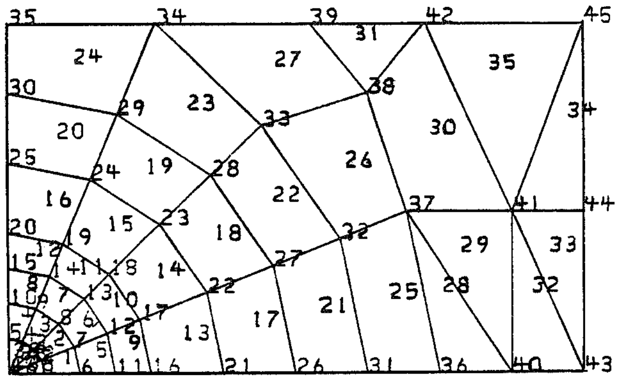
TEMPERATURE VARIATION OF
PLATE FOR A CHANGE IN POWER SETTING FROM 375 VOLTS TO 435 VOLTS



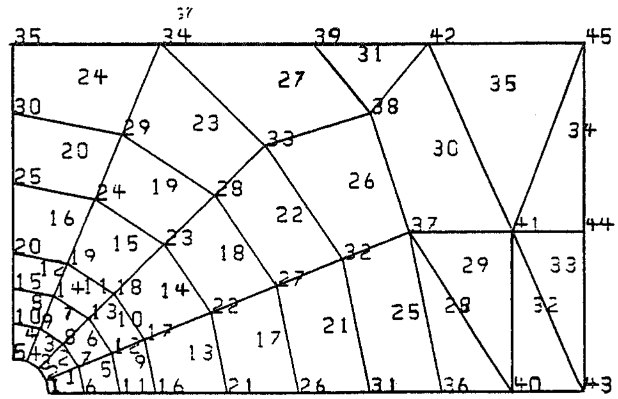
TEMPERATURE VARIATION OF
FRAME FOR A CHANGE IN POWER SETTING FROM 375 VOLTS TO 435 VOLTS



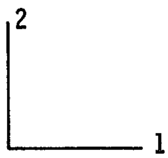
PLANE STRESS MESH FOR THE PLATE SPECIMENS



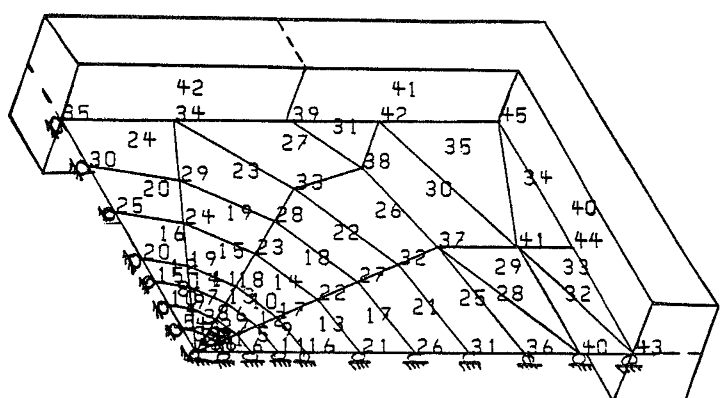
1/4 MESH - SOLID PLATE (NO HOLES)



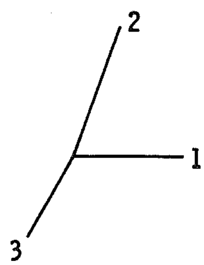
1/4 MESH - CENTER HOLE



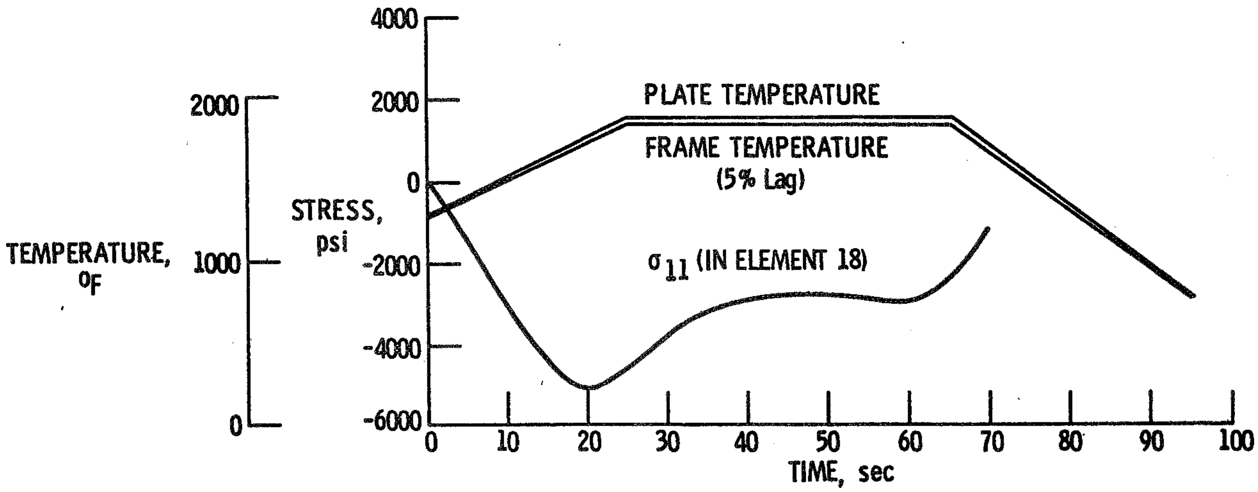
FINITE ELEMENT MODEL FOR THE FRAME AND PLATE



1/4 MESH



TIME VARIATION OF STRESS IN ELEMENT 18



STRESS-STRAIN IN ELEMENT 18