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# Evaluation of Heating Methods for Thermal Structural Testing of Large Structures

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## Abstract

*An experimental study was conducted to evaluate different heating methods for thermal structural testing of large scale structures at temperatures up to 350°F as part of the High Speed Research program. The heating techniques evaluated included: radiative/convective, forced convective, and conductive. The radiative/convective heaters included finned strip heaters, and clear and frosted quartz lamps. The forced convective heating was accomplished by closed loop circulation of heated air. The conductive heater consisted of heating blankets. The tests were conducted on an 1/8 inch thick stainless steel plate in a custom-built oven. The criteria used for comparing the different heating methods included test specimen temperature uniformity, heater response time, and consumed power. The parameters investigated included air circulation in the oven, reflectance of oven walls, and the orientation of the test specimen and heaters (vertical and horizontal). It was found that reflectance of oven walls was not an important parameter. Air circulation was necessary to obtain uniform temperatures only for the vertically oriented specimen. Heating blankets provided unacceptably high temperature non-uniformities. Quartz lamps with internal air circulation had the lowest power consumption levels. Using frosted quartz lamps with closed loop circulation of cool air, and closed loop circulation of heated air provided the fastest response time.*

## Introduction

As part of the High Speed Research (HSR) program, components and subcomponents of the proposed High Speed Civil Transport (HSCT) wing and fuselage will be subjected to structural testing at temperatures up to 350°F. The wing and fuselage to be tested have wetted surface areas of 1600 and 1100 squared feet, respectively. It is desirable to design the most efficient method of uniformly heating these large HSCT components. The main considerations are the initial cost of the heating technique and set up, the required power to reach and maintain steady state conditions at the desired temperature, the uniformity of temperatures over the specimen to avoid inducing thermal stresses, and the number of control zones required to achieve uniform temperatures.

The overall objective of this investigation was to evaluate different heating methods in a small scale test set up, with the results of the study to be used in determining the heating method for large scale components. Evaluation criteria included heater response time, power consumption, and test article temperature uniformity. Heater cost and number of control zones were not investigated in this study, because they are closely related to the overall size and shape of test specimen. The test article chosen for this study was a stainless steel plate mounted on one of the walls of a custom-built oven. Three general types of heating techniques were used: radiative/convective, forced convective, and conductive. The radiative/convective heaters included finned strip heaters, and clear and frosted quartz lamps. The heaters radiated directly upon the test article, and convection heat transfer took place either through natural convection in the oven or through forced convection by either internal circulation created by fans, or by closed loop circulation of cool air. The forced convective heating was accomplished by closed loop circulation of heated air, with the air being heated externally by strip heaters. The conductive heater consisted of installing heating blankets on the test specimen. The parameters investigated included air circulation in the oven, reflectance of oven walls, and the orientation of the test specimen and heaters.

## Background

Thermal-structural testing has been the subject of various reports since the 1950's, but the majority of work has concentrated on elevated temperature applications. Berman compared the behavior of various resistance heaters with infrared lamps for elevated temperature tests in 1954 (ref. 1). The resistance heaters included corrugated nickel-chromium strip heating elements, Kanthal rod heating elements, coiled nickel-chromium heating elements on refractory coves, and silicon carbide heaters. The infrared heaters included clear and translucent (frosted) quartz lamps. He recommended using clear quartz lamps due to their higher energy density, low thermal inertia, and relatively high efficiency. Duberg provided a brief survey of techniques used at NACA for experimental research on aircraft structures at elevated temperatures (ref. 2). An oven with internal electrical heating elements was used for temperatures up to 900$^0$F; carbon rods, quartz lamps, and supersonic nozzles were used for higher temperatures. He preferred the quartz lamps for higher temperature applications because of their faster response time and longer life time compared to carbon rods. Moran and Schiff compared quartz lamps and arc-powered devices for high-temperature structural test methods (ref. 3). Fields and Vano described a quartz lamp heating facility for simulating aerodynamic heating loads on the X-15 stabilizer in the temperature range of -50 to 750$^0$F (ref. 4).

Harpur described fatigue testing of large scale components of the Concorde supersonic transport between temperatures of -4 to 248$^0$F (ref. 5). Initially, quartz lamps were used for the heating cycle to simulate climb and cruise conditions, while ducted cool air was used for the cooling cycle to simulate descent and recovery conditions. Finally, it was decided to unify the heating and cooling technique by using ducted air for both purposes. Air was heated to 320$^0$F using gas heaters and circulated in a closed-circuit wind tunnel around the specimen. In the cooling phase, the circulating air was cooled by injection of liquid nitrogen. An advantage of such a system was the simplicity of the control system. The system only required control of the air inlet temperature and mass flow rate, while the earlier quartz lamp heater had required about a dozen control zones for regulating the heat input in different areas.

## Test Setup

For this experimental investigation, an oven was built from one inch thick ceramic boards made from refractory fibers, mounted on a carbon steel unistrut frame. The interior dimensions of the oven were 32 inches wide, 48 inches high, and 20 inches deep. The test specimen used in this study was a stainless steel plate 32 inches wide, 48 inches high, and 1/8 inch thick, mounted on one of the oven walls. The front side of the plate, the side facing the interior of the oven, was painted using a high emittance flat black paint to increase its radiation absorption characteristics. There were a total of 29 type K (nickel-chromium /nickel-aluminum) thermocouples, 0.010" in diameter, spot welded to the backside of the plate (the side attached to the oven wall). One thermocouple was used for feedback to the temperature controller. A schematic showing the layout of the thermocouples is shown in Figure 1. There were 15 thermocouples spaced 3 inches apart mounted along the plate's vertical axis of symmetry, and 7 thermocouples spaced 4 inches apart mounted along the plate's horizontal axis of symmetry. There were 7 additional thermocouples mounted at various locations on the plate as shown in Figure 1. A picture of the oven with the stainless steel test specimen mounted on the back wall is shown in Figure 2. The finned strip heaters and quartz lamps were mounted on the wall opposite the stainless steel plate, approximately 20 inches from the test specimen. In each case, nine heaters were installed with uniform spacing ( 5 inch center to center spacing) along the height and centrally located along the width of the heated wall, as shown schematically in Figure 1. A thin sheet of reflective alzac (aluminum subjected to electroplating and then a thin anodic coating) was first mounted on the oven wall before the heaters were installed. The purpose of the reflective sheet was to help reflect the heat from the heaters towards the test specimen. A picture of the heated wall with the mounted frosted quartz lamps is shown in Figure 3.

The effective heated area of the finned strip heaters was 2 inches wide by 12 inches long. The quartz lamps were 3/8 inches in diameter with an effective heating length of 11 inches. The heating blankets were 23 inches wide, 46.5 inches long and 1.75 inches thick, and included resistance heaters wrapped and packaged in insulating material. For the tests with the heating blankets, the oven side wall consisting of the test specimen and the one inch thick insulation was removed from the overall oven assembly. The heating blanket was installed directly on top of the test specimen and bolted to it using 6 bolts. Since the heating blanket could not cover the entire area of the test specimen, only the temperature readings from the thermocouples that were directly covered by the heating blanket were used. The tests were conducted with the specimen in the vertical and horizontal position. In the horizontal position, tests were conducted with the heating blanket located either above or below the test specimen.

Air circulation in the oven was achieved through either internal or external circulation. Two fan blades were mounted on the oven walls to produce internal circulation. Each fan blade was 5 inches in diameter and produced 400 cubic feet per minute internal circulation in the oven. A commercially available air recirculating system was used to produce external circulation. This unit was capable of closed loop circulation of unheated and heated air with variable volumetric flow rates up to 540 cubic feet per minute. A picture of the air recirculating system with its ductwork attached to the oven is shown in Figure 4. In order to investigate the effect of reflectance of oven walls, tests were conducted with two oven wall reflectances: high and low. Use of the bare ceramic boards resulted in a low reflectance oven. Installing alzac sheets in the oven interior to cover the other 5 walls resulted in a high reflectance oven. Tests were conducted using two oven orientations, vertical and horizontal. The heater wall and test specimen were both parallel to gravity in the vertical orientation, and perpendicular to gravity in the horizontal orientation. For the latter orientation, the oven was turned on its side in such a way that the heaters were located below the test specimen.

The measured root mean square (rms) current and voltage were used to calculate the instantaneous power supplied to the heaters. A single phase, 230 volt, 40 ampere, phase angle temperature control system was used in conjunction with a Proportional, Integral, Derivative (PID) temperature controller to provide power to the radiative/convective and conductive heaters. The commercially available air recirculating system used for the forced convective heater used 3 phase, 460 volt, 24 ampere power. Strip heaters internal to the unit and controlled by a PID temperature controller were used to heat the circulating air to the desired set point temperature. The thermocouple and the rms voltage and current data were collected using a personal computer controlled data acquisition system.

## Test Procedure

Two types of tests were conducted: controlled temperature, and system response. In the controlled-temperature tests, experiments were conducted by setting a set point temperature of 350°F and letting the PID temperature controller self tune to the desired set point. In this mode, the controller applied 100 percent power until the control thermocouple reached approximately the halfway point between the initial and set point temperature. At this point the controller determined the ideal PID parameters and adjusted the power. For these tests, the investigated parameters included oven orientation, reflectance of oven walls, and air circulation in the oven. A summary of all the performed tests is given in Table 1. In each case, the average and standard deviation of all the temperature sensors were calculated after the specimen had reached steady state conditions. The settling time, defined as the time required for the temperature sensor located in the center of the test specimen to reach and stay within ±5% of the set point temperature, was measured. The average consumed power was also measured.

In the system response tests, the response time of the heating systems were determined by subjecting them to a step power input. This was accomplished by specifying a fixed power level as a percentage of the maximum power available on the PID temperature controller. This way the true response of the heater/specimen combination could be calculated. The time required for the thermocouple located in the center of the test specimen to reach 63.2 percent of its steady state value was calculated as the time constant. The power level and the overall temperature rise were recorded. All these tests were conducted with the oven in the vertical orientation, with oven wall reflectance being low, and with air circulation.

## Results and Discussion

In the controlled-temperature tests, the PID controller was operated in the self-tune mode. This mode of operation should have produced a critically damped overall system response. However, it was observed that the self-tuning mode of operation sometimes resulted in an underdamped response. The temperature oscillations were sometimes large in magnitude and would take a long time to decay. The settling time and power consumption level determined using these tests were not only a function of the response time and the overall power requirements of the heater and specimen combination, but also a function of the PID parameters chosen by the controller. Therefore, the settling time and power consumption levels are not presented here. The results of the system response tests presented in Table 3 should be consulted for this purpose.

The temperature distributions obtained along the width of the test specimen using the finned strip heaters, with the oven in vertical and horizontal positions, with and without the reflective alzac sheets, and with and without internal air circulation are shown in Figure 5. The temperature distributions along the height of the plate under the same test conditions are given in Figure 6. As seen in this figure the reflectance of oven walls was not a significant parameter, while the oven orientation and internal air circulation were more important. The same results applied to all the other tested heating techniques. Large temperature gradients developed along the test specimen height with the oven in the vertical orientation and without air circulation. This was a result of natural convection, with the rising heated air causing higher temperatures at the top of the test specimen. Adding internal circulation reduced this temperature gradient, causing a more uniform temperature distribution along the plate height. The thermocouple located at the 33 inch vertical position along the plate height would consistently read lower than expected. As expected, internal flow circulation was not an important parameter for the tests with the oven in the horizontal orientation. In these tests, the oven was oriented with the heater located below the test specimen. Even in the absence of forced convection, the plate was heated uniformly. Similar conclusions applied to all the other heating techniques used as shown in Figures 7 through 11.

The summary of the controlled-temperature test results are presented in Table 2. Because the oven wall reflectance was not an important parameter, only the data for low oven wall reflectance are presented in this table. The mean and standard deviation of all the measured temperatures on the test specimen are listed. The ratio of the standard deviation to mean temperature, defined as the temperature non-uniformity ratio, is provided as a non-dimensional comparative measure of non-uniformity between tests. For the tests with the closed loop circulation of heated air and the oven in the vertical orientation, the supply and return lines were switched so that the flow direction would be either against gravity (up) or aligned with gravity (down). The former resulted in a less uniform temperature distribution with a significant temperature variation over the bottom 25 percent of the plate height as shown in Figure 10. The same observation also applied to the tests with frosted quartz lamps and external circulation of cool air as shown in Figure 9. The use of heating blankets resulted in the highest temperature non-uniformity ratios on the test specimen: 18.1 percent in the vertical orientation and 10 percent in the horizontal orientation. For all the other heating techniques the following results were obtained: in the vertical position the temperature non-uniformity ratio was between 7.5 to 9.7 percent for tests without air circulation, but between 1.4 to 3.9 percent for tests with air circulation. Tests in the horizontal orientation with and without air circulation resulted in temperature non-uniformity ratios between 1.2 to 1.9 percent.

The results of the system response tests are presented in Table 3. These include the applied power, the time constant, and the resulting steady-state temperature rise. The ratio of the applied power to the steady-state temperature rise, defined as the efficiency factor, is also provided in Table 3. The finned strip heaters had the longest time constant, 2830 seconds, and an efficiency factor of 8 Watts/°F. The long time constant is due to a much higher thermal inertia associated with the metallic resistance heaters. The clear and frosted quartz lamps, with internal air circulation, had time constants of 1610 and 1570 seconds with efficiency factors of 7.38 and 7.25 Watts/°F, respectively. Their time constants were almost half that of the metallic heaters, while their power ratings were almost identical. The tungsten heating element in a quartz lamps has negligible thermal inertia, resulting in a shorter time constant. The frosted quartz lamps with closed loop circulation of cool air had the lowest time constant, 790 seconds, but an efficiency factor of 18.9 Watts/°F. The closed loop circulation of cool air resulted in a higher convective heat transfer to the plate, and thus a reduced time constant. It also resulted in large convective losses from the test specimen to the cool air, which required higher heating powers applied to the quartz lamps. The closed loop circulation of heated air resulted in a time constant of 1030 seconds with an efficiency factor of 29.1 Watts/°F. The closed loop air circulation unit was a commercially available unit, and was not necessarily the most efficient convective heating system design. A significant amount of heat was lost to the external circulation loop, increasing the total power requirement. In summary, the fastest response time was achieved with frosted quartz lamps with closed loop circulation of cool air and with the closed loop circulation of heated air. The lowest efficiency factor was achieved with quartz lamps with internal air circulation.

## Concluding Remarks

A series of tests were conducted to evaluate different heating methods for heating a large scale specimen to 350°F. This research was motivated by the need to evaluate different heating techniques for efficiently heating large High Speed Civil Transport (HSCT) components for thermal structural testing at temperatures up to 350°F. The heating techniques used included radiative/convective, forced convective, and conductive. The radiative/convective heaters included finned strip heaters, and clear and frosted quartz lamps. The forced convective heating was accomplished by closed loop circulation of heated air. The conductive heater consisted of heating blankets. The test specimen used was an 1/8 inch thick stainless steel plate installed in a custom-built oven. The parameters investigated included air circulation in the oven, reflectance of oven walls, and the orientation of the test specimen and heaters (vertical and horizontal). The criteria used for comparing the different heating methods included test specimen temperature uniformity, heater response time, and consumed power.

It was found that the reflectance of oven walls was not a significant parameter. Air circulation was necessary to obtain uniform temperatures only for the vertically oriented specimen. In the vertical orientation, the temperature non-uniformity ratio was between 7.5 to 9.7 percent for tests without air circulation, but between 1.4 to 3.9 percent for tests with air circulation. For testing a horizontal specimen perpendicular to gravity, air circulation was not necessary to achieve temperature uniformity. Tests in the horizontal orientation with and without air circulation resulted in temperature non-uniformity ratios between 1.2 to 1.9 percent. Heating blankets were found to produce unacceptably high temperature non-uniformities (10 to 18 percent). The frosted quartz lamps with closed loop circulation of cool air and the closed loop circulation of heated air provided the lowest time constant. Quartz lamps with internal air circulation produced the lowest power consumption per unit temperature rise.

The choice of heating technique for large scale structural component testing is based on which parameter is more important to the researcher, the response of the heating system, or the overall power consumption. For faster response time, either quartz lamps with closed loop circulation of cool air, or closed loop circulation of heated air should be used. For lowest power consumption, quartz lamps with internal air circulation should be used.

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Table 1. Listing of Different Test Configurations

| Test Type | Heating Technique | Heat Source | Parameters<br>orientation; circulation; reflectance |
|---|---|---|---|
| controlled temperature | radiative/ convective | finned strip | vertical, horizontal; none, internal; high, low |
| | | clear quartz lamp | vertical, horizontal; none, internal; high, low |
| | | frosted quartz lamp | vertical, horizontal; none, internal, external; high, low |
| | convective | heated air circulation | vertical, horizontal; external; low |
| | conductive | heating blanket | vertical, horizontal |
| system response | radiative/ convective | finned strip | vertical; internal; low |
| | | clear quartz lamp | vertical; internal; low |
| | | frosted quartz lamp | vertical; internal, external; low |
| | convective | heated air circulation | vertical; internal; low |

Table 2. Summary of Controlled-Temperature Test Results

| Heat Source | Orientation; circulation; Flow Direction | Mean Temperature (°F) | Temperature Standard Deviation (°F) | Temperature Non-Uniformity Ratio (percent) |
|---|---|---|---|---|
| finned strip | vertical; none | 339.7 | 33.1 | 9.7 |
| finned strip | vertical; internal | 346.8 | 6.7 | 1.9 |
| finned strip | horizontal; none | 341.5 | 6.4 | 1.9 |
| finned strip | horizontal; internal | 347.4 | 4.2 | 1.2 |
| | | | | |
| clear quartz lamp | vertical; none | 332.3 | 25 | 7.5 |
| clear quartz lamp | vertical; internal | 341.9 | 4.9 | 1.4 |
| clear quartz lamp | horizontal; none | 341.4 | 5.6 | 1.6 |
| clear quartz lamp | horizontal; internal | 342.1 | 5.1 | 1.5 |
| | | | | |
| frosted quartz lamp | vertical; none | 330.7 | 30.4 | 9.2 |
| frosted quartz lamp | vertical; internal | 337.4 | 12.6 | 3.7 |
| frosted quartz lamp | horizontal; none | 339.9 | 6 | 1.8 |
| frosted quartz lamp | horizontal; internal | 342.1 | 5.7 | 1.7 |
| frosted quartz lamp | vertical; external; down | 340.3 | 10 | 2.9 |
| frosted quartz lamp | vertical; external; up | 338 | 13.3 | 3.9 |
| frosted quartz lamp | horizontal; external; lateral | 342 | 6.2 | 1.8 |
| | | | | |
| Heated air circulation | vertical; external; down | 344.2 | 5.9 | 1.7 |
| Heated air circulation | vertical; external; up | 338.2 | 10.9 | 3.2 |
| Heated air circulation | horizontal; external; lateral | 346 | 4.7 | 1.4 |
| | | | | |
| Heating blankets | vertical | 385.1 | 69.9 | 18.1 |
| Heating blankets | horizontal (heater on top) | 326.94 | 30.1 | 9.2 |
| Heating blankets | horizontal (heater on bottom) | 344.41 | 37 | 10.7 |

Table 3. Summary of System Response Test Results

| Heat Source | Circulation | Applied Power (Watts) | Time constant (seconds) | Steady-state Temperature Rise (°F) | Efficiency Factor (Watts/°F) |
|---|---|---|---|---|---|
| | | | | | |
| finned strip | internal | 1794.2 | 2830 | 224.1 | 8.01 |
| clear quartz lamp | internal | 2388.2 | 1610 | 323.5 | 7.38 |
| frosted quartz lamp | internal | 2434.9 | 1570 | 335.6 | 7.25 |
| frosted quartz lamp | external | 2151.7 | 790 | 113.5 | 18.9 |
| heated air circulation | external | 2600 | 1030 | 89.3 | 29.1 |

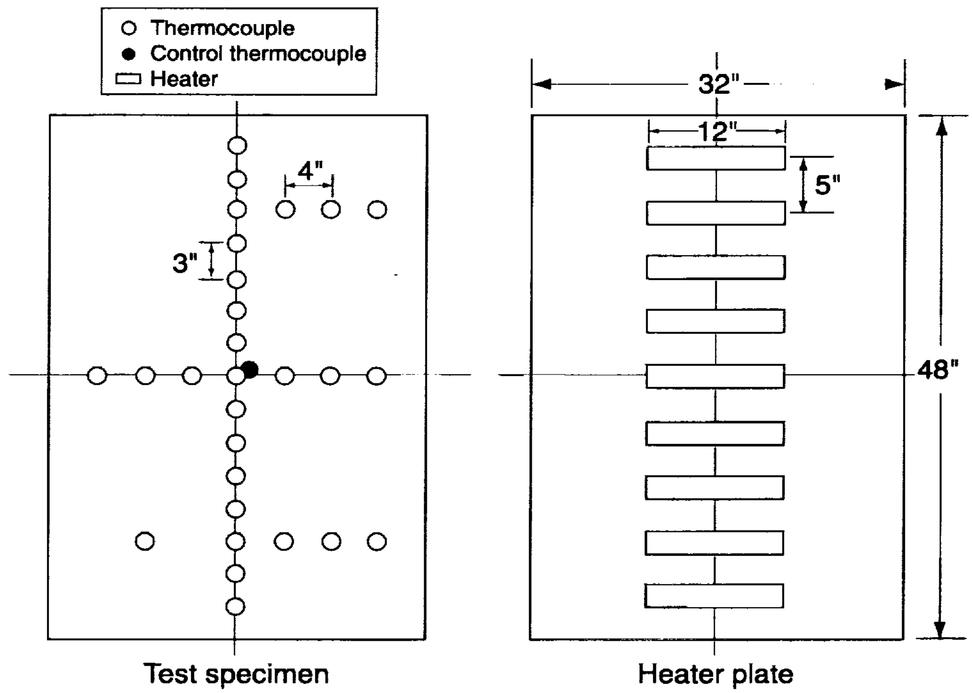


Figure 1. Schematic showing thermocouple and heater layout.

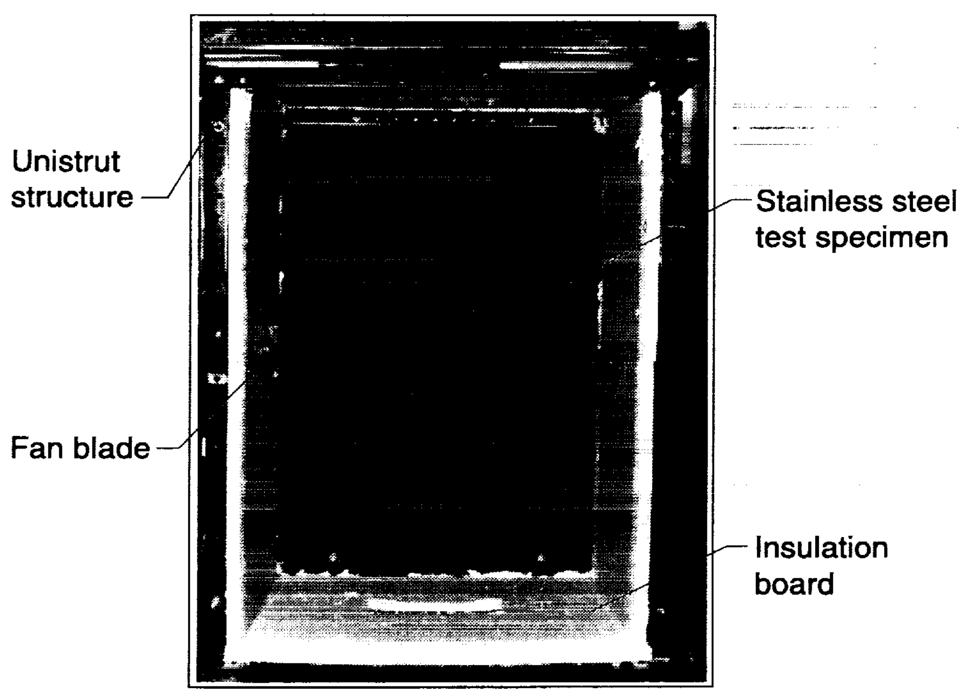


Figure 2. Picture of the oven.

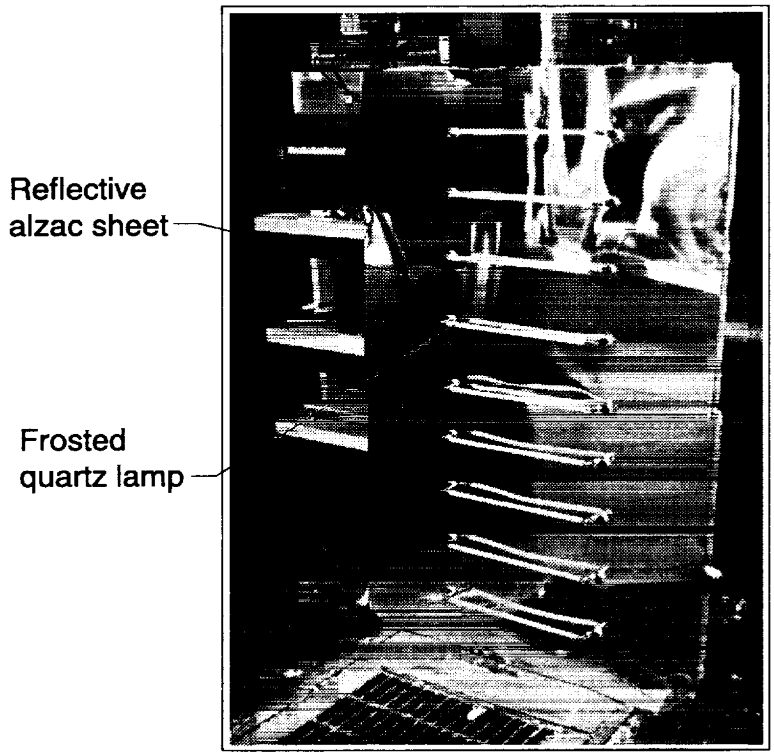


Figure 3. Picture of the heated wall of the oven with mounted frosted quartz lamp.

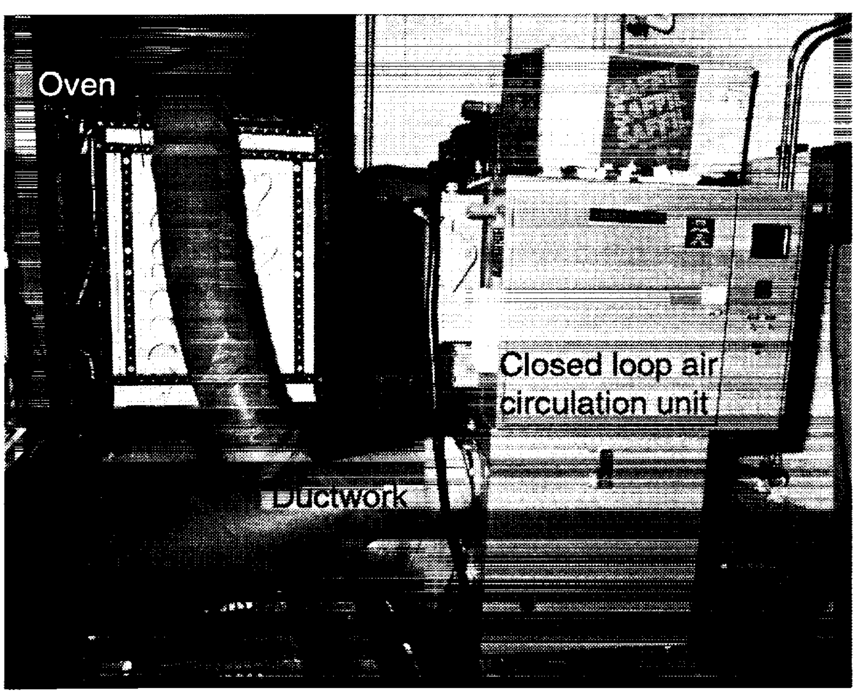


Figure 4. Picture of the commercially available closed loop air circulation unit.

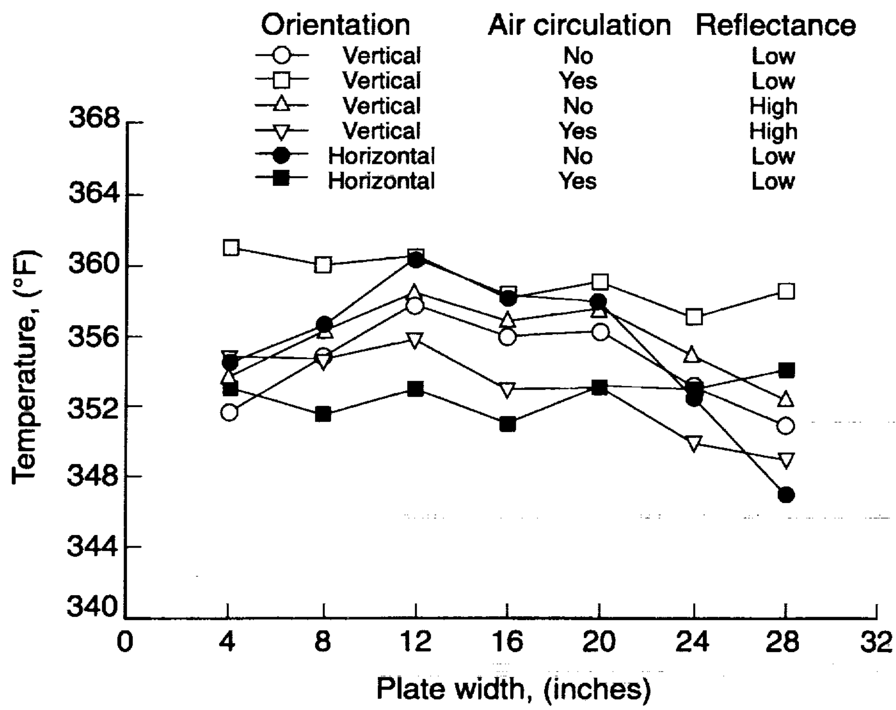


Figure 5. Temperature distribution along the width of the test specimen using finned strip heaters.

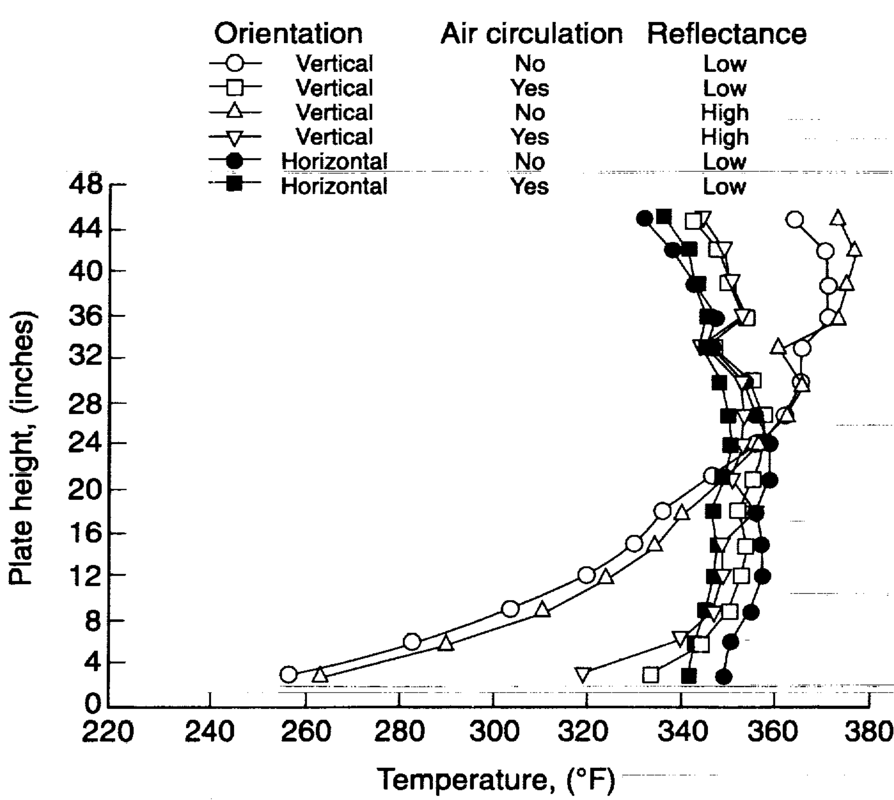


Figure 6. Temperature distribution along the height of the test specimen using finned strip heaters.

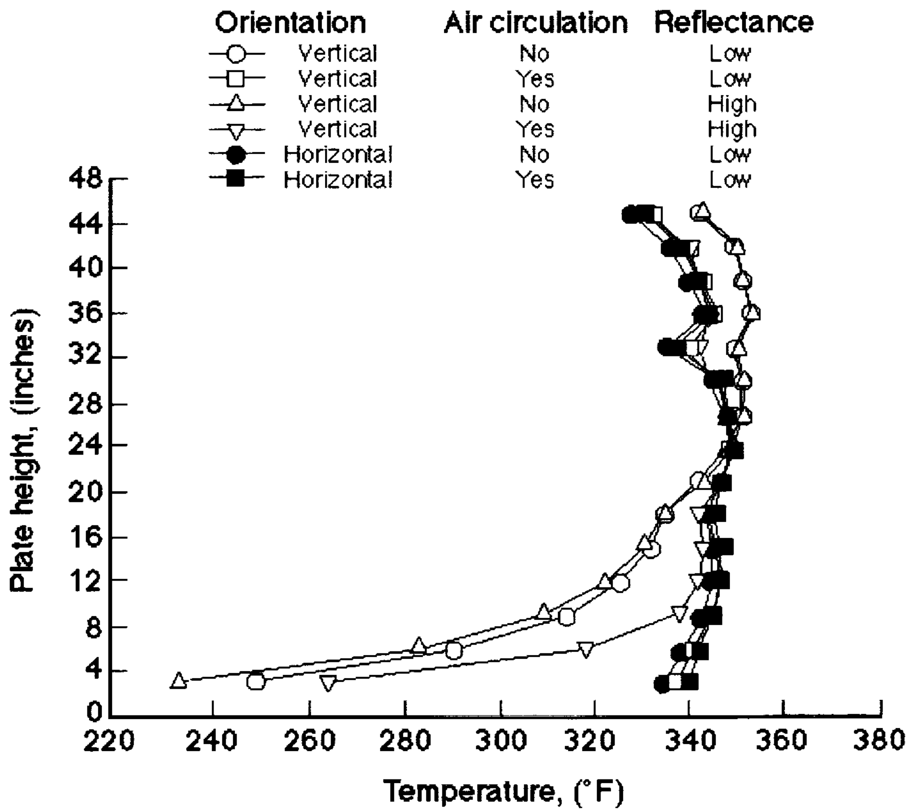


Figure 7. Temperature distribution along the height of the test specimen using clear quartz lamps.

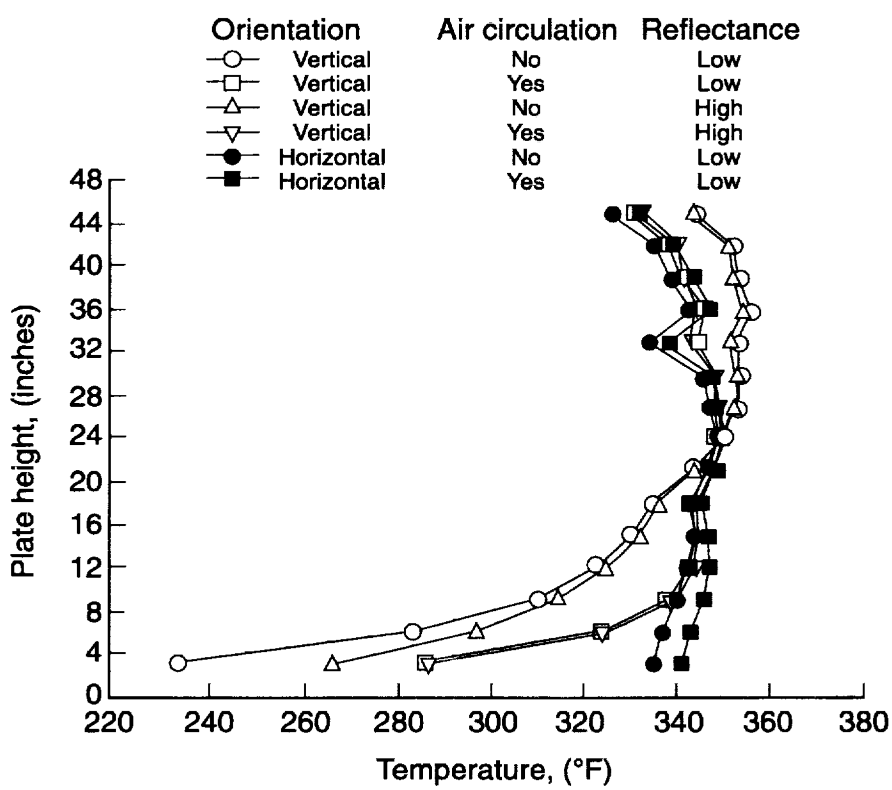


Figure 8. Temperature distribution along the height of the test specimen using frosted quartz lamps.

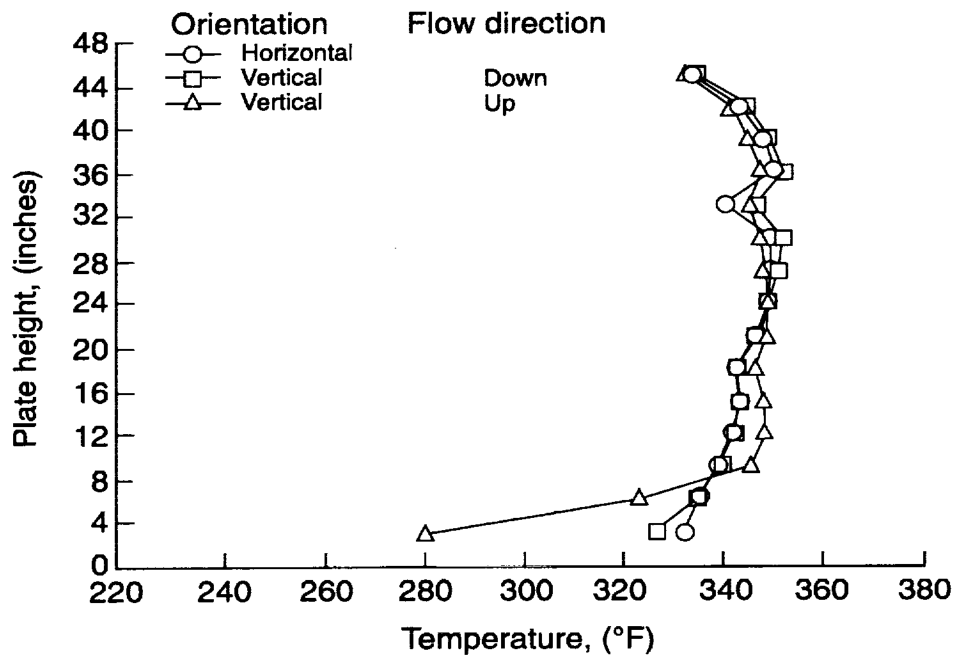


Figure 9. Temperature distribution along the height of the test specimen using frosted quartz lamps with closed loop circulation of cool air.

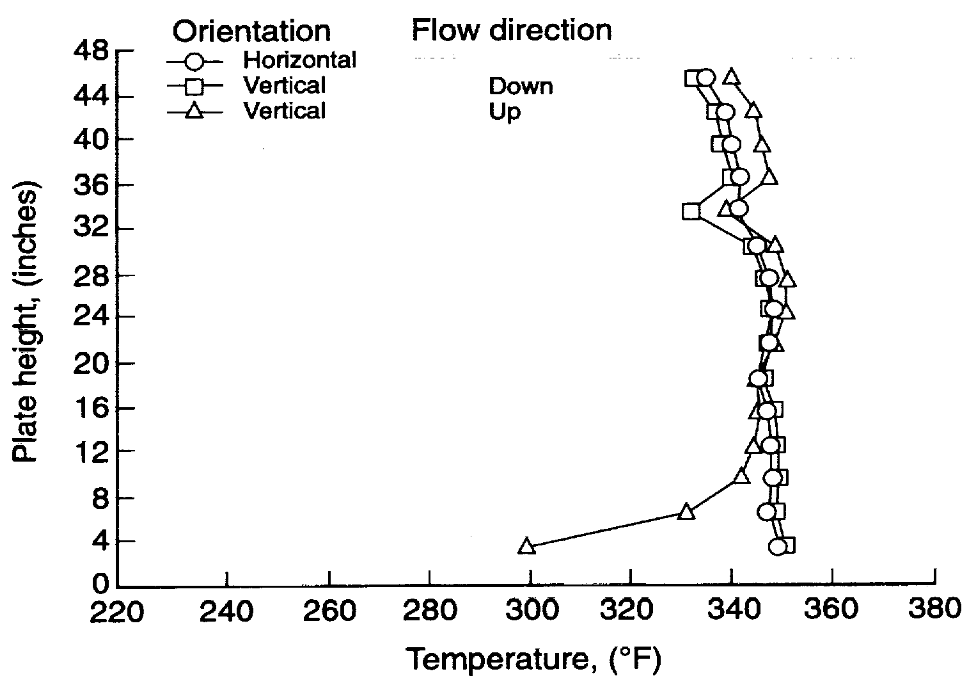


Figure 10. Temperature distribution along the height of the test specimen using closed loop circulation of heated air.

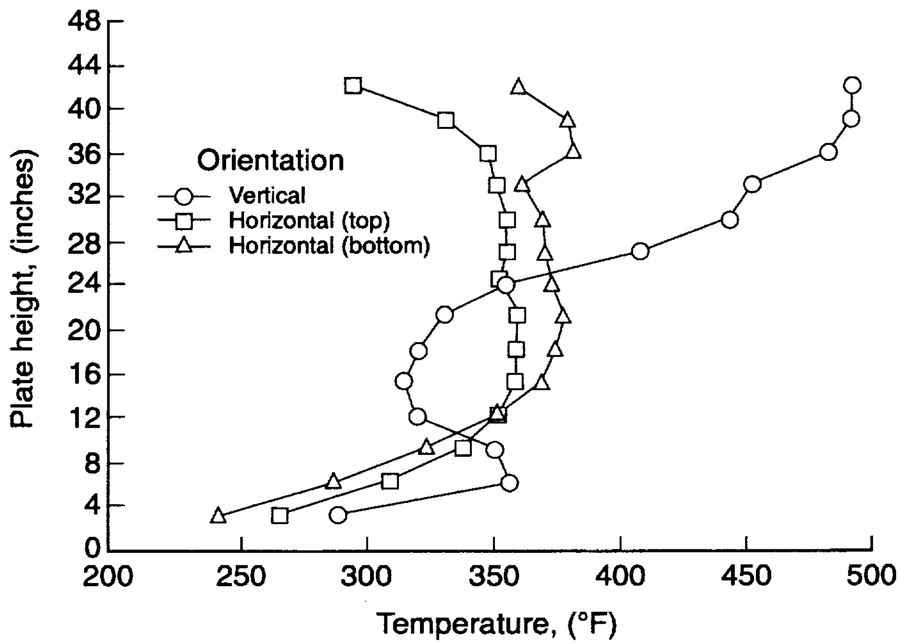


Figure 11. Temperature distribution along the height of the test specimen using heating blankets.

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