Flux Mapping of Radiant Electric Heaters

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1. Introduction

The U.S. Consumer Product Safety Commission (CPSC) staff reports that in 1999, electric heaters were associated with an estimated 4600 fire incidents[1]. Those incidents resulted in approximately 50 deaths, 290 injuries, and $109.8 million of property loss. The cause of many of the incidents is reported to be heaters too close to combustible materials. Since air heaters do not raise a material's surface temperature to its ignition point, it is possible that a significant portion of the incidents involved radiant electric heaters.

Radiant heaters possess characteristics that are different from other types of room heaters. While most fan-forced and natural-convection heaters create warm air, radiant heaters primarily generate infrared (IR) radiation. This radiation impinges on objects in front of the heater and warms their surfaces. Heaters that create warm air cannot raise the temperature of an object in the air flow path above the exhaust temperature, typically between 100° and 200° Celsius. Radiant heaters transfer heat proportional to the 4th power of the absolute temperatures of the heat source and the heat sink. Equation (1) gives the general form of the heat flux q'' (watts/area), between two bodies[2].

$$q'' = F_e F_G s \; (T_1^4 - T_2^4) \qquad (1)$$

where: F_e = The emissivity function
F_G = The geometric view factor
s = Stefan-Boltzmann constant, 5.669×10^{-8} W/(m^2 K^4)
T_1 = The temperature of the warmer body, K
T_2 = The temperature of the cooler body, K.

The heating element of a radiant electric heater reaches temperatures of 100s of degrees Celsius. The Underwriters Laboratories Inc. (UL) voluntary standards UL 1278 *Movable and Wall-or Ceiling-Hung Electric Room Heaters*, and UL 2021 *Fixed and Location-Dedicated Electric Room Heaters*, define a radiant heater as one with a "visibly glowing element," whose visible portion attains a temperature of at least 650 °C (923 K). No upper limit for heating element temperature is specified in the voluntary standards. Element temperatures this high insure a high energy flux from the heater into its environment. Reflections from shiny surfaces behind the heating element add to the total flux impinging on an object in front.

Consequently, the possibility exists that common combustibles in proximity to a radiant heater can be heated to ignition. Air heaters avoid igniting combustibles in two ways. First, no commonly-found materials ignite at the air temperatures exhausted by the heater. Second, air itself possesses a low heat capacity and is not effective in transferring large amounts of energy onto objects. Radiant energy transmission is capable of continuing to heat an object's surface until its temperature approaches that of the heating element. With ignition temperatures ranging from 233 °C for paper to 590 °C for wool[3], there is the prospect for materials with high emissivities and high geometric view factors to absorb enough IR energy to ignite.

In the voluntary standards UL 1278 and UL 2021, radiant electric heaters are evaluated using a series of performance tests, typically draping the heater with standardized combustible materials (fire indicators) or positioning the heater against a surface covered with combustible materials. A pass/fail criterion is assessed by observing ignition, emission of glowing particles, etc., within a fixed time. While this type of qualitative evaluation is easily observable, it lacks the ability to consider all the circumstances in which an electric heater may be used and can not determine "how close" the unit under test came to igniting the test materials during the test. Variations in the testing materials may have a significant effect on the outcome of the performance tests[4].

The use of fire indicators and performance tests is a qualitative and indirect way to assess whether a radiant electric heater poses a risk of igniting combustibles under foreseeable use conditions. A more quantitative and direct way (without the confounding effects of test materials) to evaluate a radiant heater would be to measure the radiant flux, and compare the maximum values to the flux necessary to ignite said combustibles. If the maximum flux values are below those required for ignition (the critical flux), such ignition is unlikely. Measured flux values above the critical flux are of more concern. The flux is a measure of energy density, not of total heat output.

2. Purpose

The purpose of this report is to demonstrate the feasibility of directly measuring the radiant flux from portable and fixed-position electric heaters. A simple method is employed, and "maps" of the radiant flux as a function of position in three axes are generated. This data is compared to prior CPSC staff work on the flux required to ignite common combustibles to assess the likelihood of ignition under foreseeable use conditions.

CPSC staff believes that using flux measurements can evaluate the ability of a radiant heater to ignite combustibles with greater standardization and repeatability than current qualitative tests. The use of flux measurements also minimizes confounding factors associated with testing materials. CPSC staff believes that this information will be useful in support of future research and discussions among knowledgeable experts concerning the potential development of quantitative testing methods for heating appliances.

CPSC staff believes that the data presented in this report is insufficient on its own to serve as the basis for any proposed changes to the voluntary safety standards UL 1278 and UL 2021. The findings discussed in this report should be used to help assess the desirability of establishing new testing methods in terms of the advantages, limitations, costs, timeliness, and utility of radiant flux measurement methods.

3. Past Studies

Prior CPSC staff reports examined the flux characteristics of electric heaters and the ignition performance of various fire indicators commonly used in safety tests. Different flux measurement techniques were used in the earlier reports than those presented in this study, and thus different results were obtained. However, it is beneficial to examine past research for completeness and to put current results into the context of decades of investigations into flux measurement techniques. Future standardization of a testing method would be expected to reconcile differences in the data generated by the various tests.

a. Flux Measurements

Electric heater flux measurements are possible using commercially-available equipment. A flux sensor is typically a thermopile (or just two thermocouples) with some of the elements separated from others by a layer of thermal resistance. When illuminated with IR radiation, the temperature difference between the two sets of elements is proportional to the incident flux. This temperature difference is expressed as a voltage on the sensor's output conductors. By measuring the voltage as the sensor is moved around in front of a heater, the position of maximum flux can be located, or a map of flux magnitudes can be generated.

In 1987, CPSC staff studied portable electric heaters[4]. A portion of the evaluation involved flux measurements on 16 models. A vertical and horizontal scan across each heater was made. Cotton batting was positioned in front of each model as an ignition test, the results of which were compared to the heater's maximum flux reading. Open flaming of the batting was achieved with an incident flux of as low as 0.54 W/cm^2. Flaming ignition with other heaters was also observed with fluxes in the range between 0.76 and 1.14 W/cm^2.

In 2000, as a part of an evaluation of fixed-position electric heaters, CPSC staff conducted flux measurements on two radiant electric heaters[5]. Both heaters were then subjected to the terrycloth and curtain draping tests described in UL 2021. At six inches from the heaters' grills, the radiant flux from the heaters was measured at 0.23 and 0.64 W/cm^2, respectively. The heater with the lower flux passed the draping tests (no flame, molten particles, etc.); while the heater with the higher flux quickly ignited the draped materials. Later testing measured over 2 W/cm^2 at a one-inch distance from the grill on the heater with the higher flux.

In 2001, in correspondence to Underwriters Laboratories, CPSC staff reported on flux measurements made on five portable radiant electric heaters[6]. Heat flux values from 0.34 to 1.24 W/cm^2 were recorded. The heaters with the higher flux values were more likely to ignite cotton materials that were placed against their grills.

b. Fire Indicator Measurements

In 2002, CPSC staff conducted a study on the radiant ignition properties of commonly used fire indicators, irrespective of the heat source or distance[7]. This study reported the critical heat flux required for ignition for various paper and cotton materials. The critical heat flux for the materials tested ranged from a low of 1.37 W/cm^2 (beige towel) to a high of 4.7 W/cm^2 (cheesecloth). Cotton duck canvas was found to have a critical heat flux of 1.52 W/cm^2.

A further CPSC staff study on fire indicators was undertaken in 2003[8]. The report showed that the surface density (in Kg/m^2) of the <u>standardized</u> cotton duck testing material failed to meet the requirements of UL 2021. Variations in the material properties of the fire indicators are confounding factors in the evaluation of heaters. Experiments demonstrated that the radiant flux required for ignition was a strong function of the number of layers of material tested and their mounting configuration, both confounding effects of a heater's evaluation. Relatively heavy materials (bed sheets, cotton duck, and terrycloth) were observed to have critical heat fluxes in the range of 0.8 to 1.2 W/cm^2. The lighter materials (cheesecloth, paper towels, and newsprint) had critical heat fluxes in the range of 1.1 to 2.5 W/cm^2. A critical heat flux of the of cotton duck used in the 2003 tests was about 1.7 W/cm^2, as indicated by Cone Calorimeter testing.

The study of fire indicators shows that the test materials themselves can have an effect on the result of a heater's evaluation. The different materials and methods used in the two fire indicator studies complicate the task of comparing their results. Standard testing textiles manufactured at different times have been shown to possess different thermal properties. Furthermore, before a heater evaluation can be attempted, the testing materials require a long period of conditioning to control their moisture content.

4. Test Method

CPSC staff constructed maps of the heat flux magnitude versus position for four models of portable and fixed-position (wall-insert) radiant electric heaters. This approach consisted of identifying a coordinate origin on the unit under test, then recording the position (height, width and distance from the heater) and flux for the various heat flux sensor locations.

The sensor used is a commercially-available device with a circular active surface area of 1.27 cm^2 (0.5 in^2), and a voltage output that is proportional to the incident radiant flux. The sensor is a Schmidt-Boelter type with a sensitivity of 3.21 mV per W/cm^2. In order to keep the sensor from thermal equalization during testing, cold water in a single-pass flow system was pumped through the sensor. Figure 1 shows a picture of the sensor used.

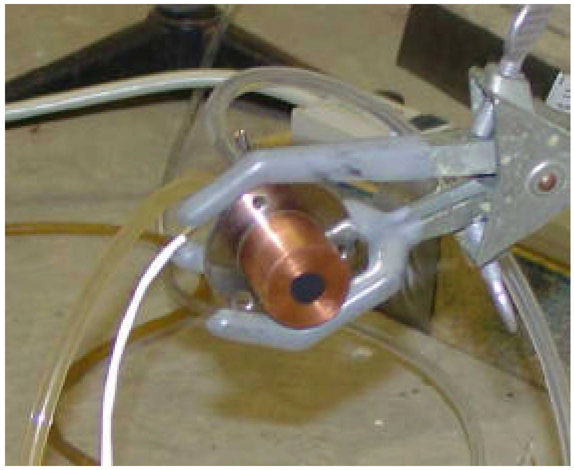

Figure 1: Radiant Flux Sensor

The sensor was placed in a clamp and mounted on a wooden block as a stand. A grid was marked on the floor of the testing area in 2-cm increments. The grid provided the width and distance from the grill (X and Z) measurements. The height (Y) was set by moving the clamp holding the sensor vertically on its support. Figure 2 shows a picture of the sensor and its support. Figure 3 shows the marked grid on the testing room floor.

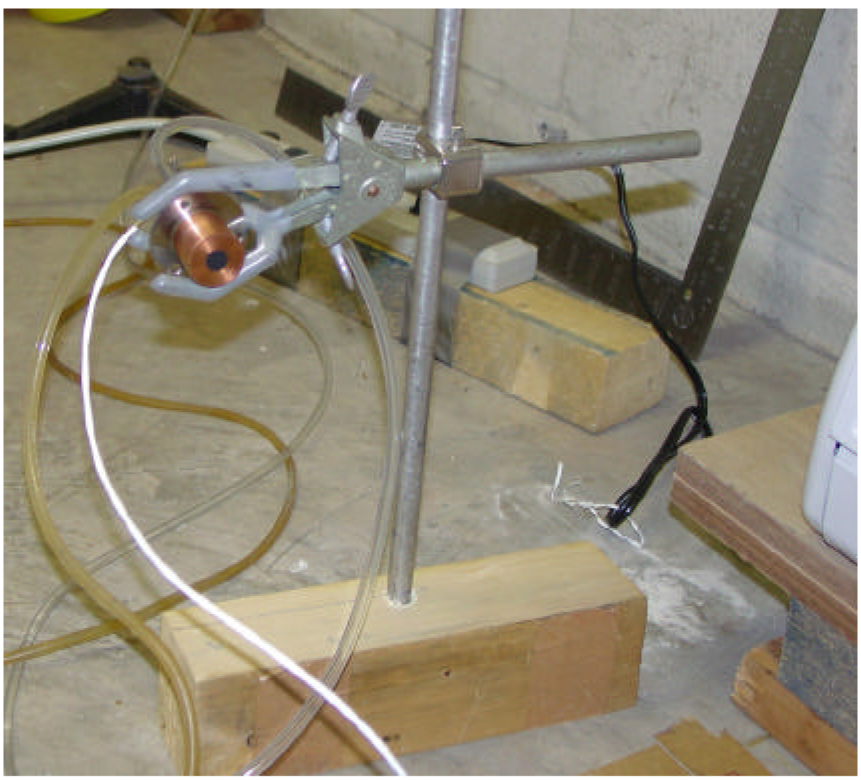

Figure 2: Sensor Mounting

Figure 3: Floor Grid

The coordinate origin on each heater was aligned with the grid on the floor so that positioning the sensor relative to the grid also positioned the sensor relative to the X- and Z-axes coordinate origin position. The initial vertical position of the sensor, when lined up with the heater's coordinate origin position, was the Y-axis origin position. After measuring the vertical height of the Y-axis origin position, subsequent vertical positions were achieved by raising the sensor in 2-cm increments.

For this test assembly, the position of the sensor had to be controlled in 5 degrees of freedom: X, Y, Z, T_X, and T_Y (T_X, and T_Y are degrees of freedom that refer to rotation about the X and Y axes, respectively.). After each vertical repositioning of the sensor, the position and tilt of the sensor was checked and re-zeroed if necessary. Figure 4 illustrates the coordinate system used with the heaters.

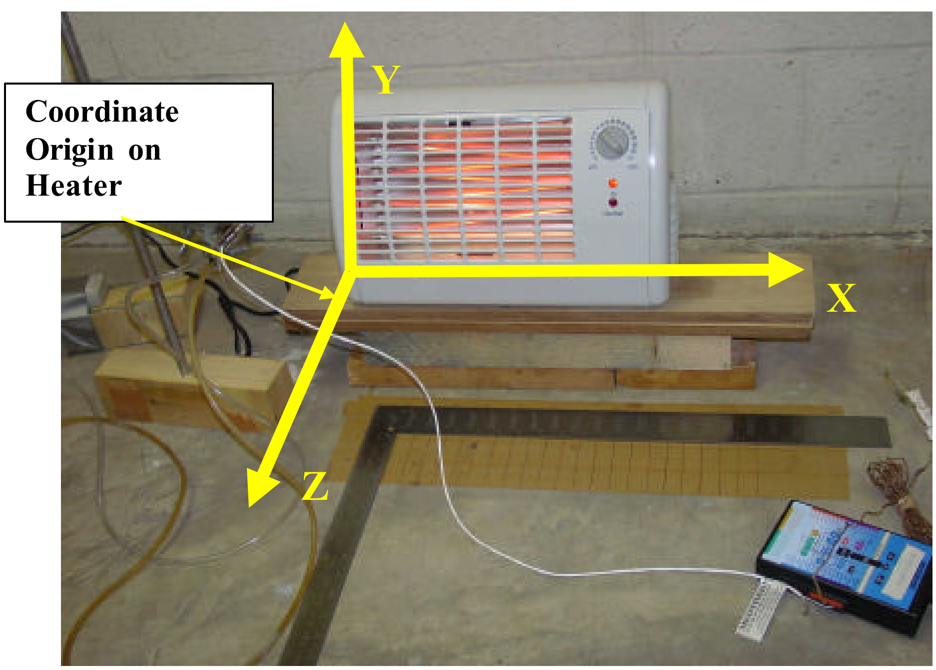

Figure 4: Heater Coordinate System

The choice of the coordinate origin point on each heater was arbitrary. The position was chosen to be at the lowest Y-position at which flux measurements were to be made, and approximately 2 cm left of the grill edge. Measurements were made left-to-right for a given vertical height. Three distances from the heater grill (the Z dimension) were chosen for flux measurements: 2 cm, 5 cm, and 10 cm.

The procedure for mapping the flux from a heater was as follows: After a Y-position was set, the sensor was set at the X = 0, Z = 2 cm position, and moved across the X dimension. Then, the sensor was repositioned at the X = 0, Z = 5 cm position, and another horizontal data set was recorded. This was repeated at the X = 0, Z = 10 cm position. By continually positioning and sampling the sensor, a map of the radiant flux at a given depth was recorded with a personal computer running data acquisition software. Spreadsheet software was used to process the data and plot the magnitude of the radiant flux as a function of X, Y, and Z positions. Repeated measurements varying the sensor's initial position and direction of sensor travel did not affect the flux values recorded.

5. Test Results

a. Heater A

Heater A is a portable heater, rated at 1320 Watts. This appliance complies with the requirements of UL 1278. The device is approximately 38 cm wide by 24 cm tall by 15 cm deep (15 inches by 9.5 inches by 6 inches). The ribbon-style heating element zigzags eight times across the heating chamber. Behind the element is a matte-finished steel reflector. The front face of the heater curves back slightly from bottom to top. The heating element inside Heater A slopes back slightly, following the curve of the grill. The heater has no legs, contains a small fan to circulate air internally, and includes a continuously-variable thermostat. The enclosure is made of painted steel. Figure 5 shows pictures of the heater's front and side views. Figure 6 shows the location of the coordinate origin.

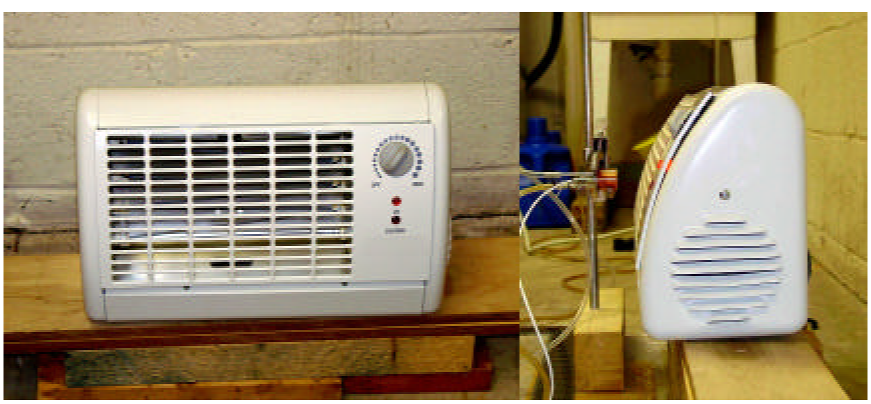

Figure 5: Heater A Front and Side Views

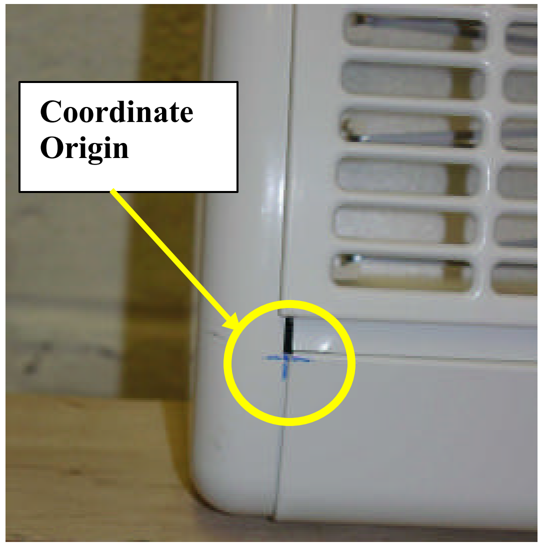

Figure 6: Coordinate Origin on Heater A

Figures 7, 8, and 9 show the maps of the radiant flux from Heater A at Z = 2 cm, 5 cm, and 10 cm, respectively, from the coordinate origin of the heater. Because the upper portion of the heater is "behind" the lower portion (due to the backwards curve of the cover), the heat flux sensor was farther from the grill for those readings with higher vertical values.

None of the data from the flux measurements were smoothed prior to plotting, in order to preserve any information on localized flux maxima or other features of the flux distribution.

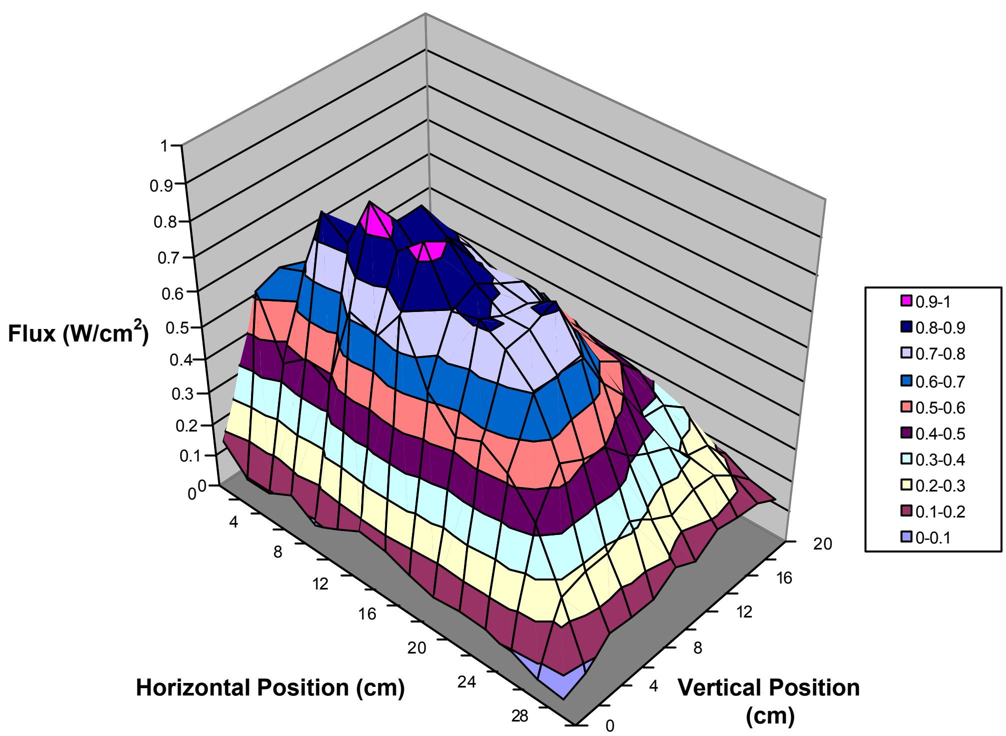

Figure 7: Heater A Flux Map, Sensor Position = 2 cm from the Heater Front

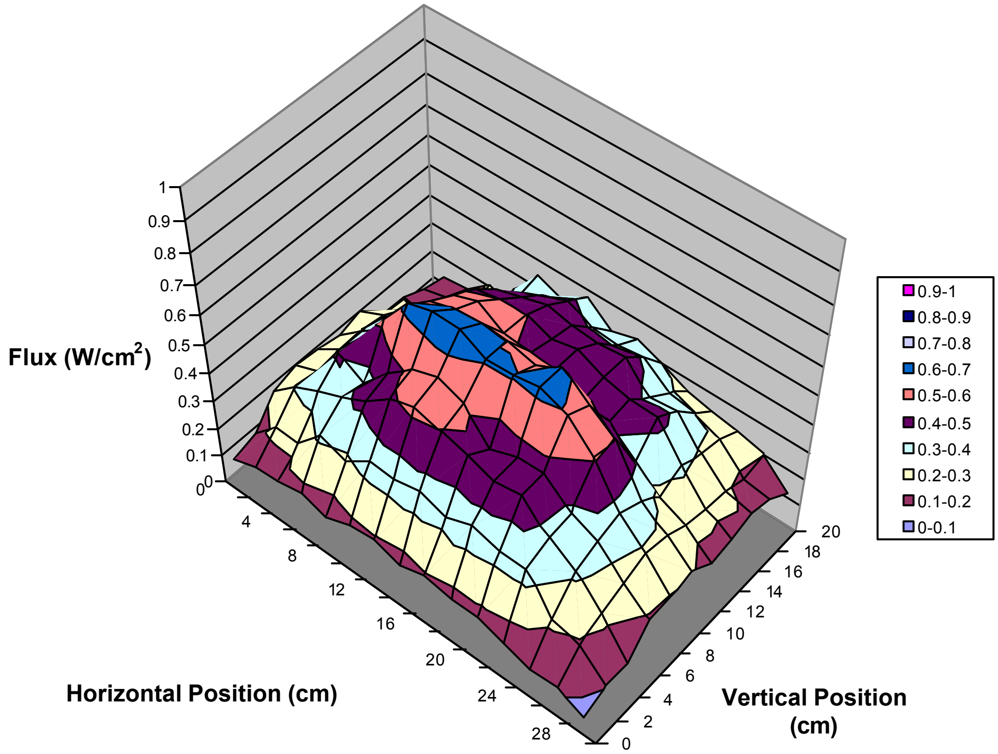

Figure 8: Heater A Flux Map, Sensor Position = 5 cm from the Heater Front

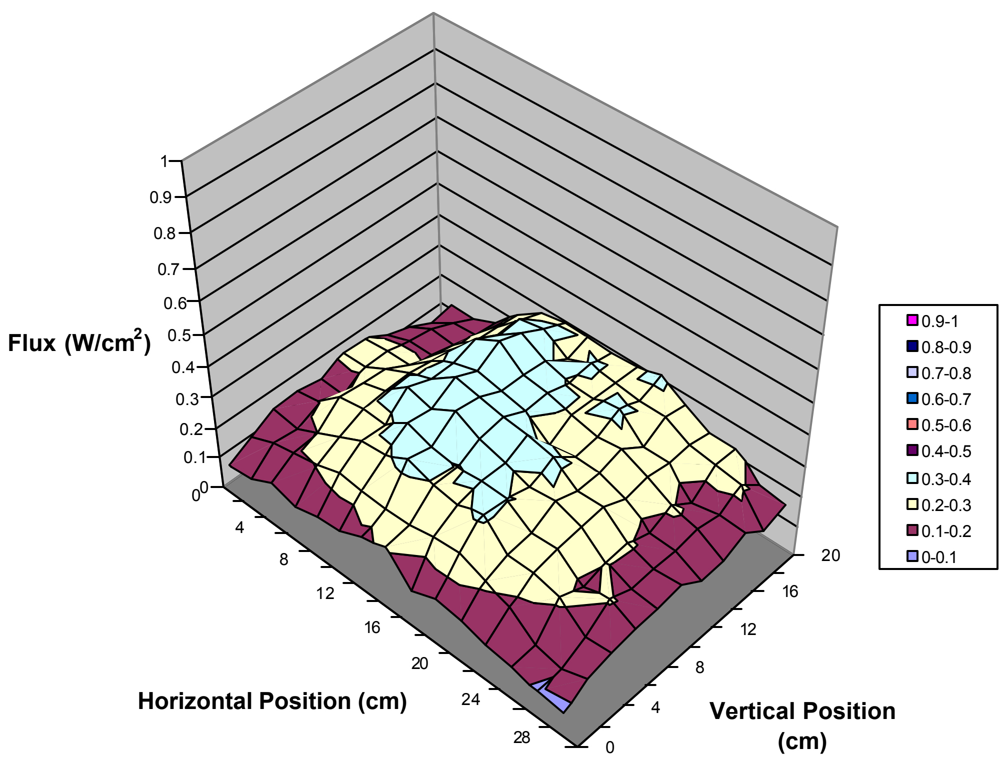

Figure 9: Heater A Flux Map, Sensor Position = 10 cm from the Heater Front

The heat flux maps show generally smooth profiles with decreasing magnitudes as a function of the Z distance. The heater's grill did not seem to have a strong effect on the flux measured at any one position. The Z = 2 cm map shows higher magnitudes at the bottom of the heater. The maximum recorded flux is found at coordinates X = 10 cm, Y = 4 cm, Z = 2 cm. This location is near the center of the grill, but close to the bottom, rather than towards the vertical center of the grill, as might be expected. The magnitude of the maximum heat flux is 0.97 W/cm^2.

b. Heater B

Heater B is a fixed-position heater, rated at 1000 Watts. This appliance complies with the requirements of UL 2021. The device is approximately 32 cm wide by 43 cm tall by 5.1 cm deep (12.5 inches by 17.125 inches by 2 inches). The steel sheathed heating element is positioned vertically in an aluminum enclosure, which serves to reflect the IR radiation outwards. A steel mesh grill covers the front of the heater and holds the thermostat. Figure 10 shows a picture of the heater. Figure 11 shows the location of this heater's coordinate origin.

Figure 10: Heater B

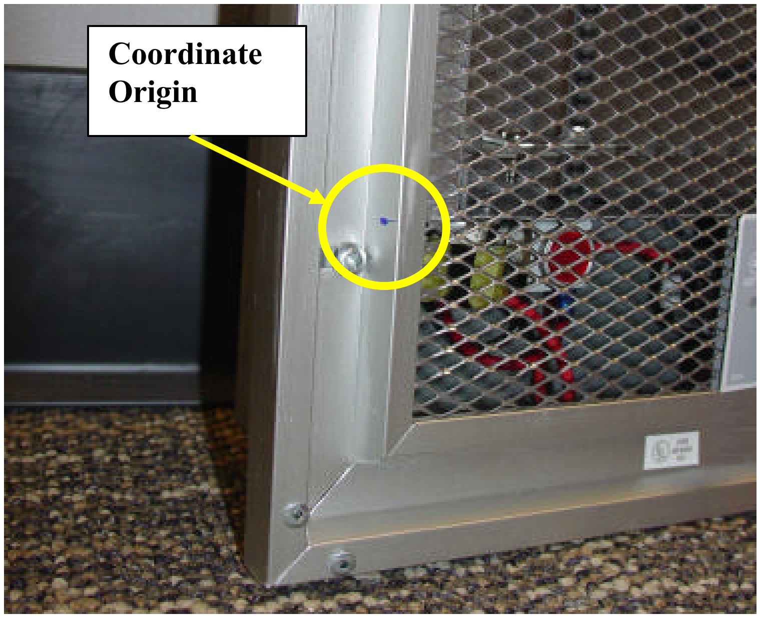

Figure 11: Coordinate Origin on Heater B

Figures 12, 13, and 14 show the maps of the radiant flux from Heater B at Z = 2 cm, 5 cm, and 10 cm, respectively from the coordinate origin of the heater.

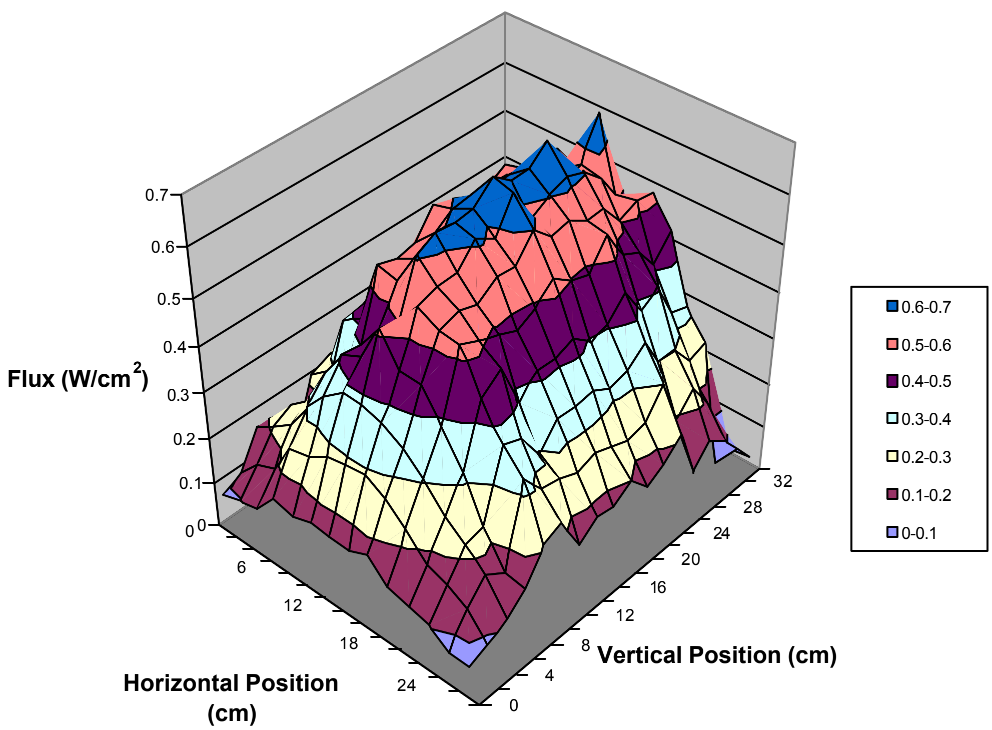

Figure 12: Heater B Flux Map, Sensor Position = 2 cm from the Heater Front

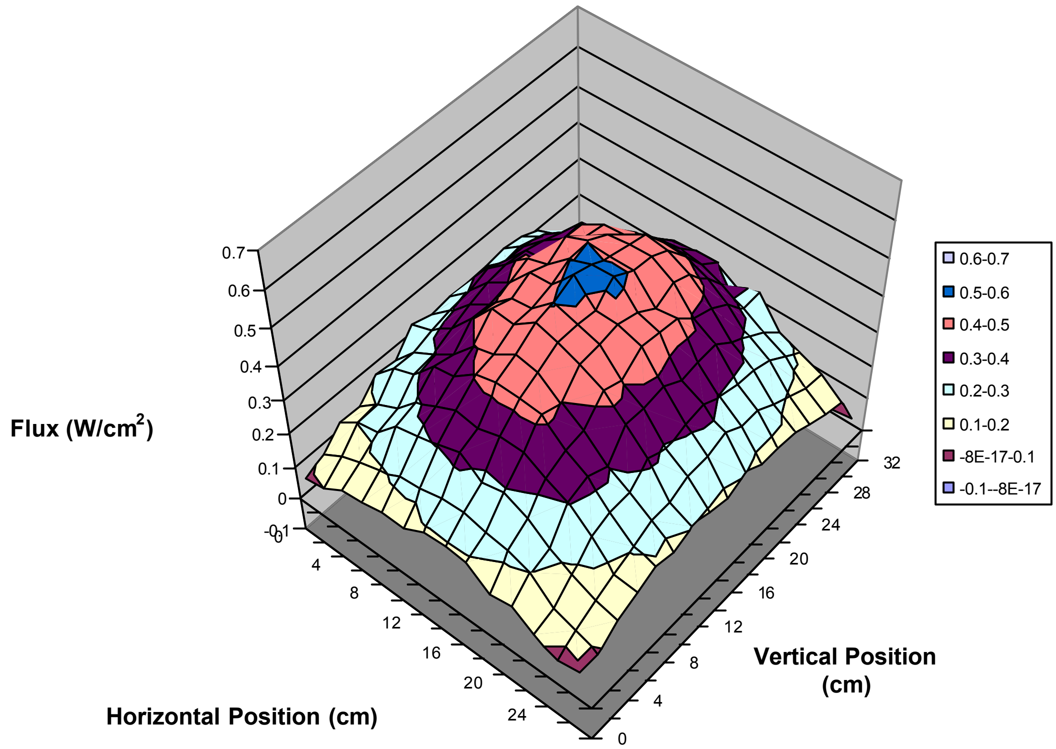

Figure 13: Heater B Flux Map, Sensor Position = 5 cm from the Heater Front

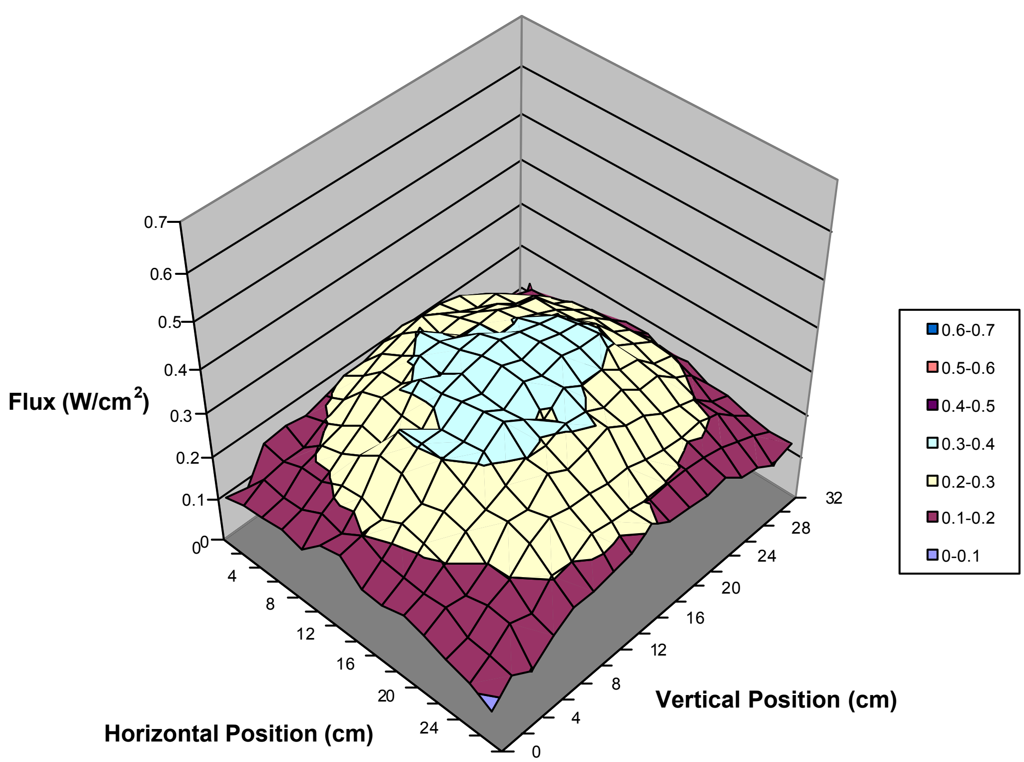

Figure 14: Heater B Flux Map, Sensor Position = 10 cm from the Heater Front

The heat flux maps also show smooth profiles with decreasing amplitudes as a function of the Z distance. The mesh on the heater's grill is considerably smaller than the active area of the flux sensor, which would tend to mask any IR radiation blocking effects. The maximum recorded flux is found at coordinates X = 12 cm, Y = 18 cm, Z = 2 cm. This numerical maximum is in a large area in the heater center where several flux amplitudes are approximately equal. The flux spike near the top of the heater appears to be an anomalous reading that is not repeated at other Z distances from the heater. The magnitude of the maximum heat flux is 0.66 W/cm^2.

c. Heater C

Heater C is a portable heater, rated at 1500 Watts. This heater complies with the requirements of UL 1278. The device is approximately 38 cm wide by 29 cm tall by 17 cm deep (15 inches by 11.25 inches by 6.75 inches). The ribbon-style heating element zigzags 10 times across the heating chamber, with 3 additional loops behind the bottommost loops. Thus, half of the heating element is in the bottom third of the heating enclosure. Behind the element is a square shiny steel reflector. With the legs attached, this heater's front face leans slightly backwards. The heater has a small fan to circulate air internally and includes a continuously-variable thermostat. The enclosure is made of painted steel with plastic side panels. The central vertical bar on the grill has flattened areas that have a larger surface area than Heater A and Heater B grills. Figure 15 shows pictures of the heater's front and side views. Figure 16 shows the location of the coordinate origin.

Figure 15: Heater C Front and Side Views

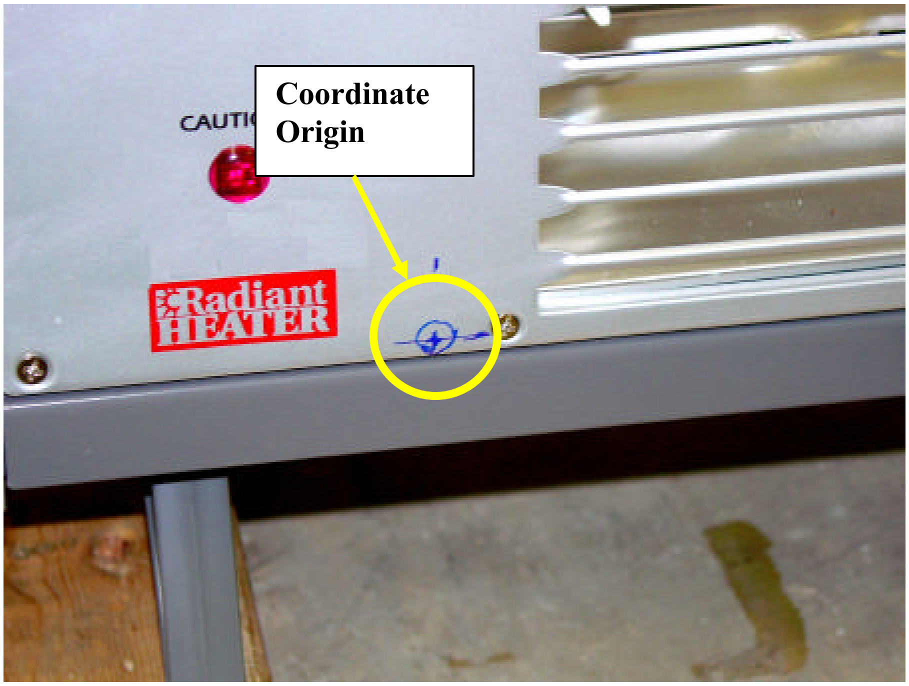

Figure 16: Coordinate Origin on Heater C

Figures 17, 18, and 19 show the maps of the radiant flux from Heater C at Z = 2 cm, 5 cm, and 10 cm, respectively from the coordinate origin of the heater. As with Heater A (but to a much smaller degree), the upper portion of the heater is farther from the heat flux sensor than is the lower portion of the heater.

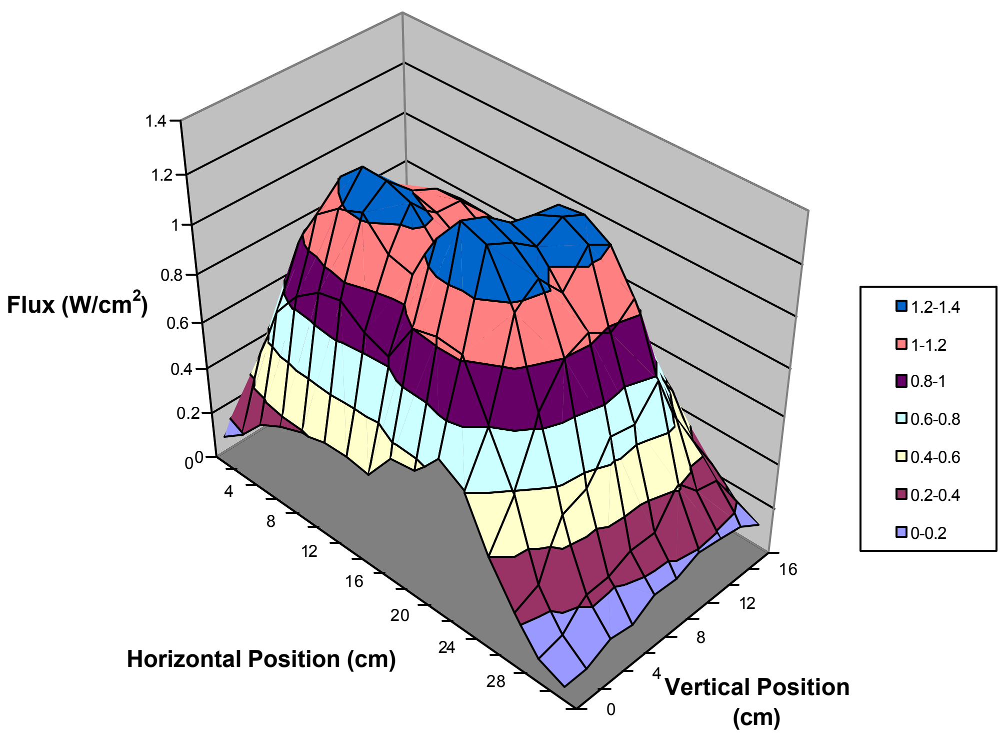

Figure 17: Heater C Flux Map, Sensor Position = 2 cm from the Heater Front

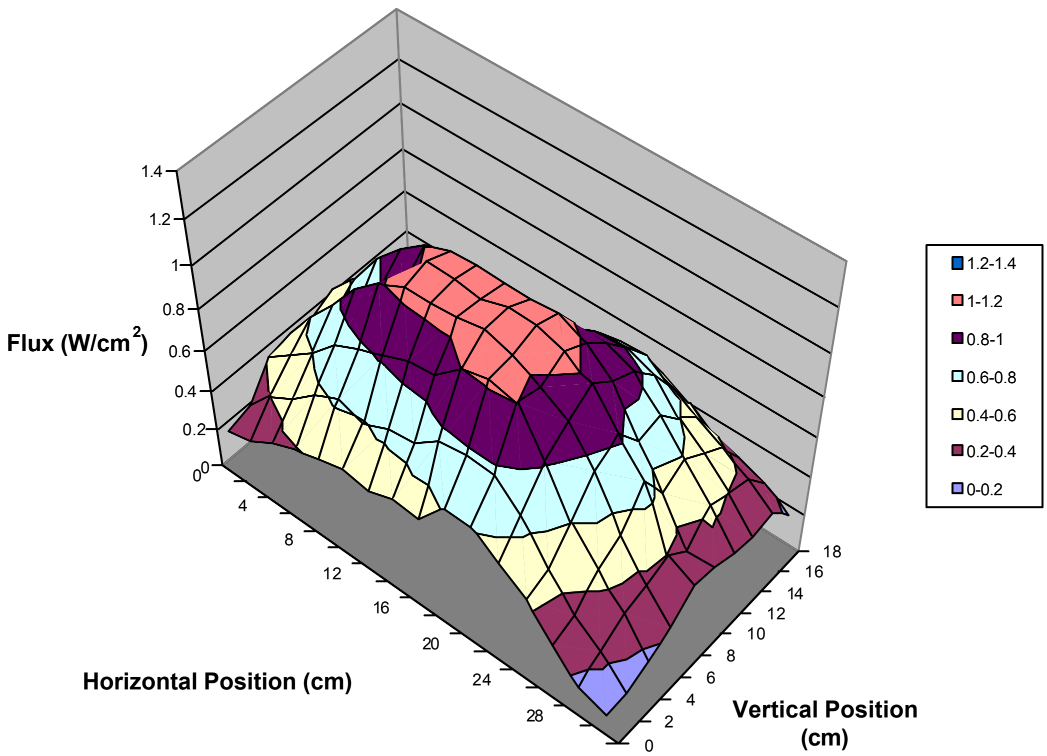

Figure 18: Heater C Flux Map, Sensor Position = 5 cm from the Heater Front

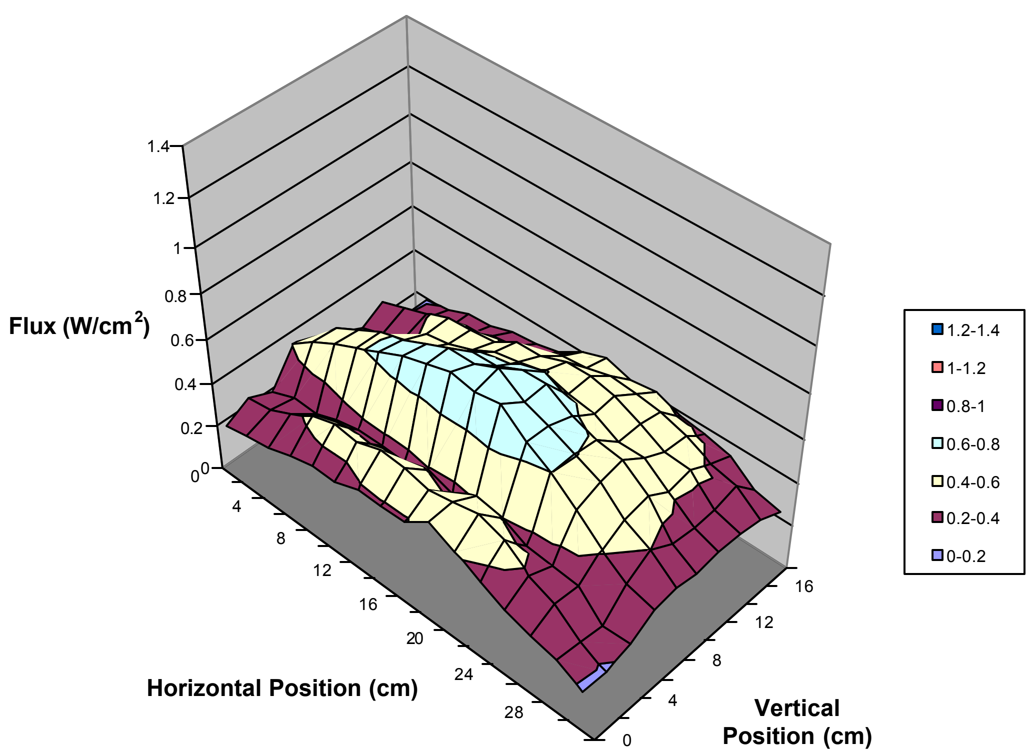

Figure 19: Heater C Flux Map, Sensor Position = 10 cm from the Heater Front

The heat flux maps a lumpy profile at the Z = 2 cm distance and smooth profiles with decreased amplitudes at Z = 5 cm and Z = 10 cm. The bar in the center of the grill noticeably attenuated the radiant flux emitted from the heater in that area for the Z=2 cm map. The resultant flux map shows three distinct local maxima, one on the left side and two on the right. The radiant flux emitted from the heater is not symmetric. There are no features on the grill or the reflector behind the heater to indicate that this would be the case, either for the left-right magnitude asymmetry or the top-bottom asymmetry on the right side. A visual examination of the heater shows symmetry with regards to the heating element positioning and reflector shape.

The magnitude of the maximum heat flux is 1.41 W/cm^2. The maximum recorded flux is found at coordinates X = 18 cm, Y = 4 cm, Z = 2 cm. This is off-center of the right-side grill area, slightly closer to the vertical bar. The vertical position of the maximum flux is approximately in the center of the area where 5 loops of the heating element are located.

d. Heater D

Heater D is a fixed-position heater, rated at 1500 Watts. This appliance complies with the requirements of UL 2021. The device measures approximately 28 cm wide by 51 cm tall by 7.6 cm deep (11 inches by 20 inches by 3 inches). The heating element is an open coil mounted in a ceramic block 22 cm wide by 13 cm tall (8.5 inches by 5 inches). An aluminum grill covers the front of the heater. The thermostat for this heater is positioned at the bottom center. Figure 20 shows a picture of the heater. Figure 21 shows the location of this heater's coordinate origin.

Figure 20: Heater D

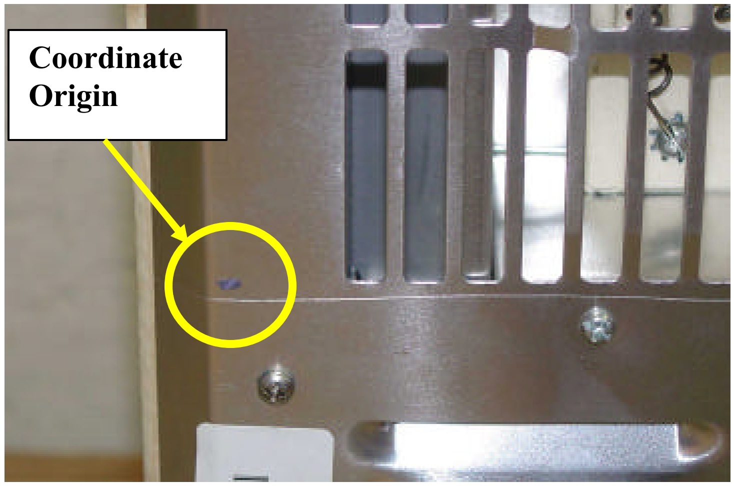

Figure 21: Coordinate Origin on Heater D

Figures 22, 23, and 24 show the maps of the radiant flux from Heater D at Z = 2 cm, 5 cm, and 10 cm, respectively from the coordinate origin of the heater.

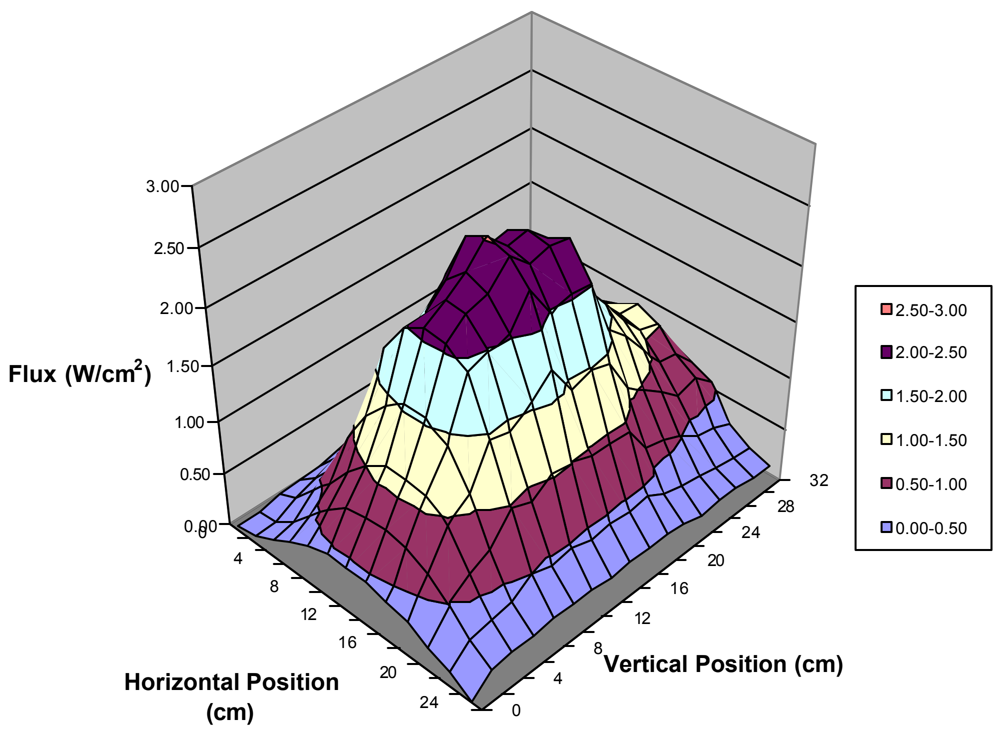

Figure 22: Heater D Flux Map, Sensor Position = 2 cm from the Heater Front

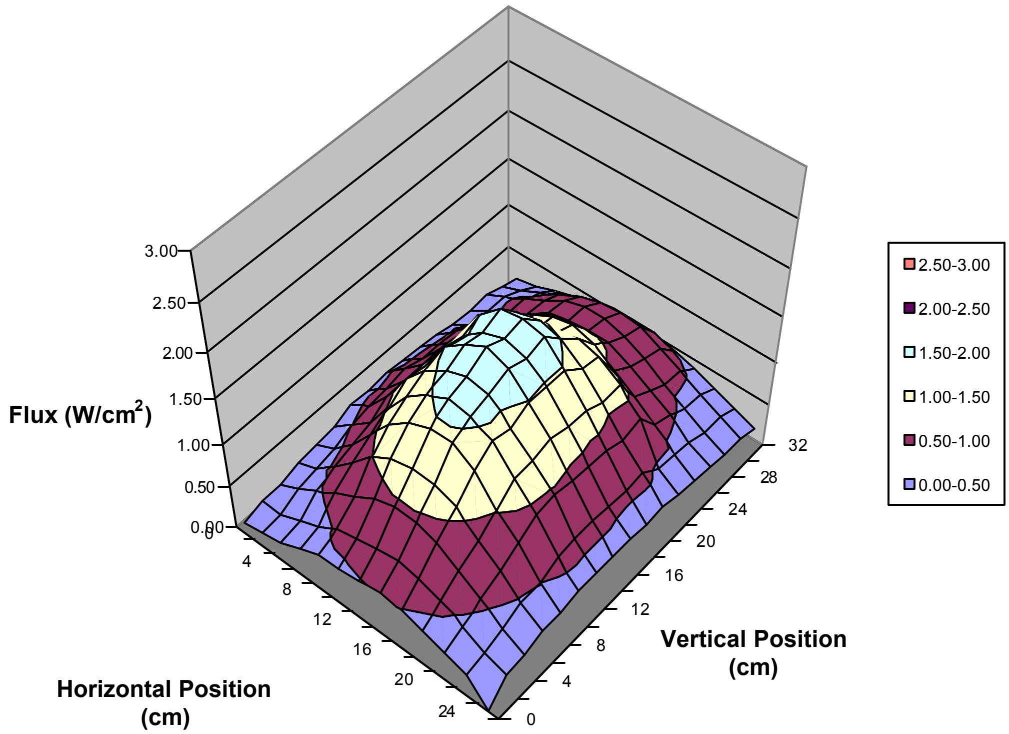

Figure 23: Heater D Flux Map, Sensor Position = 5 cm from the Heater Front

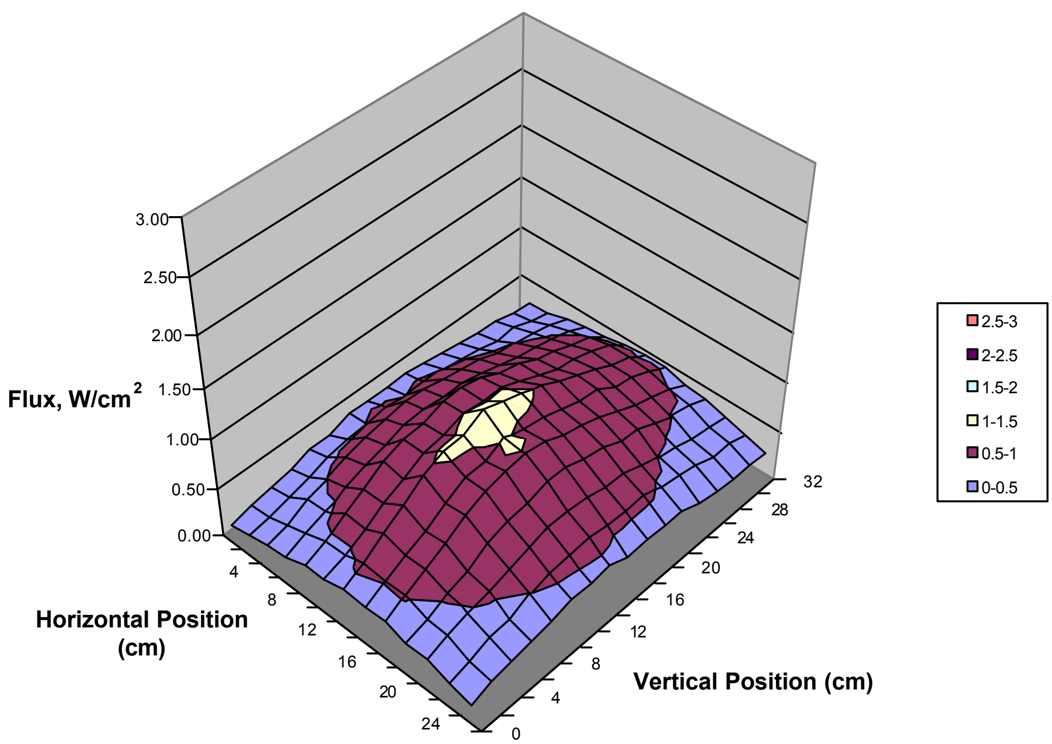

Figure 24: Heater D Flux Map, Sensor Position = 10 cm from the Heater Front

The heat flux maps show very high amplitudes relative to the other heaters tested. Even at Z=10 cm, a flux above 1.1 W/cm^2 was measured. The heating element's ceramic mounting block precludes reflection of IR radiation from the coil off the rear of the heater. The grill does not seem to show any blocking of the IR radiation from the coil for the sensor used. The maximum recorded flux is found at coordinates X = 14 cm, Y = 12 cm, Z = 2 cm. This is approximately at the center of the heating element. The magnitude of the maximum heat flux is 2.53 W/cm^2.

6. Discussion

a. Test Method

Measurement of the radiant heat flux as a function of position for electric heaters was found to be a straightforward task. Proper calibration of the heat flux sensor, adequate control of the sensor's position in five degrees of freedom, and the ability to keep the sensor cool during testing were the only criteria required to generate accurate data. None of those factors is highly sensitive to use or varies appreciably during testing. This implies that robust processes for evaluating radiant heaters can be developed using heat flux sensors for radiant heater evaluation. The staff believes that automating the sensor positioning and data collection would be an uncomplicated task.

There are advantages to quantitatively measuring the performance of an electric heater over observing the result of a pass/fail threshold test.

1. Relative results can be generated through measurements. An estimate of "how close" a unit under test comes to igniting a test material is not available with pass/fail evaluations. By comparing the measured heat flux with known critical heat fluxes for fire indicator materials, an estimate of the likelihood that a unit could ignite combustibles in a consumer setting can be made.
2. Non-obvious or second-order effects of the heater design and construction can be observed. If the reflector and heating element geometry tend to focus the IR radiation and create a local "hot spot," that focal point can be found without extensive optical analyses.
3. The area of maximum flux is readily identified without assuming the emission pattern of the radiated emission.
4. The confounding effects inherent in testing material variability are eliminated.
5. The performance effects of a design change in a heater can be quickly evaluated. Fire indicator sample preparation requires long conditioning periods to minimize the effects of variable moisture content and sample aging.

b. Heater Testing

The heat flux maps identified the area of maximum amplitude for each heater. Heater C has 3 local flux maxima, a characteristic that would be difficult to discern by visual observation. The asymmetry of the emission became readily apparent once the map was generated. Heaters A and C have their highest radiant emission at the bottom of their grills, rather than towards the center as might be expected. The amplitude of Heater D's maximum radiant flux was found to be over 380% higher than the other fixed-position heater, Heater B, and almost 80% higher than the other 1500 Watt heater, Heater C. The flux magnitude indicates that this Heater D may be more likely to ignite nearby combustibles than other models.

c. Correlation with Fire Indicators

Previous studies found the critical heat fluxes of some of the tested materials to be in the range of 1.1 to 1.4 W/cm^2. Two of the heaters tested (Heaters C and D) have radiant flux emissions equal to or above those levels. This indicates that they may be more likely than Heaters A and B to ignite nearby combustibles in consumer settings.

7. Conclusions

Radiant heater flux measurements were demonstrated as relatively simple and repeatable. Flux mapping can be used to identify the location and amplitude of maximum emission of a radiant electric heater. The map data is available for any desired efforts to shape the emission pattern or control the amplitude of heat flux from a radiant electric heater. Correlation with fire indicator critical heat fluxes is straightforward. If experiments with fire indicators are used to establish a permissible maximum flux for a radiant heater, the materials, their preparation, and the test procedures should be carefully considered.

8. References

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