U.S. CONSUMER PRODUCT SAFETY COMMISSION

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FIRE INDICATORS

Engineering Project Report

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Introduction

The heat flux – or heat energy per unit area – produced by some electrical appliances may be sufficient to create a fire hazard by igniting surrounding combustibles. Various combustible materials are specified in a number of voluntary standards for heat-producing appliances to serve as indicators of the potential for ignition as a result of contact with or exposure to hot surfaces. The fire indicators are typically fabrics, textiles or other relatively thin fibrous materials, such as surgical cotton or cotton gauze. The use of such materials can provide an assessment of the potential presented by heat-producing devices for ignition of ordinary household combustibles, but does not provide a quantitative measure of the heat energy required to ignite combustibles that are likely to be near such devices. In addition, fire indicators can be affected by environmental conditions, such as humidity; and differences in manufacturing practices may also affect the ability of the fire indicator to consistently and accurately demonstrate a fire hazard.

If a maximum heat flux value that will not result in ignition of household combustibles could be determined, a voluntary standard requirement for mapping of the heat flux generated by an appliance could be developed. If the measured heat flux were below the maximum, the product would pass. If not, the product would fail. Data resulting from heat flux mapping would also provide manufacturers information that could lead to further product safety improvements.

Purpose

The purpose of testing described in this report was to quantify the heat flux required to ignite various household combustibles and fire indicators and to measure the heat fluxes generated by several consumer appliances. The heat flux values measured for the appliances were compared to the minimum heat flux required to ignite combustibles (fire indicators and household combustibles). The data acquired from these tests may be used to determine a baseline value for heat flux mapping tests.

Heat Flux Measurements of Electrical Appliances

Heat flux measurements were recorded for seven household heat-producing appliances. The appliances included an iron, a toaster oven, two in-wall air heaters, and three toasters. The intended purpose of this testing was to determine approximate heat flux values produced by appliances that may be present in consumers' homes. Engineering Sciences staff performed this testing at the CPSC Engineering Laboratory.

A heat flux transducer is a sensor that can directly measure heat transfer rates. The transducer converts the heat transfer rate to a proportional millivolt signal. The range for the transducer was 0 – 2 W/cm^2 although the specifications allow for an overrange of 150% of the full range or to 3 W/cm^2. Tubes are included on the transducer to introduce water into the transducer to cool it and maintain a relatively stable temperature. According to the users manual, water is not required for measurements that will not increase the temperature of the face of the transducer above 400 °F. Water was not used for any of the testing except where mentioned. A Heat Flux Meter was used to provide a digital readout in heat flux units.

Iron

The charts below show the results of heat flux tests for an iron. The iron was filled with water and set on the highest heat setting. Figure 1 shows the data collected during a horizontal scan from left to right. This scan was performed at approximately the vertical center of the sole-plate of the iron, with the transducer as close to the sole-plate as possible without touching it. The maximum recorded heat flux value was 0.17 W/cm^2. The unusual shape of the graph is easily explained by the construction of the iron – the heating element is located near the outside edge of the sole-plate – hence, higher values are measured near the left and right edges of the iron.

Figure 1. Heat Flux of Iron at Sole-Plate (Horizontal Scan)

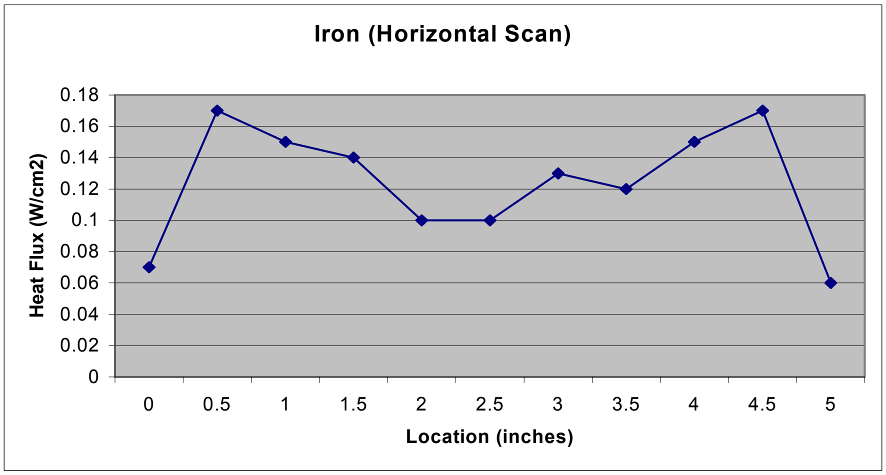
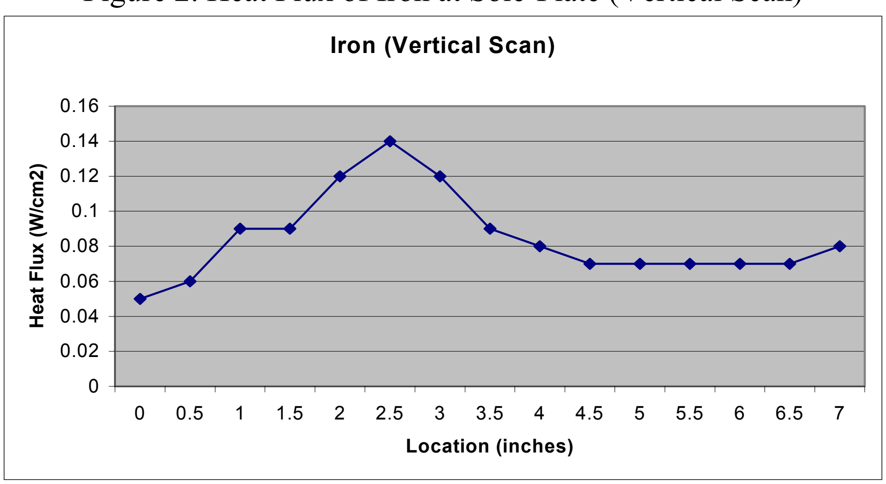


Figure 2 shows a vertical scan from the top down at the approximate center of the sole-plate (the 2.5-inch mark shown in Figure 1 above). The shape of the sole-plate was typical of irons sold today, with the top forming a point and spreading out at the bottom. The peak value of 0.14 W/cm^2 at the 2.5-inch mark was where the heating element was located. The graph shows that the heat transfer rate is lower and more consistent near the bottom of the iron. This is due to the fact that the heat energy is spread out over a wider area near the bottom of the iron.

Figure 2. Heat Flux of Iron at Sole-Plate (Vertical Scan)



Toaster Oven

The charts below show the results of heat flux tests for a toaster oven in which the oven was set at 500 °F. Figure 3 shows a vertical scan from the top to the bottom of the toaster oven, adjacent to the door handle, and with the transducer approximately 0.25 inch away from the front of the toaster oven. The graph shows that the maximum heat flux was located approximately 0.5 inch from the top of the toaster oven; this is the location of the top edge of the door. The maximum value recorded was 0.45 W/cm^2.

Figure 3. Heat Flux of Toaster Oven/Oven Mode (Vertical Scan)

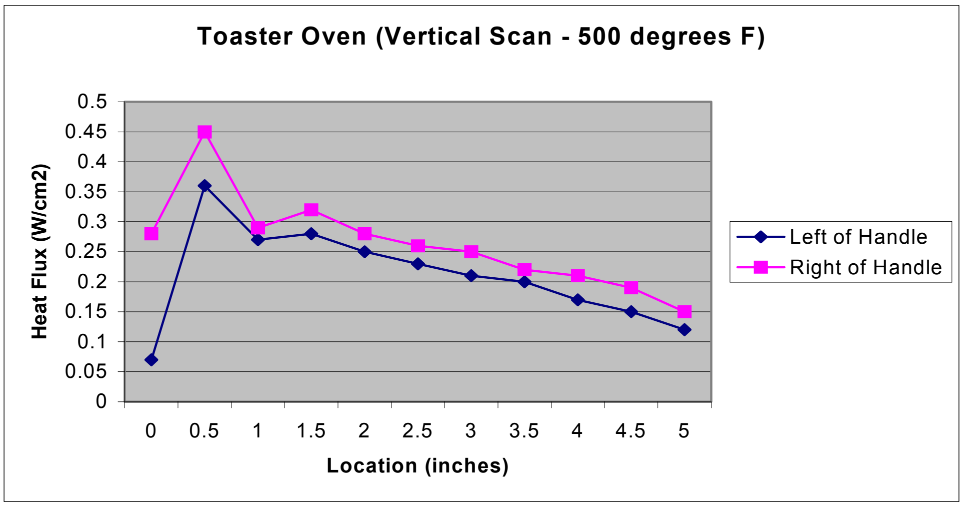
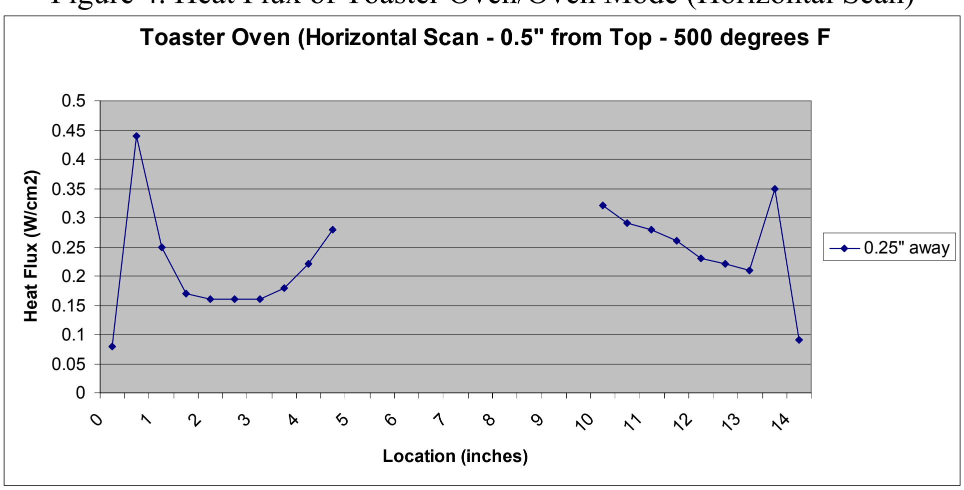


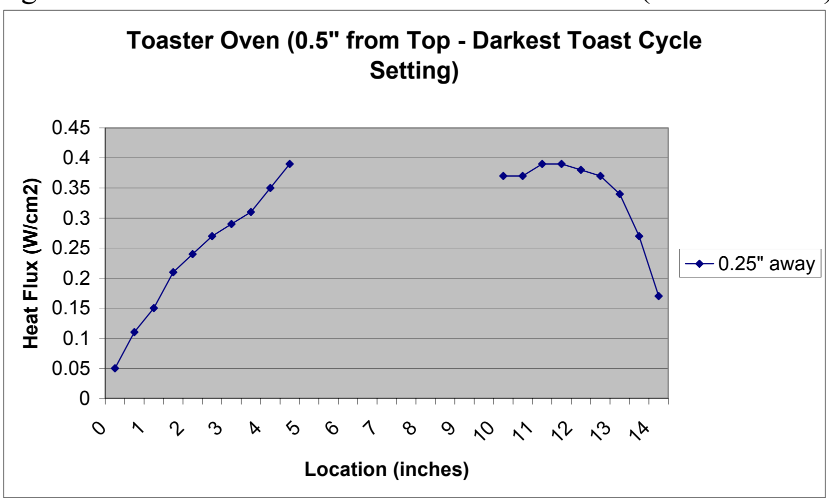
Figure 4 shows the horizontal scan, from left to right, of the front of the toaster oven at approximately 0.5 inch from the top. The transducer was held approximately 0.25 inch from the toaster oven. The graph shows a gap in the data, which corresponded to the location of the door handle and which interfered with the placement of the heat flux transducer. Again, the maximum heat fluxes were recorded at the edges of the door, with the left edge having the maximum heat flux of 0.44 W/cm^2.

Figure 4. Heat Flux of Toaster Oven/Oven Mode (Horizontal Scan)



The next chart shows the results of heat flux tests for the toaster oven while being used in the toast mode, at the darkest toast cycle setting. During these tests, the toast cycle was started and allowed to complete one toast cycle while monitoring and recording the maximum measured heat flux. Figure 5 below shows the horizontal scan, from left to right, of the front of the toaster oven at approximately 0.5 inches from the top. The transducer was held approximately 0.25 inches from the toaster oven. Each data point in the graph corresponds to a separate toast cycle. Again, the graph shows a gap in the data, which corresponds to the location of the door handle. In this mode, the maximum heat flux was slightly lower than that measured previously (with the oven set at 500 °F). The difference in heat flux may be due to the temperature of the toast cycle compared to the oven setting, a different combination of heating elements, or it may be due to the short duration of cooling between toast cycles. The maximum recorded heat flux was 0.39 W/cm^2.

Figure 5. Heat Flux of Toaster Oven/Toast Mode (Vertical Scan)



Radiant Heater 1

Figure 6 shows the test results for one radiant heater. To determine the location of maximum heat flux, several left-to-right scans were taken at varying distances away from the heater. This was done because, for some models, the heater's reflector may focus the heat energy at some distance in front of the heater. As can be seen in the chart, however, this was not the case with this heater. The heat flux decreased as the distance away from the heater increased.

The first two scans, one at 1 inch away and one at 7 inches away, were performed at the vertical center of the heater. The scan at 1 inch away at the vertical center was used to determine the horizontal location of the maximum heat flux. The maximum heat flux was measured at 5 inches from the left edge. Then a vertical scan (not shown) at the 5-inch point was used to determine the maximum heat flux in the vertical direction. This position was identified at 3 inches above the vertical center. All remaining scans are from this vertical position. The maximum heat flux measured at 1 inch away from the heater was 0.59 W/cm^2.

Figure 6. Heat Flux of Radiant Heater 1

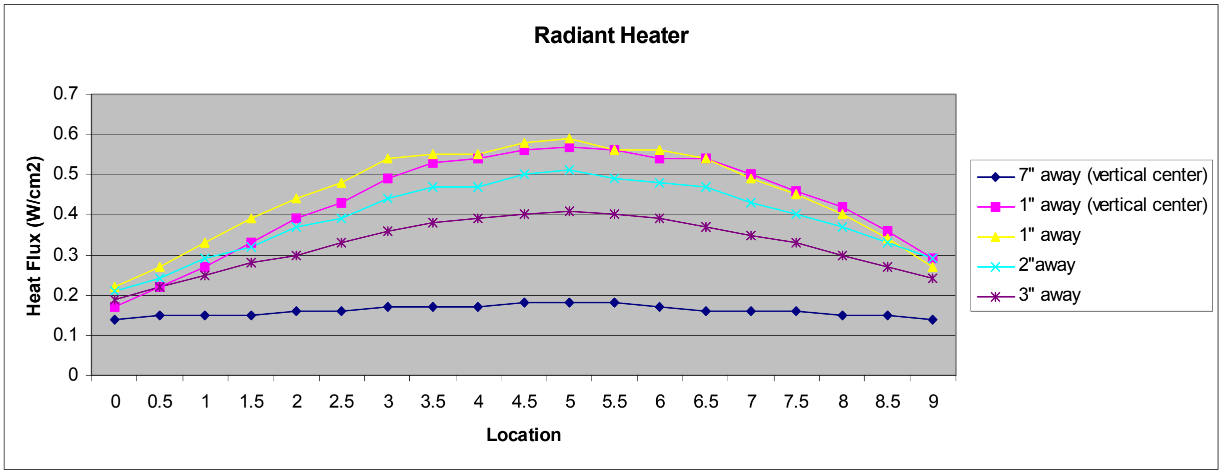
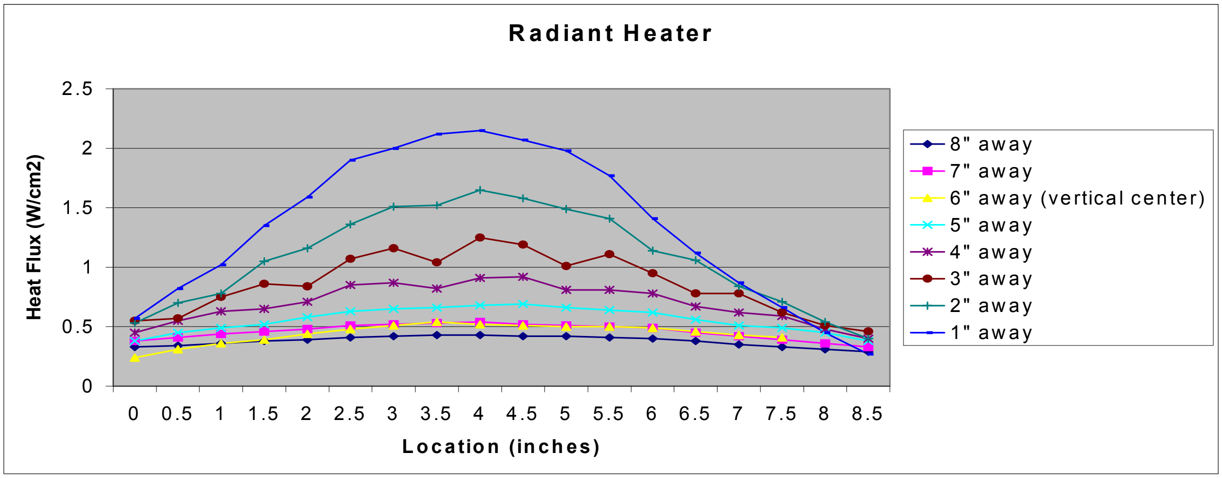


Figure 7 shows the test results for a second radiant heater. As with the first heater, several scans were performed to find the location of maximum heat flux. Again, the heat flux decreased as the distance from the heater increased. To identify the location of maximum heat flux, a horizontal scan was performed at the vertical center 6 inches away from the heater; the location of maximum heat flux was identified at the 3.5-inch horizontal location. A vertical scan was performed (not shown) at the 3.5-inch location to identify the location of the maximum heat flux in the vertical direction. The location identified was about 0.5 inches below the vertical center. This location was used for all other horizontal scans. The maximum heat flux measured was 2.15 W/cm^2 at 1 inch away from the heater.

Figure 7. Heat Flux of Radiant Heater 2



Toasters

Three toasters were tested. The measurements were very sporadic, and it was not possible to record a value that would accurately indicate the true heat flux. Thinking that water may stabilize the measurements, water was then introduced into the transducers. Adding water did not stabilize the measurements. Water did appear to have an effect on the maximum heat flux value. The measurements with water are higher than those without water.

In all previous testing, the transducer was in a horizontal orientation. Due to the configuration of toasters, the transducer had to be mounted vertically. This may account for the sporadic readings. The transducers are total heat flux transducers. They measure both radiant and convective heat energy. With the transducers mounted in a vertical position, the convective currents naturally occurring plus possible external air currents (such as from the air conditioning system) may have caused the sporadic readings. The convective currents and external air currents would also affect the readings in a horizontal orientation but not as drastically since heat normally rises.

Since most of the radiant energy in a toaster is directed horizontally to brown the bread or other food item, most of the heat energy coming from the top of a toaster is likely convective energy. Since most of the heat energy is absorbed by the food item in the toaster slot(s), it is probably not as likely that the remaining convective heat energy would ignite proximate combustibles.

The test procedure for each of the toasters was to start a toast cycle and monitor the heat flux during the entire toast cycle. The maximum observed value was recorded. As mentioned, the measured values were very sporadic and varied between tenths of a watt per square centimeter up to the recorded values thoughout the entire toast cycle. Since the toaster readings were very sporadic and it was not possible to determine an accurate heat flux measurement, the data will not be used to draw any conclusions.

Figures 8, 9, and 10 show the test results of the three toasters tested. The scans using water are indicated in the figures. Toaster 3 was only measured using water.

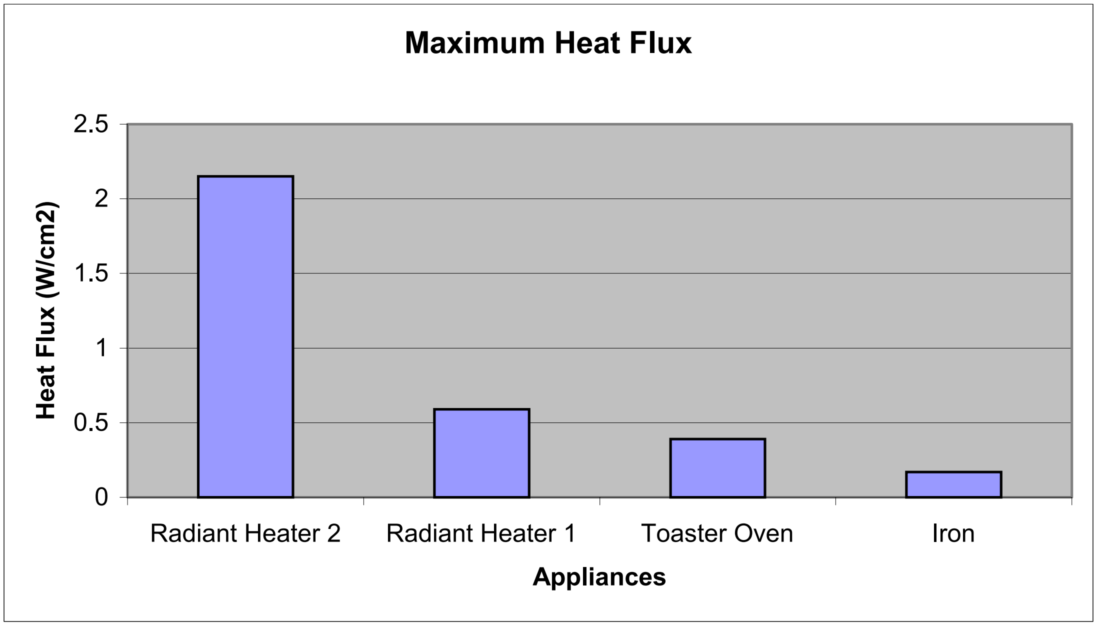
Figure 8. Heat Flux of Toaster 1

Figure 9. Heat Flux of Toaster 2

Figure 10. Heat Flux of Toaster 3

Figure 11 shows the maximum measured heat flux values of each of the four appliances previously described. The two radiant heaters had the highest measured heat flux and are the most likely to ignite proximate combustibles. Based upon the information gathered from the University of Maryland testing discussed below, it is not likely that either the toaster oven or the iron would ignite proximate combustibles unless there is a failure of the appliance, i.e., loss of thermostatic control and failure of the thermal cutoff if so equipped.

Figure 11. Maximum Heat Fluxes of Appliances



Testing of Household Combustibles and Standard Fire Indicators

Under contract to CPSC, the University of Maryland (U of M) conducted tests to determine the critical heat flux of five materials (chosen to represent common, household combustibles) and five standard fire indicators. The materials tested are outlined in the table below. The critical heat flux is the minimum heat flux required to ignite the combustible.

Household Combustibles	Fire Indicators
Newsprint (black and white)	Tissue paper (white)
Paper towel (white)	Surgical cotton
White cotton blanket	Cheesecloth
Beige terry cloth towel	Canvas (cotton duck)
Blue upholstery fabric	White terrycloth towel

In the tests, the combustibles were subjected to a range of constant radiant heat fluxes to determine the minimum heat fluxes needed to cause unpiloted glowing or flaming ignition of the material. (Pilot sparks and flames were not used as part of the testing protocol, so the test results represent unpiloted ignition.) A report of the tests conducted by U of M, along with the test results, is described in their report, *Ignition characteristics of various fire indicators subjected to radiant heat fluxes*, which is attached as Appendix A.

The testing conducted by U of M was limited to a single layer of the combustible material. For the materials tested, the critical heat flux values ranged from a low of 13.7 kW/m^2 (1.37 W/cm^2) to a high of 47 kW/m^2 (4.7 W/cm^2). The data also showed that the heat flux required to ignite the combustible decreased as the density of the combustible increased. This characteristic suggests that perhaps the critical heat flux would be lower if the material had a backing or if multiple layers of the material were used.

Another observation from the testing showed that the cotton duck (canvas) ignited at the lowest heat flux and demonstrated the most consistent results.

Conclusions and Recommendations

The testing performed by CPSC staff and by the University of Maryland showed that there are heat-producing appliances in consumers' homes that have the potential to ignite surrounding combustibles. In CPSC staff tests, the measured maximum heat fluxes generated by selected household appliances ranged from 0.17 W/cm^2 (1.7 kW/m^2) to 2.15 W/cm^2 (21.5 kW/m^2). In tests conducted by U of M, the minimum heat fluxes required to ignite single layers of selected combustible materials were found to be in the range of 1.37 W/cm^2 (13.7 kW/m^2) to 4.7 W/cm^2 (47 kW/m^2). The table below shows the 10 materials tested by U of M and their corresponding critical heat fluxes. This table is a summary of the data contained in Table 4. *Minimum heat fluxes for ignition* included in Appendix A.

Combustible Material	Critical Heat Flux (W/cm^2)
Tissue Paper	3.62
Cheesecloth	4.70
Paper Towel	2.41
Newsprint	2.84
Surgical Cotton	2.52
Canvas	1.52
Blanket	1.49
Upholstery	1.73
Beige towel	1.37
White towel	1.46

Of the appliances tested, only one of the radiant heaters produced sufficient heat energy to ignite some of the combustibles tested, but it would not be sufficient to ignite all of the materials. Those tested materials that had the potential to be ignited by the heater were the canvas, the white cotton blanket, the upholstery fabric, the beige towel, and the white towel.

The data showed that the heat flux required to ignite the combustibles decreased as the density of the combustible increased. This indicates that if multiple layers of the combustible or a single layer of the combustible with a backing were tested, the critical heat flux may be lower. In addition, combustibles in a consumer's home (e.g., a pile of clothing, a roll of paper towels, an upholstered pillow, etc.) will not likely be limited to a single layer of material.

> *Recommendation*: Conduct additional testing to determine the critical heat flux of combustibles using multiple layers and also single layers of the combustible with various backing materials.

Critical heat flux tests showed that the cotton duck ignited at the lowest heat flux, and it demonstrated the most consistent results. Based on this, it appears that cotton duck is a good fire indicator. Currently, it is used only on a very limited basis in the voluntary standards. However, if the ignition characteristics of the material were better understood, it may prove to have more widespread usefulness in the voluntary standards.

> *Recommendation*: Conduct additional tests of cotton duck to better characterize the material.

Heat flux testing of a limited number of heat-producing appliances has been conducted. Tests of additional appliances should be performed, and testing and data acquisition should be automated to provide more comprehensive results for analysis.

> *Recommendation*: Conduct additional tests of heat-producing appliances to demonstrate the feasibility of the test method and to improve upon it. Manufacture/purchase a programmable controller to automate heat flux data acquisition.

The ultimate goal of this study is to identify a quantitative method to test the propensity for a consumer product to ignite surrounding combustibles. An initial step has been made with the tests that have been conducted thus far. However, it is still premature to propose an alternative test method with threshold values. The additional testing recommended above will help to focus on the appropriate threshold values.

Appendix A

Ignition characteristics of various fire indicators subjected to radiant heat fluxes

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Abstract

Various combustible materials are specified in a number of fire test standards for heat-producing consumer products to serve as indicators of the potential for ignition as a result of contact with or exposure to hot surfaces. The objective of this study has been to collect data on the heat energy required to ignite ordinary household combustibles that might be located near heat-producing consumer products. Samples of ten different household combustibles were subjected to a range of constant radiant heat fluxes in a Cone Calorimeter and in a LIFT apparatus to determine the minimum heat fluxes needed to cause unpiloted glowing or flaming ignition of the materials. Test results are analyzed in terms of thermally thin and thermally thick theories for ignition.

Keywords: Ignition, thermally thin, thermally thick, critical heat flux

Introduction

Various combustible materials are specified in a number of fire test standards for heat-producing consumer products to serve as indicators of the potential for ignition as a result of contact with or exposure to hot surfaces. The fire indicators specified in these standards are typically fabrics, textiles or other relatively thin fibrous materials, such as surgical cotton or cotton gauze. The use of such materials can provide a realistic assessment of the potential presented by heat-producing devices for ignition of ordinary household combustibles, but does not provide a quantitative measure of the heat energy required to ignite combustibles that are likely to be near such devices.

The objective of this study has been to collect data on the heat energy required to ignite ordinary household combustibles that might be located near heat-producing consumer products. To collect this data, samples of ten different household combustibles were subjected to a range of constant radiant heat fluxes in a Cone Calorimeter [1] and in a LIFT apparatus [2]. The samples were supported in the test devices without the backing materials normally used in the Cone Calorimeter and the LIFT apparatus so as to represent a "thermally thin" exposure condition. Pilot sparks and flames were not used as part of the testing protocol, so the test results represent unpiloted ignition. Many samples produced glowing combustion but not flaming combustion in the absence of a pilot source, while others would exhibit flaming combustion before evidence of glowing, particularly at higher heat fluxes. For the present study, ignition was considered to have occurred when visible glowing was observed on the surface of a material or when flaming ignition was observed, whichever occurred first.

Test materials

The ten different household combustibles used for this study include:

- Newsprint (black and white)
- Tissue paper (white)
- Paper towel (white)
- Surgical cotton
- Cheesecloth
- Canvas
- White cotton blanket
- White terrycloth towel
- Beige terrycloth towel
- Blue upholstery fabric

Representative surface densities for each material were measured by weighing 150 mm by 150 mm (6 in. by 6 in.) samples of each material. These representative surface densities are reported in Table 1, with materials ranked from the lightest to the heaviest.

Test specimen preparation and mounting

The objective of this study was to evaluate the ignition propensity of the thin household combustibles by themselves, independent of the impact of substrates. Consequently, the test specimen preparation and mounting procedures normally employed for the Cone Calorimeter and the LIFT apparatus were altered to accommodate this testing.

For testing in the Cone Calorimeter, square samples with dimensions of 178 mm by 178 mm (7 in. by 7 in.) were cut from larger sections of material. Then 38 mm by 38 mm (1.5 in. by 1.5 in.) square pieces were cut from each of the corners of the sample. A representative Cone Calorimeter sample is illustrated in Figure 1. The sample was then draped over a nominal 100 mm by 100 mm by 76 mm (4 in. by 4 in. by 3 in.) deep Cone Calorimeter specimen holder. Finally, a standard Cone Calorimeter sample retainer frame was placed over the top of the specimen and the specimen holder, acting to hold the specimen taut over the top of the specimen holder while exposing a 94 mm by 94 mm (3.7 in. by 3.7 in.) area to the imposed heat flux from the Cone heater. In this way, the sample was not in contact with a substrate material. The final assembly is illustrated in Figure 2.

For testing in the LIFT apparatus, square samples with dimensions of 229 mm by 229 mm (9 in. by 9 in.) were cut from larger pieces of material. Then 38 mm by 38 mm (1.5 in. by 1.5 in.) square pieces were cut from each of the corners of the square sample. A representative LIFT apparatus sample is illustrated in Figure 3. The sample was then draped over a nominal 150 mm by 150 mm (6 in. by 6 in.) frame of 25.4 mm (1 in.) thick calcium silicate board. The frame had a central opening with dimensions of approximately 125 mm by 125 mm (5 in. by 5 in.), such that the calcium silicate board was not located behind the sample in this central area. Finally, the sample and frame were inserted into the ignition sample section of the standard LIFT sample holder. This LIFT apparatus mounting arrangement is illustrated in Figure 4.

Before testing, test specimens were conditioned by storing them over a dessicant in a sample conditioning chamber within the air-conditioned laboratory for a period of days.

Test procedures

Testing in the Cone Calorimeter was performed by first establishing and measuring the heat flux from the cone heater element at the plane of the sample surface. Once the desired heat flux was established, a sample mounted in the sample holder was inserted beneath the cone heater with an aluminum radiation shield covering the sample to protect it from the incident thermal radiation. The radiation shield was then quickly removed from the sample surface while a stopwatch was simultaneously started. Observations were made of the surface of the test samples under the incident thermal radiation and the following times were recorded:

- Time to first observation of surface discoloration;
- Time to first observation of smoking;
- Time to first observation of surface glowing;
- Time to first observation of flaming.

The oxygen consumption calorimetry measurements normally made in Cone Calorimeter tests were not included in this testing because the purpose of the tests was to evaluate ignition characteristics, not heat release rates once the materials ignited.

Testing in the LIFT apparatus was performed by first establishing and measuring the heat flux from the gas-fired radiant panel to the center of the plane of the sample surface. Once the desired heat flux was established, the heat flux measurement gauge and assembly were removed from the apparatus. Within a short period of time, a sample holder with a sample mounted at the ignition end was rapidly inserted into the apparatus and a stopwatch was simultaneously started. Observations were made of the surface of the test samples under the incident thermal radiation and the times identified above were recorded.

Between tests in both the Cone Calorimeter and the LIFT apparatus, the incident heat fluxes were varied in an effort to find and bracket the minimum incident heat flux at which ignition was observed. Tests were conducted for periods of up to 20 minutes, consistent with the standard LIFT testing protocol. Because these tests were conducted without a pilot ignition source, the time to ignition was considered to be the time to first observation of surface glowing or flaming, whichever occurred first.

Test results

Test results for the ten materials are provided in Tables 2 and 3 and in Figures 5 through 14. In Table 2, the time to ignition is tabulated as a function of the incident heat flux for tests conducted in the Cone Calorimeter. In Table 3, the time to ignition is tabulated as a function of the incident heat flux for tests conducted in the LIFT apparatus. In Figures 5 through 14, the inverse of the time to ignition, i.e., t_{ig}^{-1}, is plotted as a function of the incident heat flux for each of the ten materials. This form is relevant to the “thermally thin” analysis presented in the next section. In Figures 15 through 24, the inverse of the square root of the time to ignition, i.e., $t_{ig}^{-1/2}$, is plotted as a function of the incident heat flux for each of the ten materials. This form is relevant to the “thermally thick” analysis presented in the next section. Data for both the Cone Calorimeter tests and the LIFT apparatus tests are provided in each figure.

The minimum heat fluxes for ignition of each material are provided in Table 4 and in Figures 25 through 27. For each material, Figures 25 and 26 provide the minimum heat fluxes at which ignition was observed, represented by “Min,” the maximum heat fluxes at which ignition was not observed, represented by "Max," and the average of the minimum and maximum values, represented by "Avg." Figure 25 presents the data obtained in the Cone Calorimeter, while Figure 26 presents the data from the LIFT apparatus. Figure 27 presents a side-by-side comparison of the average values for the minimum heat flux for ignition obtained in the two test devices for each material.

Analysis

Test results are analyzed in terms of thermally thin and thermally thick theories for ignition. A thermally thin material is a material that is thin enough for thermal gradients through the thickness of the material to be negligible; the material can be treated as if it has a uniform temperature through its thickness. A thermally thick material is one that is thick enough that the temperature of the unexposed surface is unaffected by the heat transfer through the material. For ignition analysis, it is common to treat materials as inert until they reach an effective ignition temperature (T_{ig}) and to have constant effective thermal properties (k, ρ, c). These assumptions are made here, although the limitations of these assumptions should be recognized.

For thermally thin materials, the energy per unit area that must be absorbed to raise the material to its effective ignition temperature is:

$$q_{ig} = \rho\delta c(T_{ig} - T_o) \qquad (1)$$

where $\rho\delta$ represents the surface density, or mass per unit area, of the material (kg/m^2), as presented in Table 1, c is the specific heat of the material (kJ/kg.K) and (T_{ig}-T_o) is the temperature rise (K) needed to cause ignition. For a constant net rate of energy absorption, $\dot{q}_{net}$, the time to ignition can be represented as:

$$q_{ig} = \int_0^{t_{ig}} \dot{q}_{net}\,dt = \dot{q}_{net} t_{ig} \quad \text{or} \quad t_{ig} = \frac{q_{ig}}{\dot{q}_{net}} \qquad (2)$$

Due to convective and radiative heat losses from the surfaces of a material as it heats up, the net rate of energy absorption will only be some fraction of the incident heat flux:

$$\dot{q}_{net} = \chi_{net}\dot{q}_{inc} \qquad (3)$$

where χ_{net} represents the absorbed fraction of the incident heat flux. While the value of χ_{net} is expected to vary as the material heats up under the incident heat flux, as a first approximation it is treated as constant. In this case, the time to ignition can be determined in terms of the incident heat flux, rather than the net heat flux, as:

$$t_{ig} = \frac{q_{ig}}{\chi_{net}\dot{q}_{inc}} \qquad (4)$$

Note the inverse relationship between the time to ignition and the incident heat flux, which suggests that a plot of t_{ig}^{-1} versus $\dot{q}''_{inc}$ should yield a linear relationship with a slope of χ_{net} / q_{ig}. Alternatively, the product of the ignition time by the incident heat flux, i.e., $t_{ig}\dot{q}''_{inc} = q_{inc,ig} = q_{ig} / \chi_{net}$, represents the total incident heat load for ignition. To the extent that the absorbed fraction of incident heat flux is a constant and the ignition temperature is independent of the heating rate, the total incident heat load for ignition should also be constant. To test this hypothesis, the total incident heat load for ignition was determined for all the samples that ignited. These results are shown in Figures 28 and 29 for the Cone Calorimeter and LIFT Apparatus results, respectively. The scatter in the data illustrated in Figures 28 and 29 suggests that this hypothesis does not appear to be valid.

For thermally thick materials, the time to ignition is related to a constant net heat flux at the exposed surface as:

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_o}{\dot{q}''_{net}} \right]^2 \qquad (5)$$

As for the thermally thin case, the net rate of energy absorption will only be some fraction of the incident heat flux due to convective and radiative heat losses from the exposed surface of the material as it heats up:

$$\dot{q}''_{net} = \chi_{net} \dot{q}''_{inc} \qquad (3)$$

where χ_{net} represents the absorbed fraction of the incident heat flux. While the value of χ_{net} is expected to vary as the material heats up under the incident heat flux, as a first approximation it is treated as constant. With this assumption, the ignition time can be related to the incident heat flux as:

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_o}{\chi_{net} \dot{q}''_{inc}} \right]^2 \qquad (6)$$

This suggests that a plot of $t_{ig}^{-1/2}$ versus the incident heat flux should yield a linear relationship with a slope of $\frac{2\chi_{net}}{(T_{ig} - T_o)\sqrt{\pi k\rho c}}$. Alternatively, the product of the ignition time by the square of the incident heat flux should be a constant if the material thermal inertia and ignition temperature are constant, the net heat flux fraction is constant and the thermally thick theory of ignition is valid. This product is:

$$t_{ig}\dot{q}''^{2}_{inc} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_o}{\chi_{net}} \right]^2 \equiv TERP \qquad (7)$$

where *TERP* stands for the thermal effective response parameter. The *TERP* is similar to the thermal response parameter (*TRP*) defined by Tewarson [3]. These terms are related as:

$$TERP = (TRP / \chi_{net})^2 \quad (8)$$

Values for the *TERP* are shown in Figures 30 and 31 for the Cone Calorimeter and LIFT Apparatus results, respectively. The scatter in the data illustrated in Figures 30 and 31 suggest that the assumptions stated above are not valid. There seems to be a general trend that the TERP increases as the heat flux approaches the critical heat flux, suggesting that the net heat flux fraction decreases as this limit is approached.

Discussion

The primary purpose of this investigation has been to determine the minimum heat fluxes for ignition of different household combustibles. For all of the materials evaluated in both the Cone Calorimeter and the LIFT Apparatus, except the surgical cotton, the minimum heat flux for ignition was found to be slightly lower in the LIFT Apparatus than in the Cone Calorimeter. The reason for this has not been conclusively determined. Possible reasons include the differences in sample size (100 mm x 100 mm versus 150 mm x 150 mm), sample orientation (horizontal versus vertical) and radiant source (electrical coil versus gas-fire panel).

Another potential reason for the differences in the minimum heat fluxes for ignition between the Cone Calorimeter and the LIFT Apparatus was the sample mounting procedure used. While the intention of the sample mounting was to permit the materials to be freely suspended in air without a backing material, in the LIFT Apparatus, one of the vertical edges of the sample was in contact with the supporting Marinite test frame, as shown in Figure 7. During testing in the LIFT Apparatus, it was observed that the section of material in contact with the Marinite test frame would typically discolor first and ignition would typically occur first in this area, suggesting that contact of the test sample with the test frame influenced the heating of the sample in this area. Additional testing should be conducted to further explore the magnitude of these effects. This observation also suggests that multiple thicknesses of the test materials should be evaluated to determine the effect on the minimum heat flux for ignition.

The experimental data generally seems to indicate an inverse relationship between the surface density and the minimum heat flux for ignition, with the heavier materials igniting at lower heat fluxes than the lighter materials. This seems to be related to the rapid loss of pyrolyzates for the lighter materials. Contrary to the assumption of inert materials that do not pyrolyze until reaching a well-defined ignition temperature, these real materials would begin smoking at relatively low temperatures, but would not ignite, presumably because an ignitable concentration of pyrolyzates did not form at the surface of the material.

In the LIFT Apparatus, the cotton canvas, the cotton blanket and the beige and white cotton terrycloth towels all exhibited similar minimum heat fluxes for ignition in the range of 12 to 15 kW/m^2. In the Cone Calorimeter, these same materials exhibited minimum heat fluxes for ignition in the range of about 17 to 25 kW/m^2, with the cotton canvas demonstrating the lowest minimum heat flux for ignition. In general, the cotton canvas seemed to exhibit behavior among the most consistent of all the materials tested. This may be due to its relatively smooth surface in comparison with these other materials. In view of its low minimum heat flux for ignition and its fairly consistent ignition behavior, the canvas may be the best candidate to serve as a fire indicator of the ten materials evaluated.

Neither the thermally thin or thermally thick theories of ignition developed in the analysis section provide a fully consistent quantitative explanation of the experimental data. This is evidenced by the failure of either the total incident heat load or the thermal effective response parameter to yield constant values for any of the materials. At least one reason for this is apparent; the fraction of heat absorbed by a material is expected to be less at near critical heat fluxes than at significantly supercritical heat fluxes. Both the incident heat load data and the thermal effective response parameter data support this observation, with most materials exhibiting asymptotic behavior at near critical heat fluxes.

To compensate for the lower net heat flux at near-critical incident heat fluxes, some investigators [3,4] have suggested that the net heat flux can be taken as the difference between the incident heat flux and the critical heat flux, i.e.,

$$\dot{q}''_{net} = \dot{q}''_{inc} - \dot{q}''_{crit} \tag{9}$$

This approach tends to overestimate surface heat losses, particularly during early periods before the surface has heated up significantly. This approach was applied to the experimental data, but it did not yield results perceptibly better than those presented in the analysis section, so it is not presented here.

Summary and Conclusions

A series of 142 Cone Calorimeter tests and 122 LIFT Apparatus tests have been conducted with ten ordinary household combustible materials to evaluate their ignition characteristics under unpiloted radiant exposure conditions. The combustible materials were relatively thin household materials that might be located near, and ignited by, an adjacent heat-producing appliance. The potential for ignition by direct contact with a hot surface was not evaluated as part of this investigation.

Minimum heat fluxes for unpiloted ignition of the ten test materials were determined by bracketing the incident heat fluxes where ignition was and was not observed. In general, it was found that there was an inverse relationship between the surface density of a material and the minimum heat flux for ignition, with the heavier materials igniting at the lowest heat fluxes. Minimum heat fluxes in the range of 12 to 15 kW/m^2 were observed for materials with surface densities in the range of 0.27 to 0.37 kg/m^2. Of the materials tested, cotton canvas seemed to exhibit the lowest minimum heat flux for ignition and among the most consistent results, suggesting that it would be a suitable candidate to serve as a fire indicator. Alternatively, a measured heat flux of approximately 10 kW/m^2 might be used as a conservative indication of incipient ignition, based on the experimental data acquired to date. However, it would be useful to acquire additional data, e.g., for multiple thicknesses of the tested materials or for materials with substrates, before deciding upon a specific heat flux to be associated with incipient ignition of different fire indicators.

While the primary purpose of this work was to determine the minimum heat fluxes for unpiloted ignition of the ten ordinary household combustible materials, additional data was acquired in an effort to characterize the ignition characteristics of the materials. Thermally thin and thermally thick theories of heating and ignition were applied to the experimental data. While neither theory is clearly correct or superior to the other, both theories are consistent with the experimental data and can be used to derive useful effective material properties related to ignition characteristics. Additional data and a more detailed numerical analysis would be useful to further explore and characterize the material and ignition properties of the ten household combustibles evaluated in this investigation.

References

1. ASTM International, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, Standard E1354-02, 2002.
2. ASTM International, Standard Test Method for Determining Material Ignition and Flame Spread Properties, Standard E1321-97a, 2002.
3. Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," Section 3 / Chapter 4 in *The SFPE Handbook of Fire Protection Engineering (3rd edition)*, P. J. DiNenno, Editor-in-Chief, Society of Fire Protection Engineers, 2002.
4. Fleischmann, C.M., and Chen, F.F., "Radiant Ignition of Upholstered Furniture," *Proceedings of the International Conference on Engineered Fire Protection Design*, Society of Fire Protection Engineers, 2001.

Table 1. Representative surface densities for materials, ranked from lightest to heaviest.

Material	**Surface density (kg/m^2)**
Tissue paper (white)	0.016
Cheesecloth	0.040
Paper towel (white)	0.041
Newsprint (black and white)	0.049
Surgical cotton	0.072
Canvas	0.273
Blanket (White cotton)	0.285
Upholstery fabric (blue)	0.336
Beige towel (terrycloth)	0.356
White towel (terrycloth)	0.366

Table 2. Times to ignition as function of heat flux for Cone Calorimeter tests.

Heat flux (kW/m^2)	Tissue	Heat flux (kW/m^2)	Cheesecloth	Heat flux (kW/m^2)	Paper towel	Heat flux (kW/m^2)	Newsprint	Heat flux (kW/m^2)	Surgical cotton	Heat flux (kW/m^2)	Canvas	Heat flux (kW/m^2)	Blanket	Heat flux (kW/m^2)	Upholstery	Heat flux (kW/m^2)	Beige towel	Heat flux (kW/m^2)	White towel
34.9	NI	43.5	NI	22.5	NI	22.8	NI	22.5	NI	15.9	NI	17.3	NI	20.1	40	17.0	NI	24.1	NI
36.2	23	47.0	6	28.1	NI	27.1	NI	25.2	NI	16.5	NI	20.4	NI	20.8	40	17.3	NI	24.3	NI
36.3	NI	47.8	NI	29.5	NI	27.1	NI	25.2	NI	16.7	NI	22.0	NI	20.9	43	17.3	NI	25.0	NI
36.7	NI	48.1	NI	30.1	NI	28.4	12	25.2	NI	17.1	175	22.1	NI	21.5	35	18.4	191	25.2	72
36.7	NI	48.5	NI	30.6	NI	28.9	10	25.2	19	17.1	276	22.3	84	21.7	38	18.6	165	25.8	70
37.5	NI	48.8	13	30.6	14	28.9	11	26.2	16	17.4	225	22.4	NI	22.0	33	19.1	145	26.7	NI
37.5	38	49.0	NI	30.7	11	28.9	13	27.3	18	18.6	154	22.8	57	22.2	40	19.4	132	27.3	30
37.5	26	49.0	15	30.7	NI	28.9	NI	28.7	20	20.1	118	23.1	61	22.3	40	20.4	111	28.1	NI
38.0	NI	49.4	NI	31.5	11	29.3	NI	32.0	16	22.5	72	32.4	24	22.5	NI	22.8	88	28.7	63
38.4	NI	49.4	9	32.0	12	29.6	20	41.6	6	32.0	30	41.0	12	22.5	104	32.4	28	29.0	62
38.5	16	50.7	9	32.4	10	30.1	13	50.6	3	40.9	11	50.3	9	22.8	42	41.0	12	29.2	59
39.5	6	52.0	15	40.9	5	30.6	12			49.9	9			22.8	40	50.3	8	29.3	NI
41.2	6	54.5	7	49.9	4	31.4	9							23.1	40			29.7	20
		58.3	4			32.4	10							24.0	632			30.4	15
						41.0	5							24.3	1060			34.3	12
						50.3	3							25.2	35			41.1	12
														25.8	40			54.5	5
														26.2	38				
														27.3	34				
														28.7	170				
														31.3	28				
														41.6	20				
														50.6	9				

Test 3. Times to ignition as function of heat flux for LIFT Apparatus tests.

Heat flux (kW/m^2)	Tissue	Heat flux (kW/m^2)	Cheesecloth	Heat flux (kW/m^2)	Paper towel	Heat flux (kW/m^2)	Newsprint	Heat flux (kW/m^2)	Surgical cotton	Heat flux (kW/m^2)	Canvas	Heat flux (kW/m^2)	Blanket	Heat flux (kW/m^2)	Upholstery	Heat flux (kW/m^2)	Beige towel	Heat flux (kW/m^2)	White towel
35.8	NI			20.6	NI	24.1	NI	24.1	NI	13.7	NI	13.41	NI	16.7	NI	11.92	NI	13.7	NI
35.8	NI			22.1	NI	28.3	NI	29.8	NI	13.71	NI	13.71	NI	16.7	NI	12.22	NI	14.6	NI
36.1	NI			22.1	NI	28.6	NI	29.8	16	13.71	NI	13.71	NI	16.7	NI	12.22	NI	14.6	754
37.5	76			22.4	NI	28.6	NI	29.8	17	15.2	350	14.9	532	17.3	NI	13.7	995	16.1	652
37.5	103			24.1	120	29.5	84	29.8	NI	15.5	298	15.2	480	17.3	865	13.71	815	17.6	345
38.4	62			32.8	77	29.5	96	29.8	5	16.4	236	15.2	529	18.5	570	15.2	481	18.5	275
38.4	59			32.8	13	29.8	NI	30.7	10	16.4	166	16.4	291	18.5	NI	15.2	510	18.5	327
43.5	28			32.8	11	29.8	NI	31.0	10	18.5	213	16.4	237	18.5	NI	16.4	240	20.6	115
43.5	26			47.7	3	30.7	7	32.8	5	18.5	135	18.5	196	18.5	911	18.5	286	20.6	206
47.7	10					30.7	8	47.7	5	20.6	92	18.5	189	20.6	54	18.5	236	20.6	102
						30.7	8			20.6	101	20.6	110	20.6	54	20.6	120	22.6	105
						30.7	6			24.1	48	20.6	123	20.6	260	20.6	106	24.1	67
						32.8	9			33.1	27	24.1	50	22.1	250	24.1	64	25.3	63
						32.8	7			43.5	19	32.8	23	24.1	31	24.1	59	27.7	52
						32.8	6					47.7	14	32.8	22	32.8	36	33.1	40
						47.7	4							47.7	14	47.7	15	43.5	14

Table 4. Minimum heat fluxes for ignition

Material	Tissue	Cheesecloth	Paper towel	Newsprint	Surgical cotton	Canvas	Blanket	Upholstery	Beige towel	White towel
Cone data										
Min	36.2	47	30.6	28.4	25.2	17.1	22.3	20.1	18.4	25.2
Max	38.4	49.4	30.7	29.3	25.2	16.7	22.4	22.5	17.3	29.3
Avg	37.3	48.2	30.7	28.9	25.2	16.9	22.4	21.3	17.9	27.3
LIFT data										
Min	37.5		24.1	29.5	29.8	15.2	14.9	17.3	13.7	14.6
Max	36.1		22.4	29.8	29.8	13.7	13.7	18.5	12.2	14.6
Avg	36.8		23.3	29.7	29.8	14.5	14.3	17.9	13.0	14.6

Min Minimum heat flux at which ignition was observed
Max Maximum heat flux at which ignition was not observed
Avg Average of Min and Max heat flux values

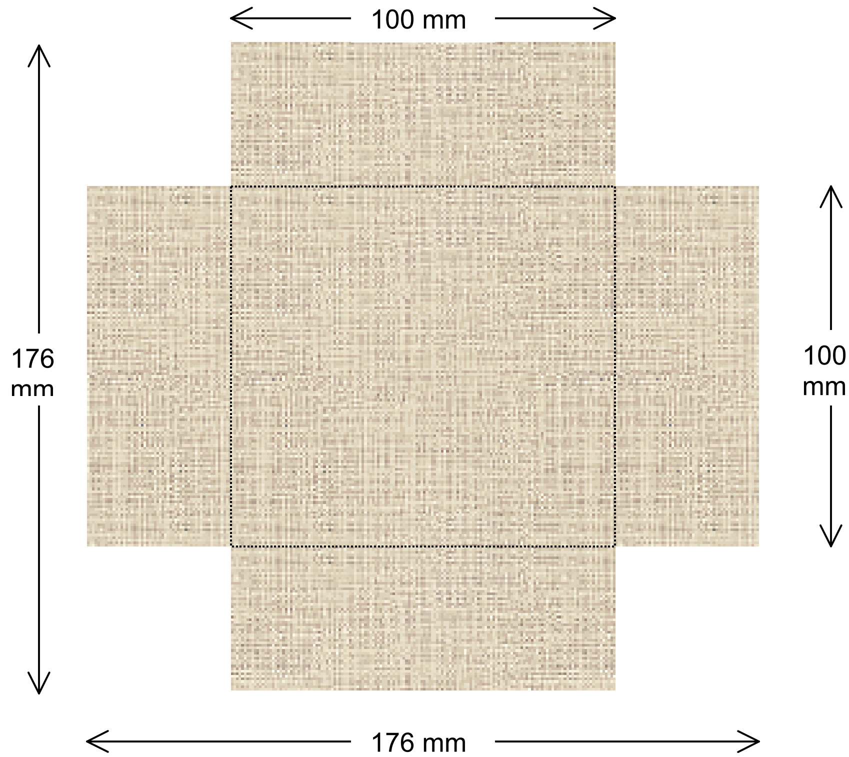

Figure 1. Sample dimensions for Cone Calorimeter testing.

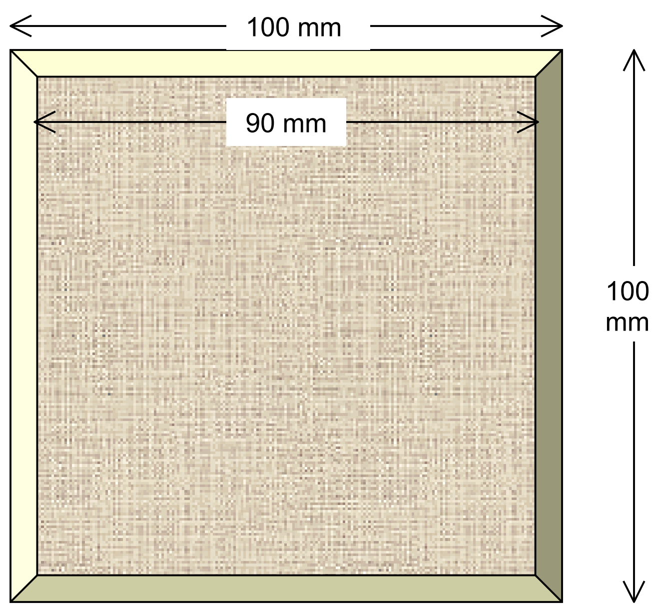

Figure 2. Representative sample mounted in Cone Calorimeter sample holder.

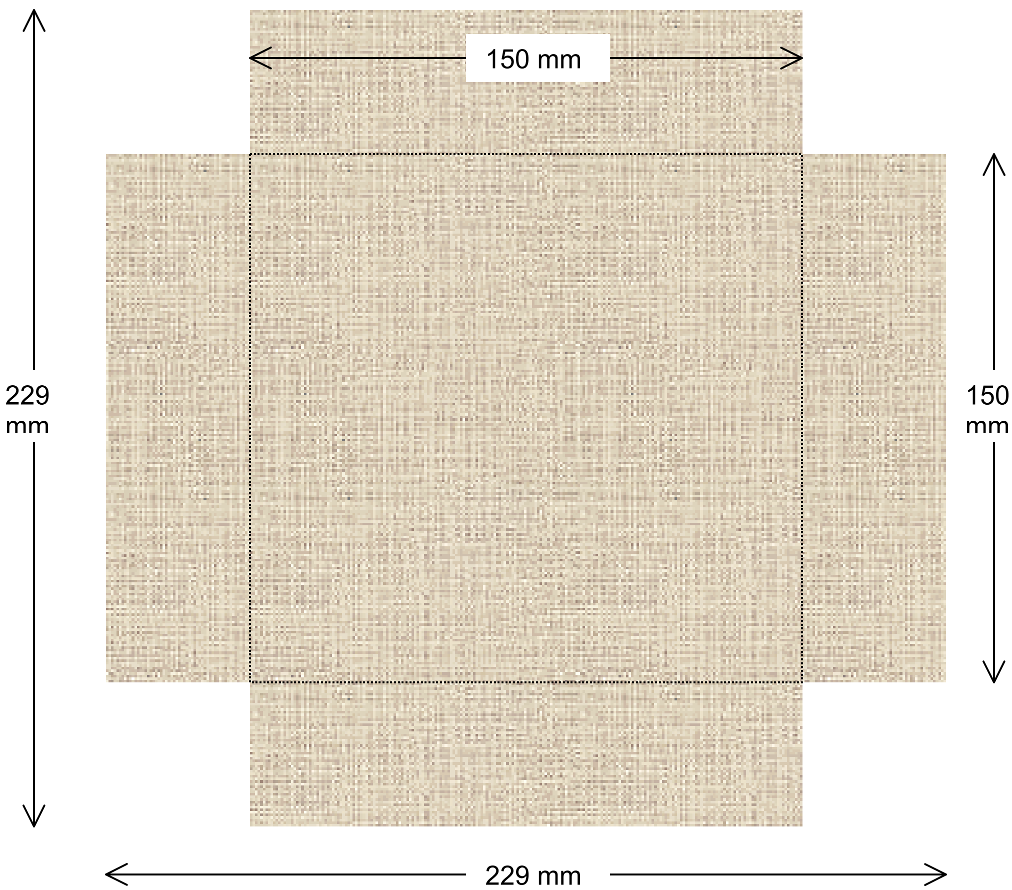

Figure 3. Sample dimensions for LIFT Apparatus testing.

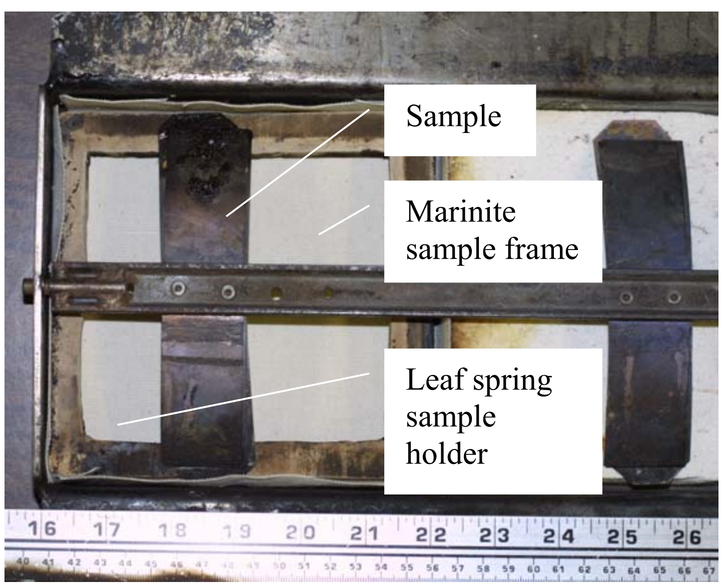

Figure 4. Representative sample mounted in LIFT Apparatus sample holder as viewed from back.

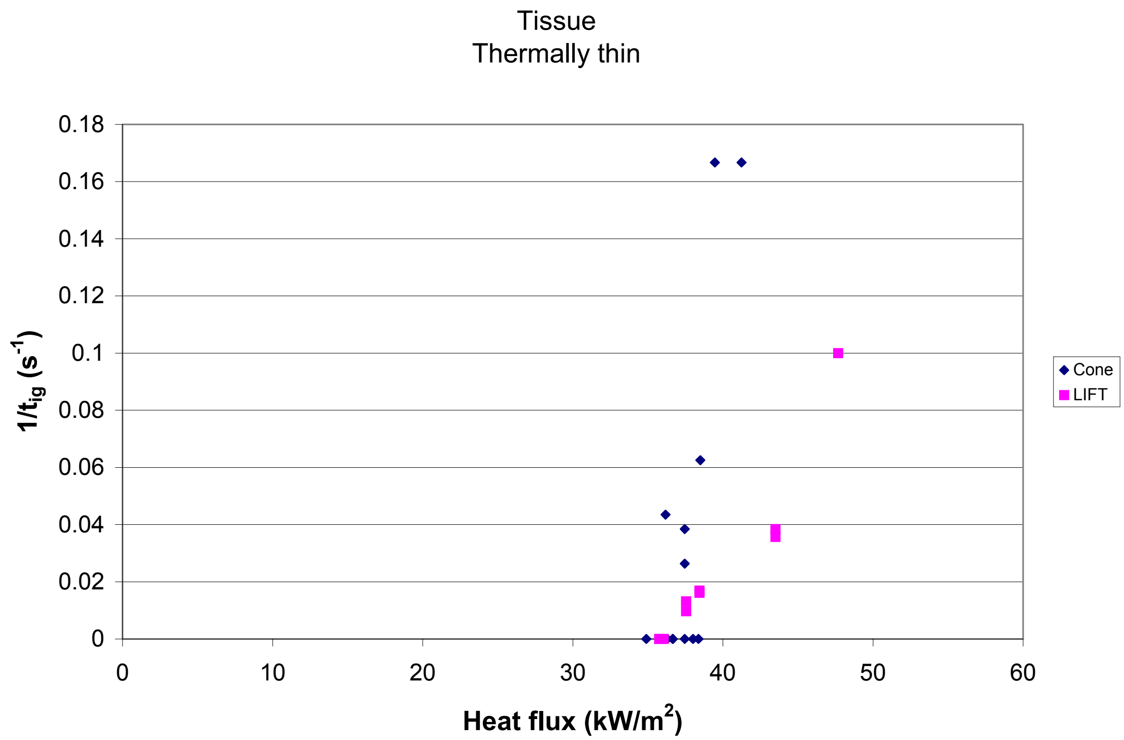

Figure 5. Tissue paper results based on thermally thin analysis.

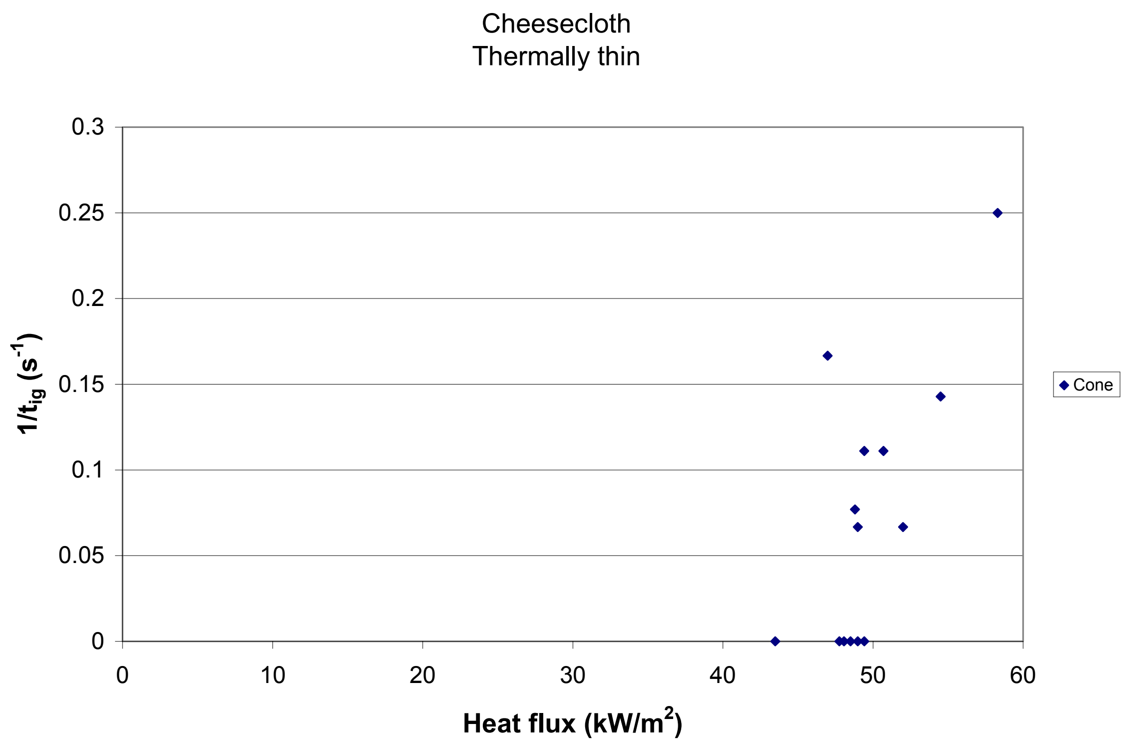

Figure 6. Cheesecloth results based on thermally thin analysis.

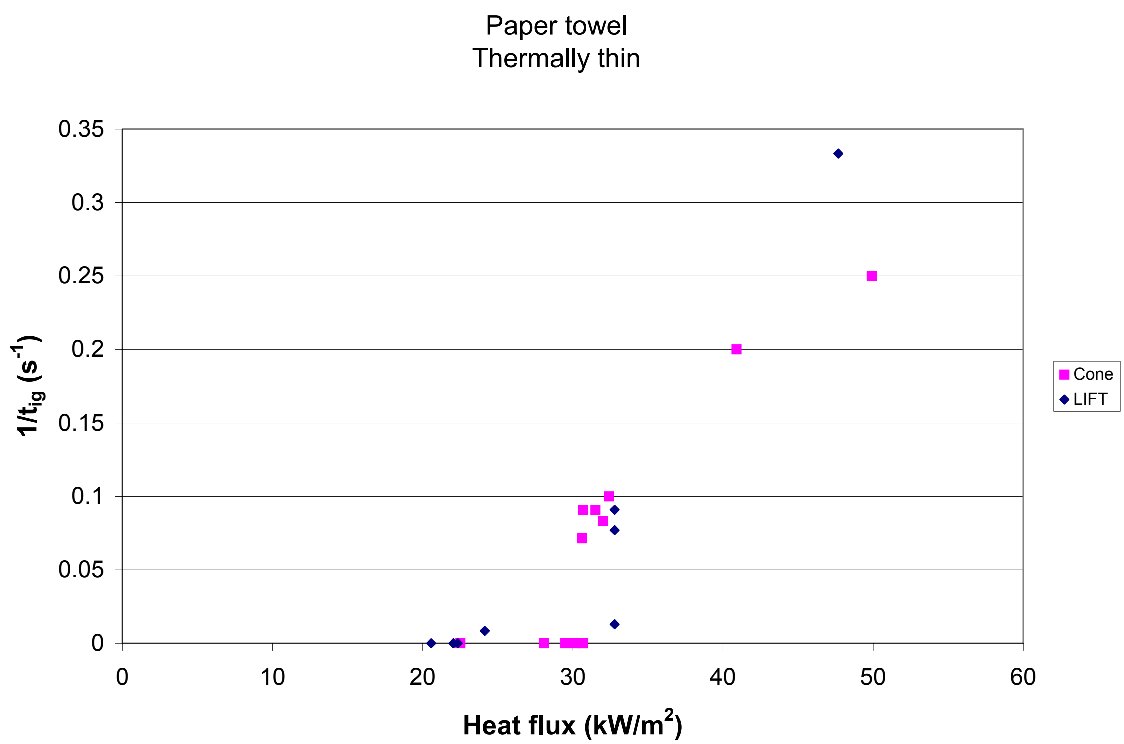

Figure 7. Paper towel results based on thermally thin analysis.

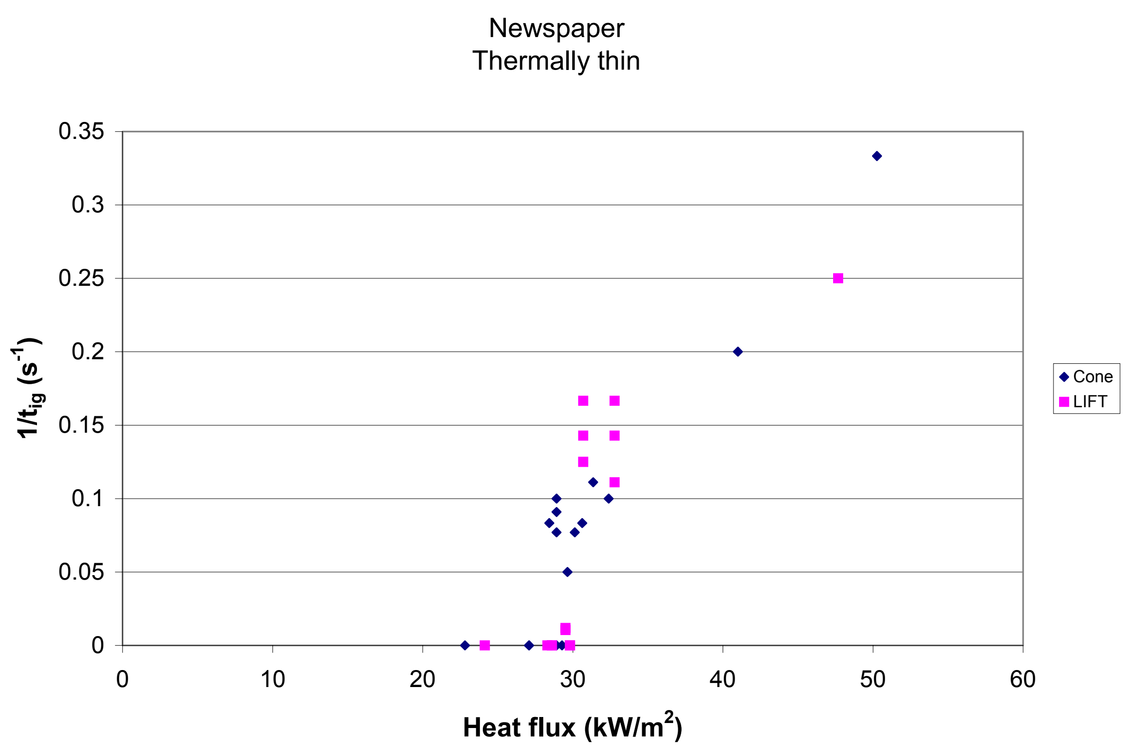

Figure 8. Newspaper results based on thermally thin analysis.

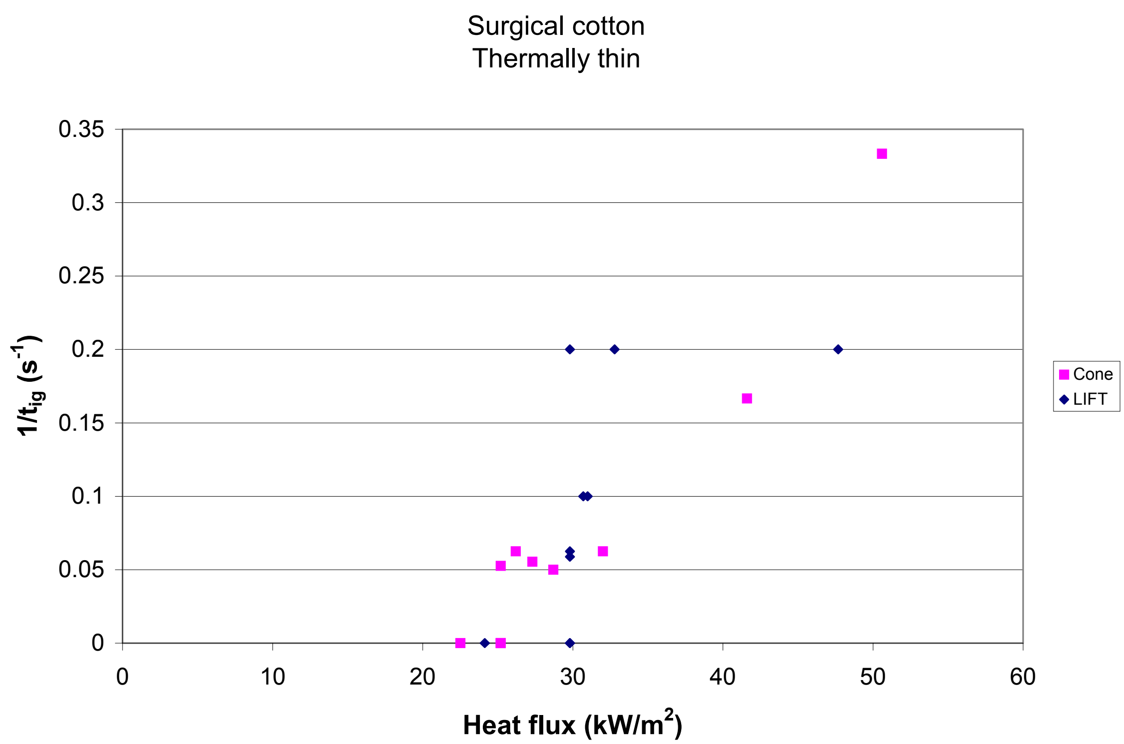

Figure 9. Surgical cotton results based on thermally thin analysis.

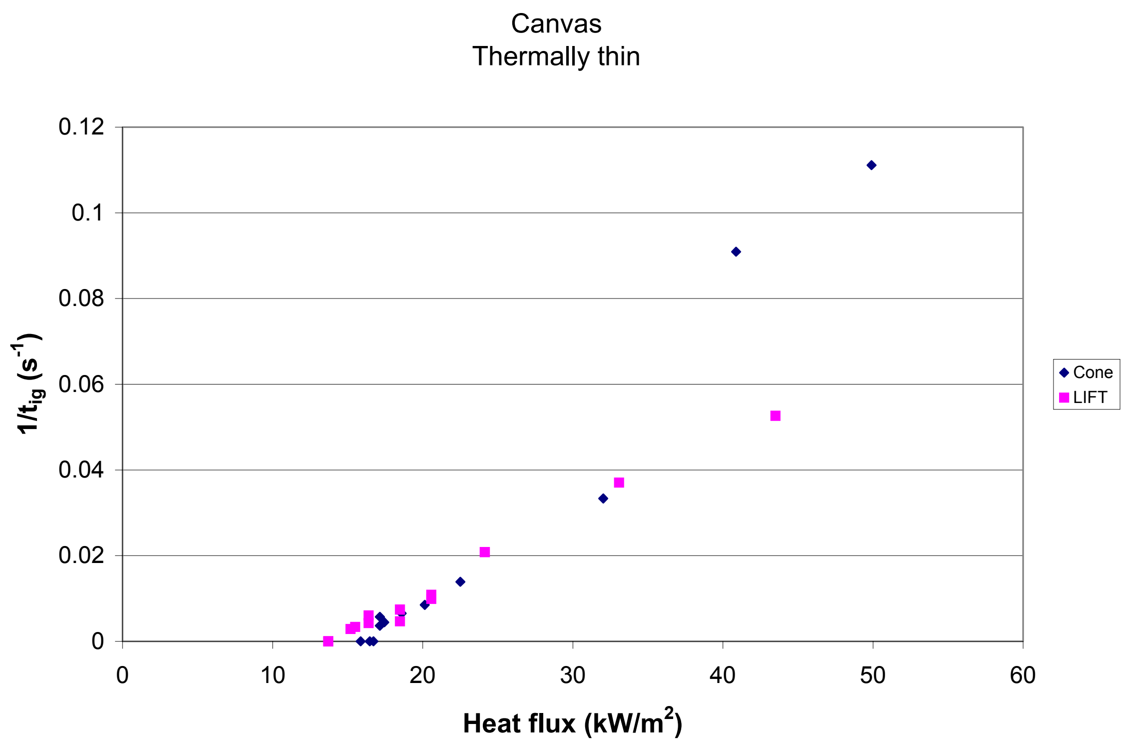

Figure 10. Canvas results based on thermally thin analysis.

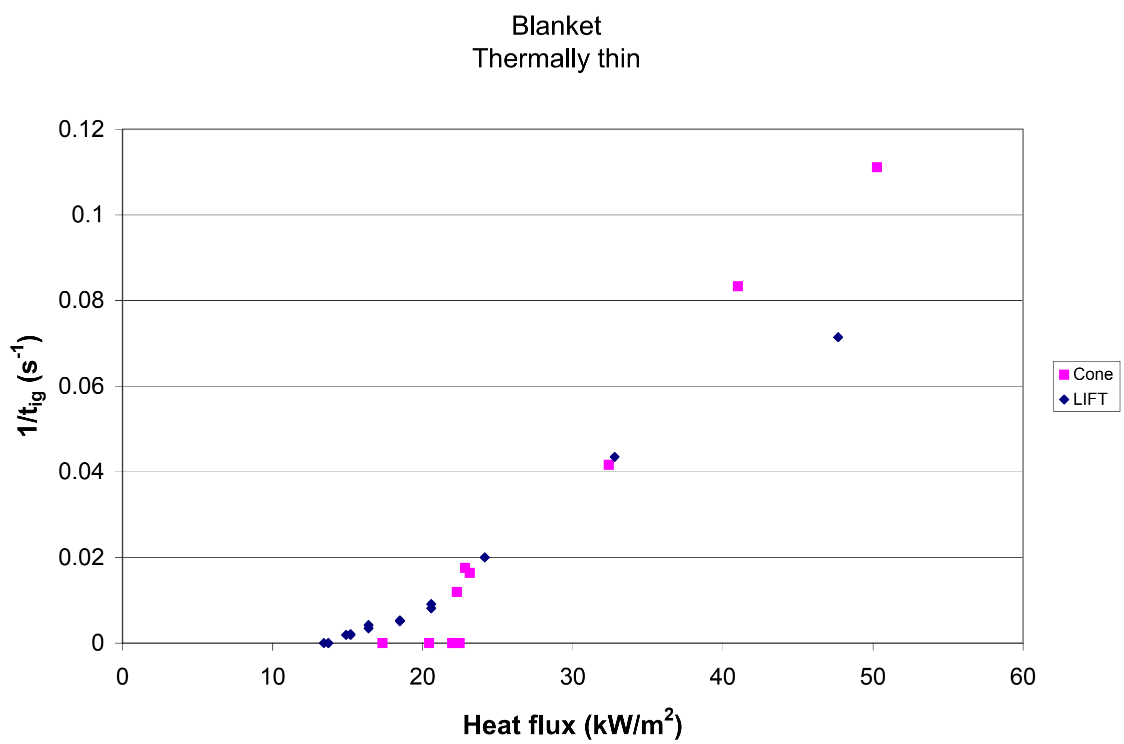

Figure 11. Cotton blanket results based on thermally thin analysis.

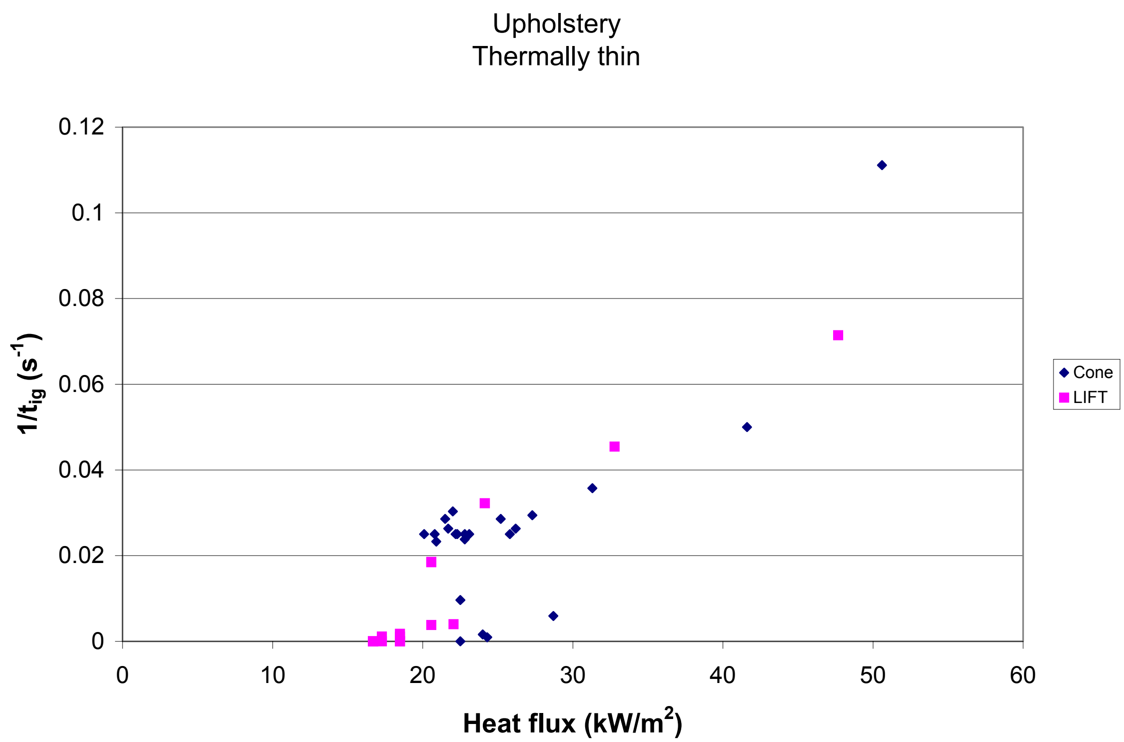

Figure 12. Blue upholstery fabric results based on thermally thin analysis.

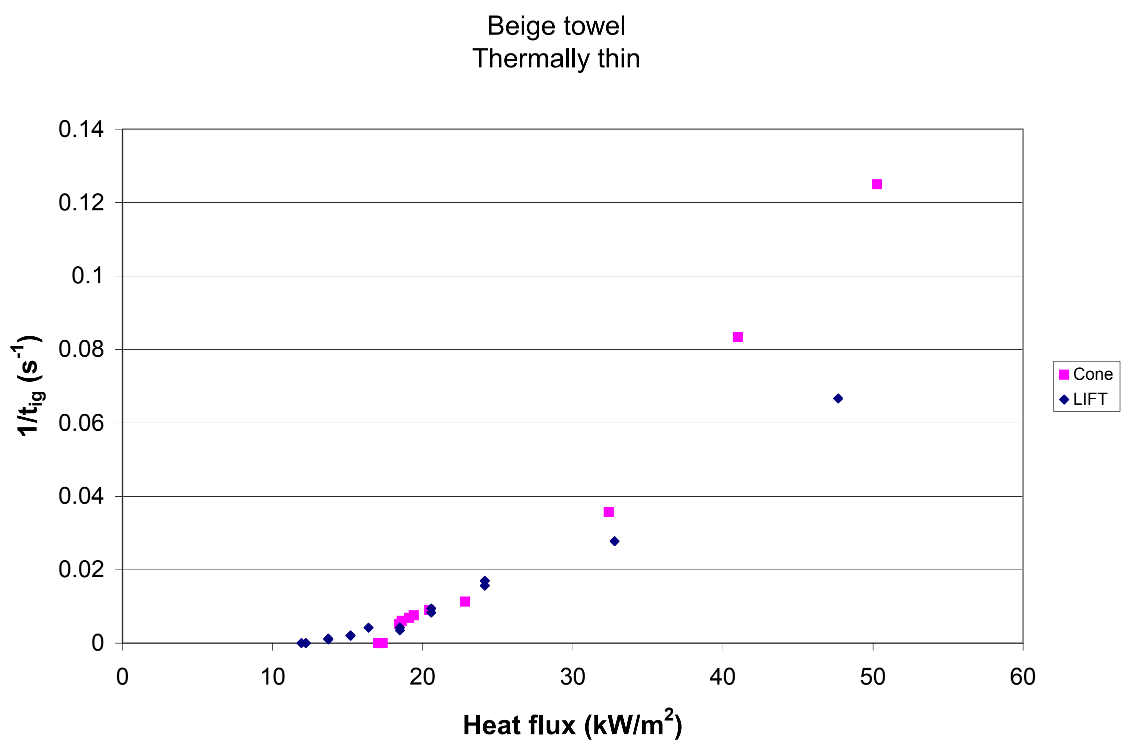

Figure 13. Beige terrycloth towel results based on thermally thin analysis.

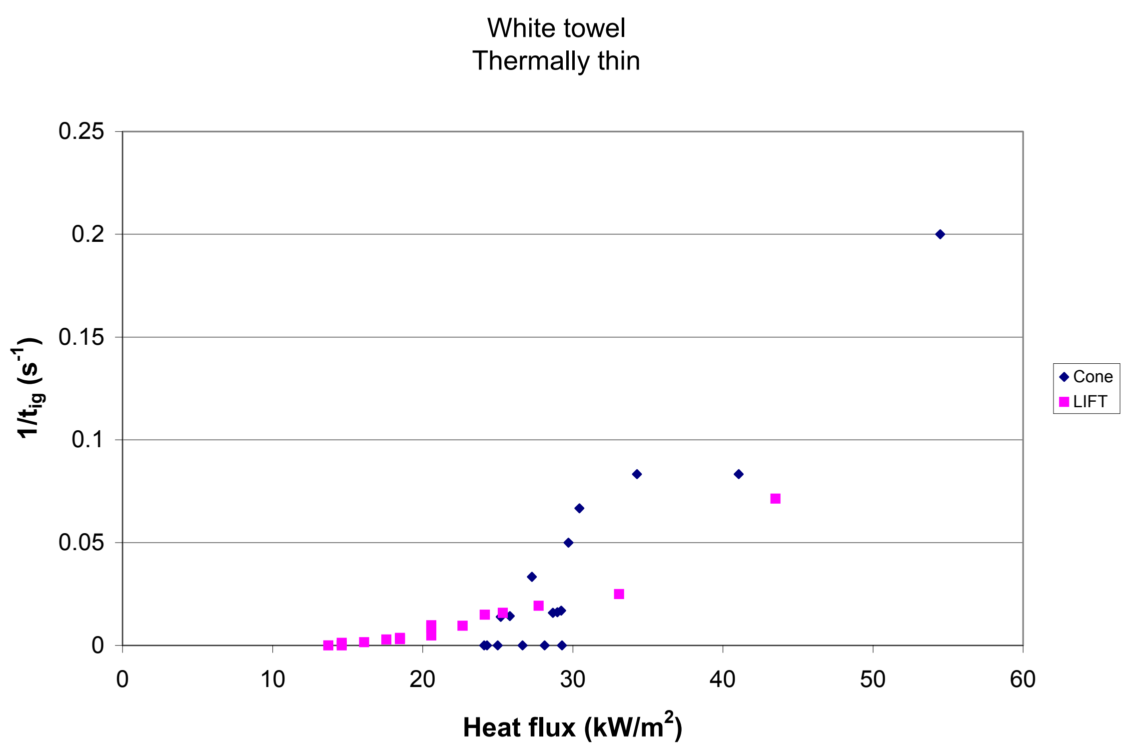

Figure 14. White terrycloth towel results based on thermally thin analysis.

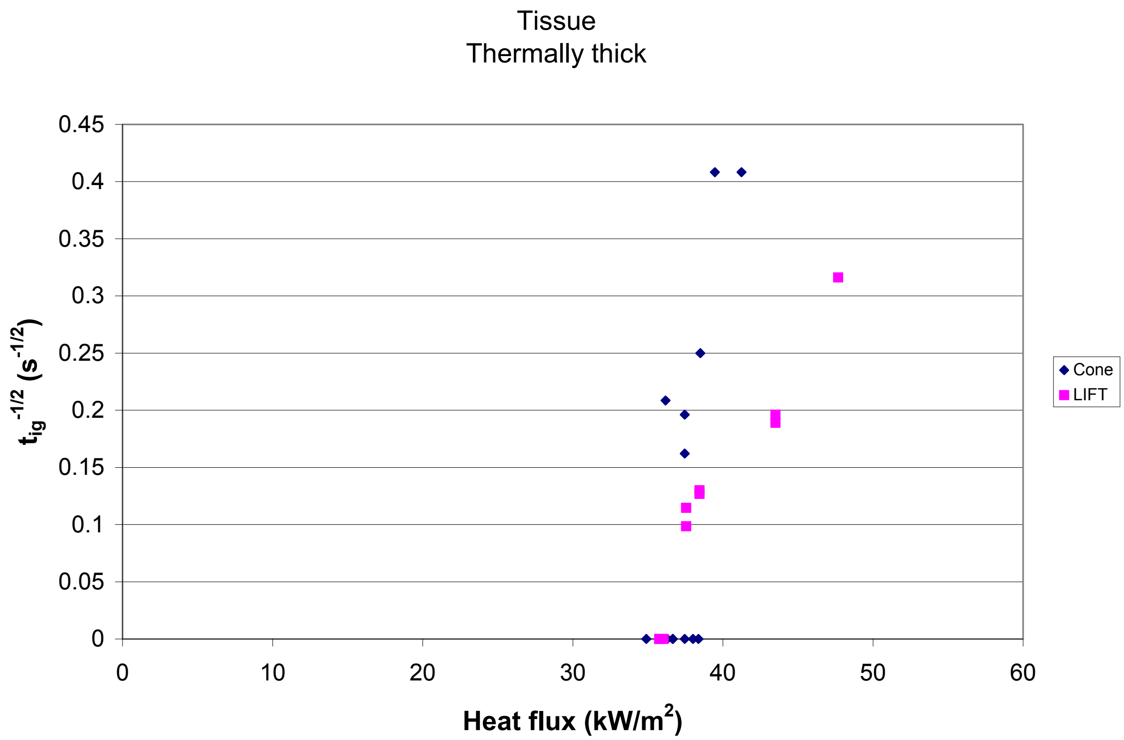

Figure 15. Tissue paper results based on thermally thick analysis.

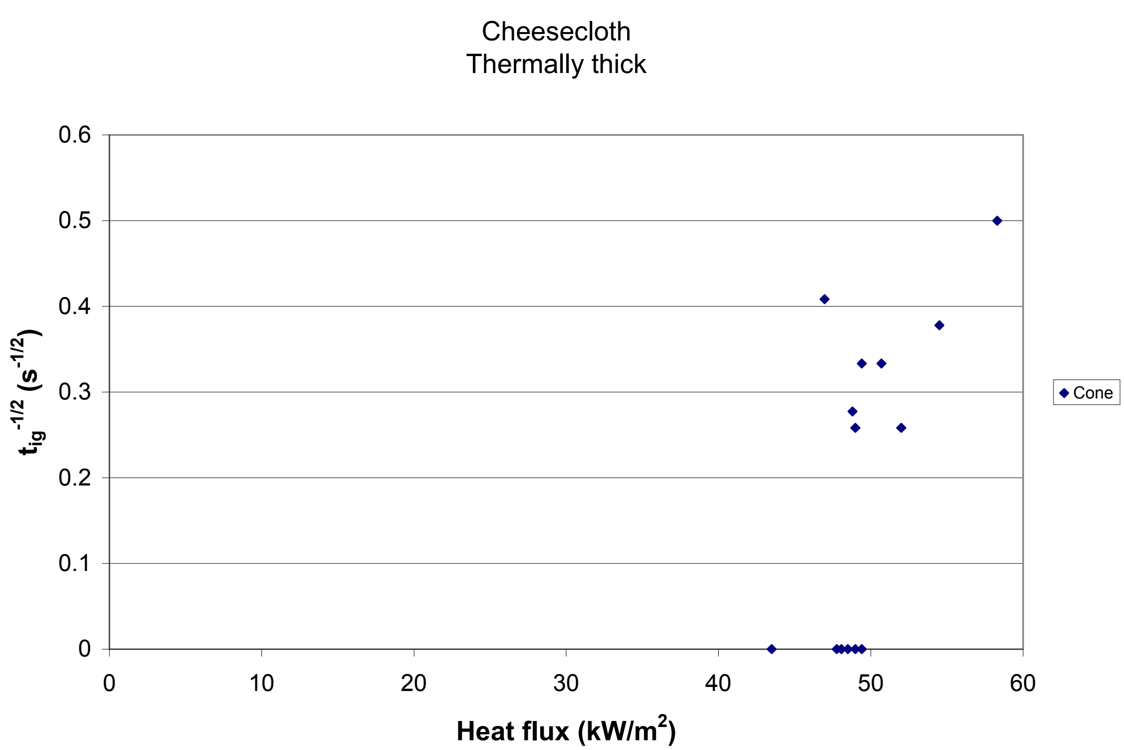

Figure 16. Cheesecloth results based on thermally thick analysis.

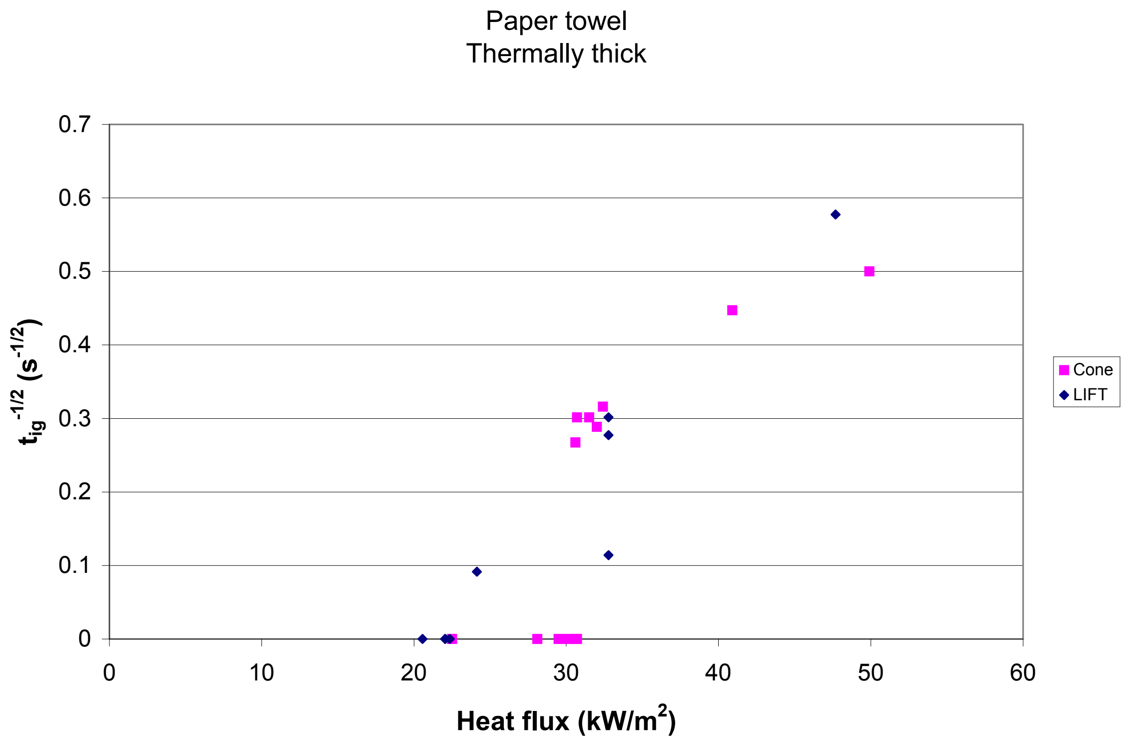

Figure 17. Paper towel results based on thermally thick analysis.

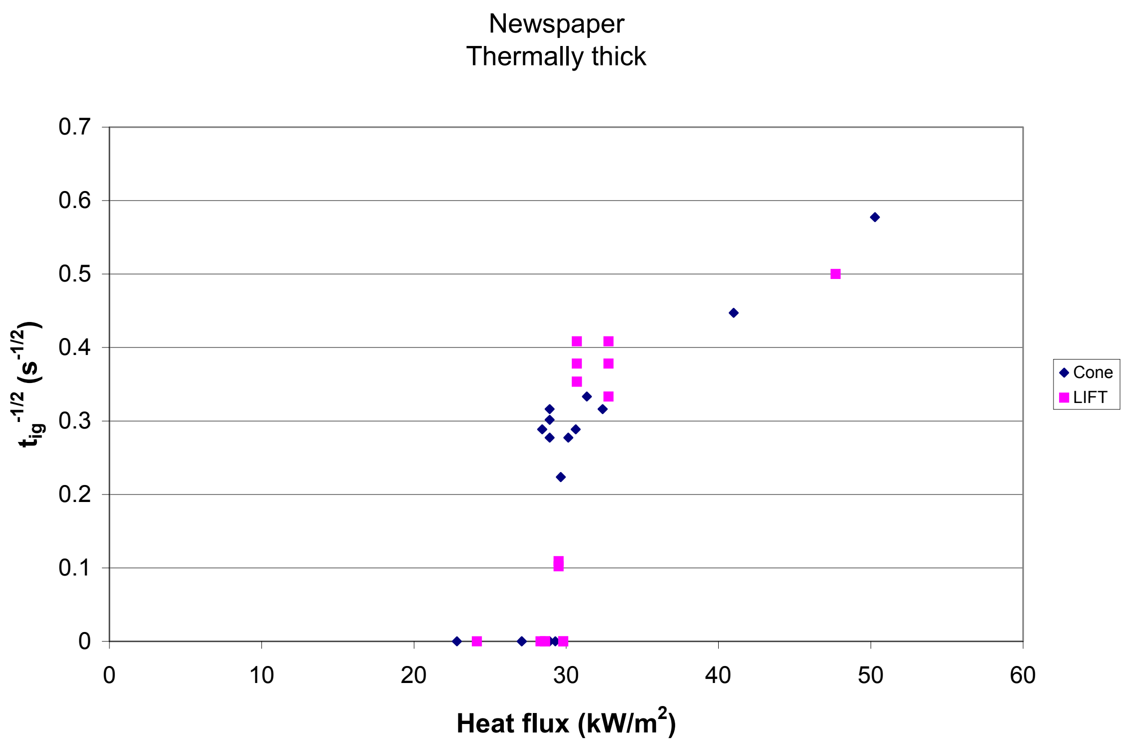

Figure 18. Newspaper results based on thermally thick analysis.

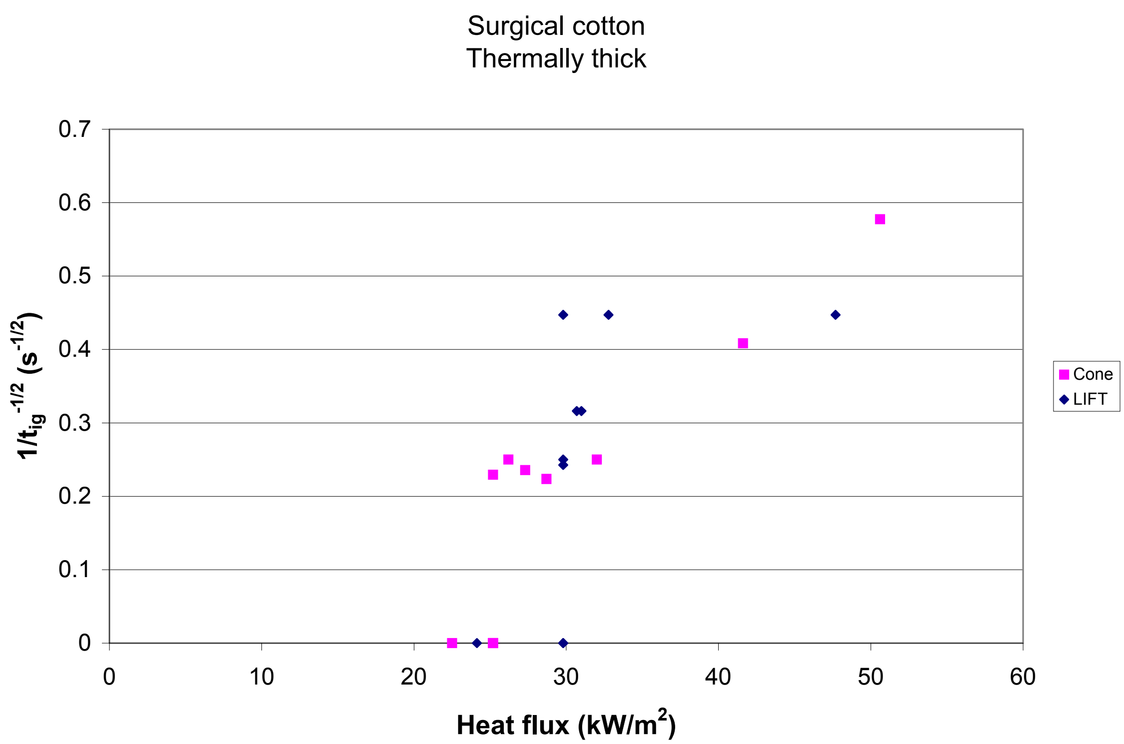

Figure 19. Surgical cotton results based on thermally thick analysis.

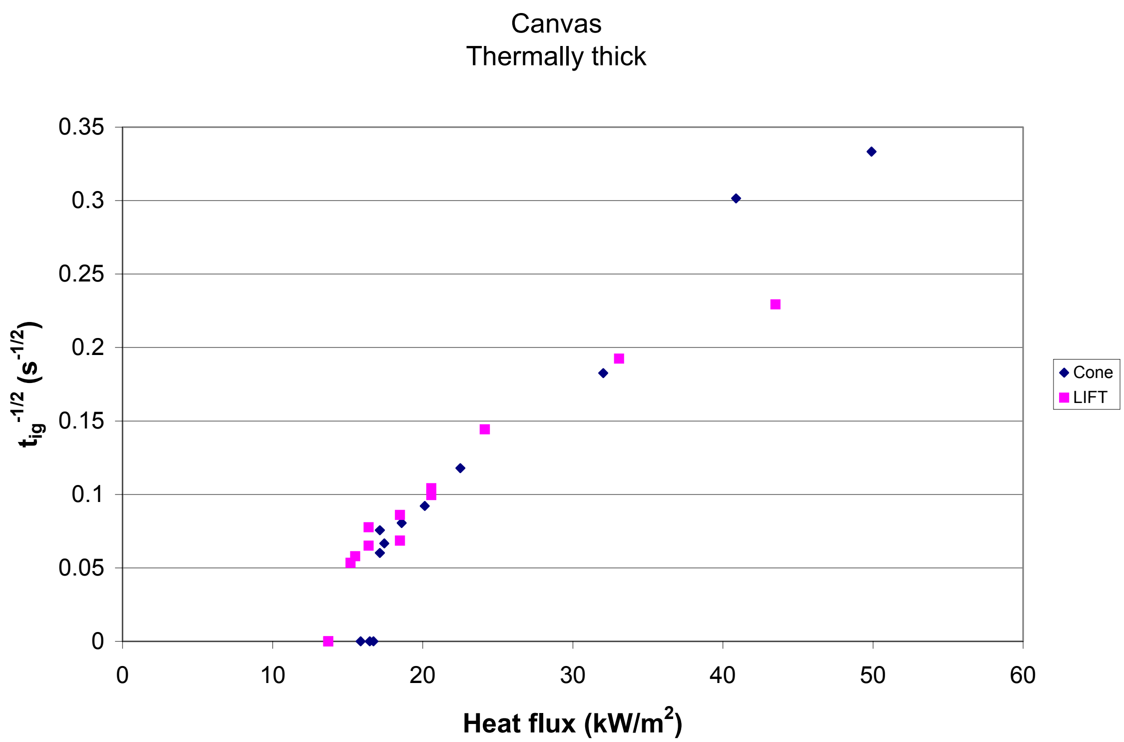

Figure 20. Canvas results based on thermally thick analysis.

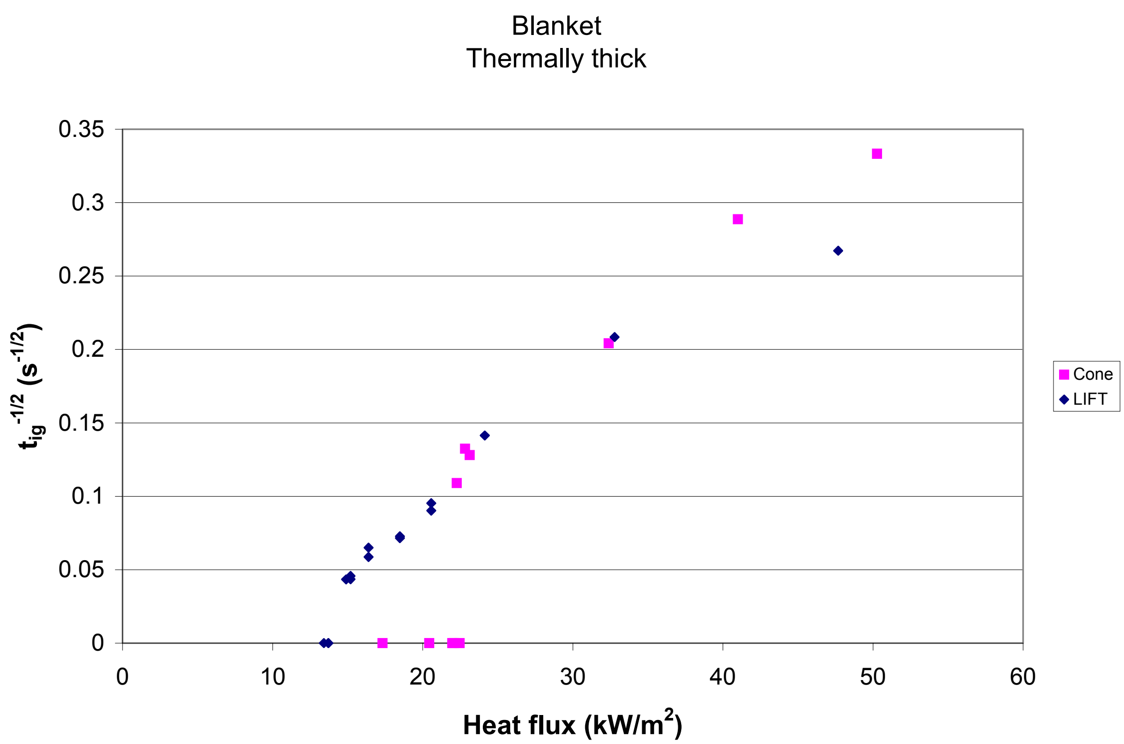

Figure 21. Cotton blanket results based on thermally thick analysis.

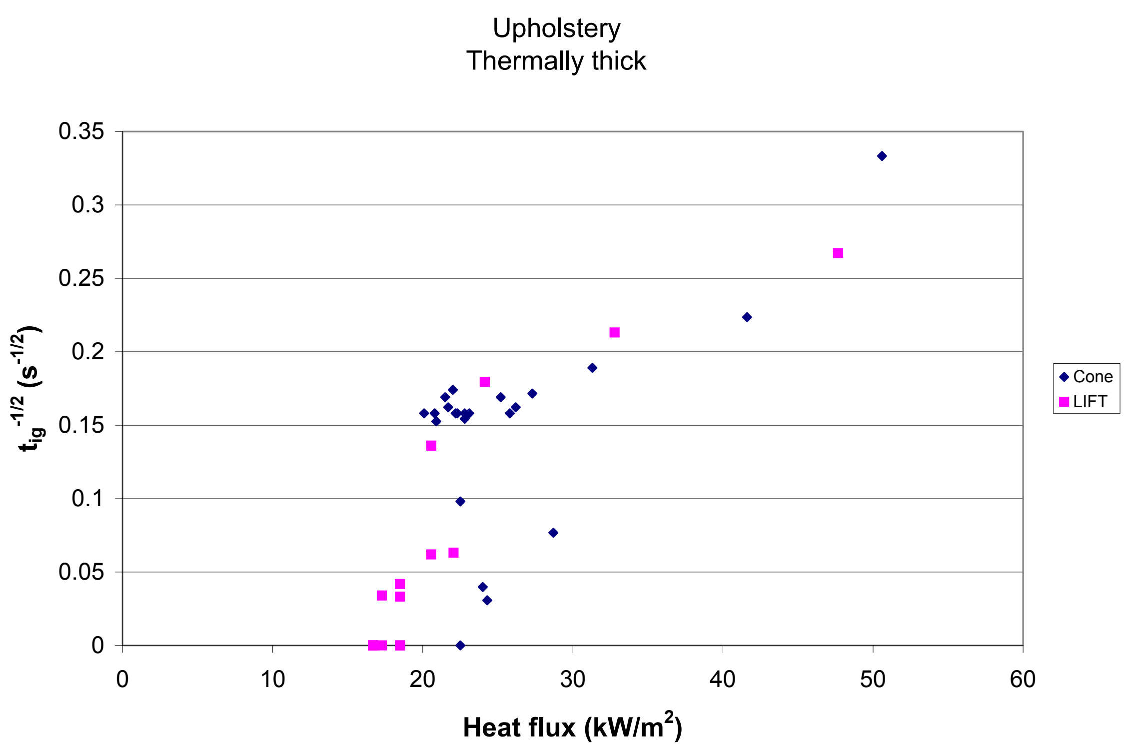

Figure 12. Blue upholstery fabric results based on thermally thick analysis.

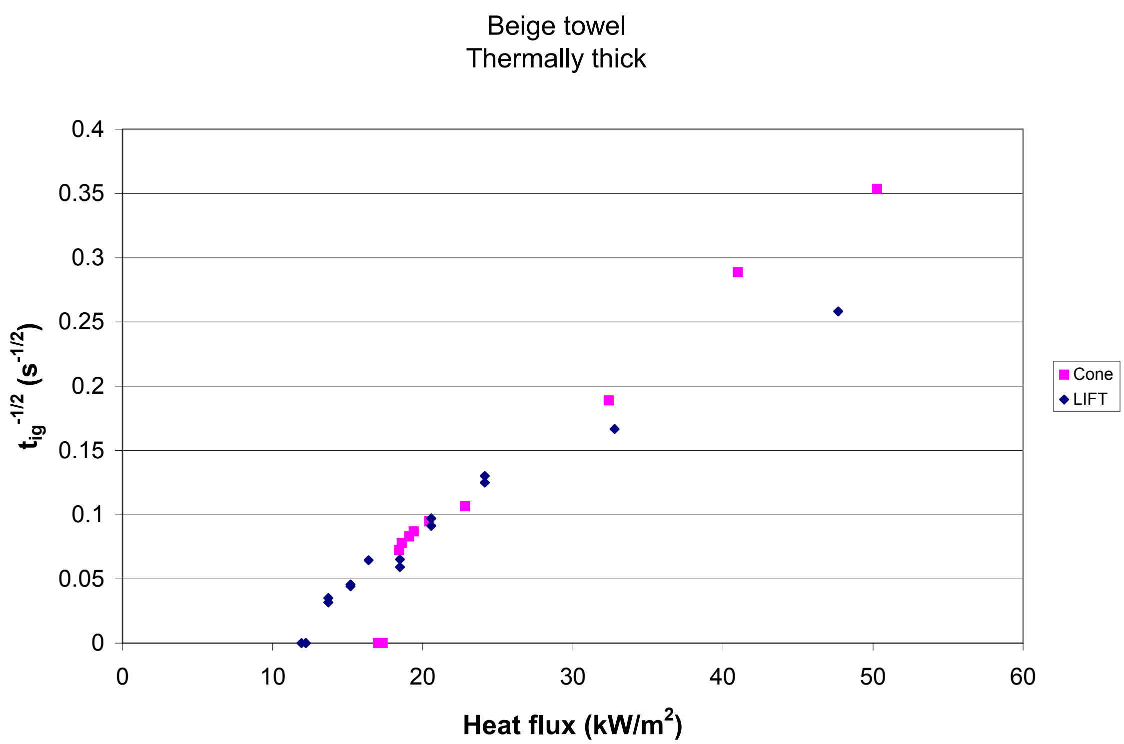

Figure 23. Beige terrycloth towel results based on thermally thick analysis.

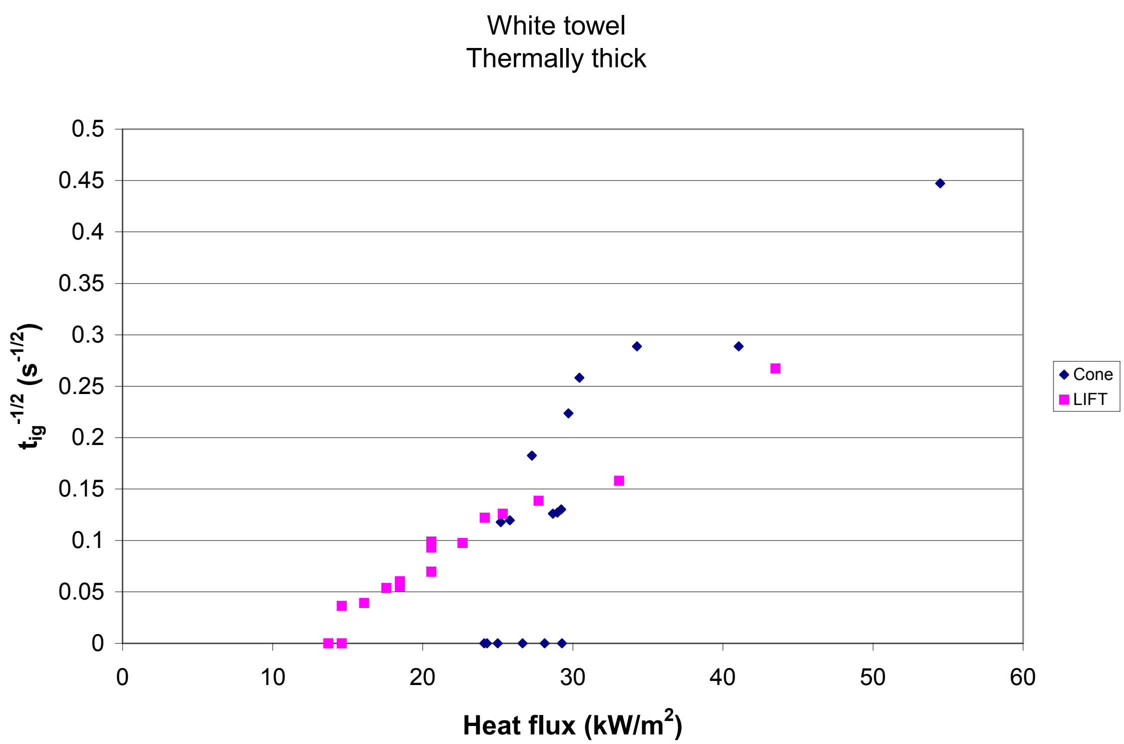

Figure 24. White terrycloth towel results based on thermally thick analysis.

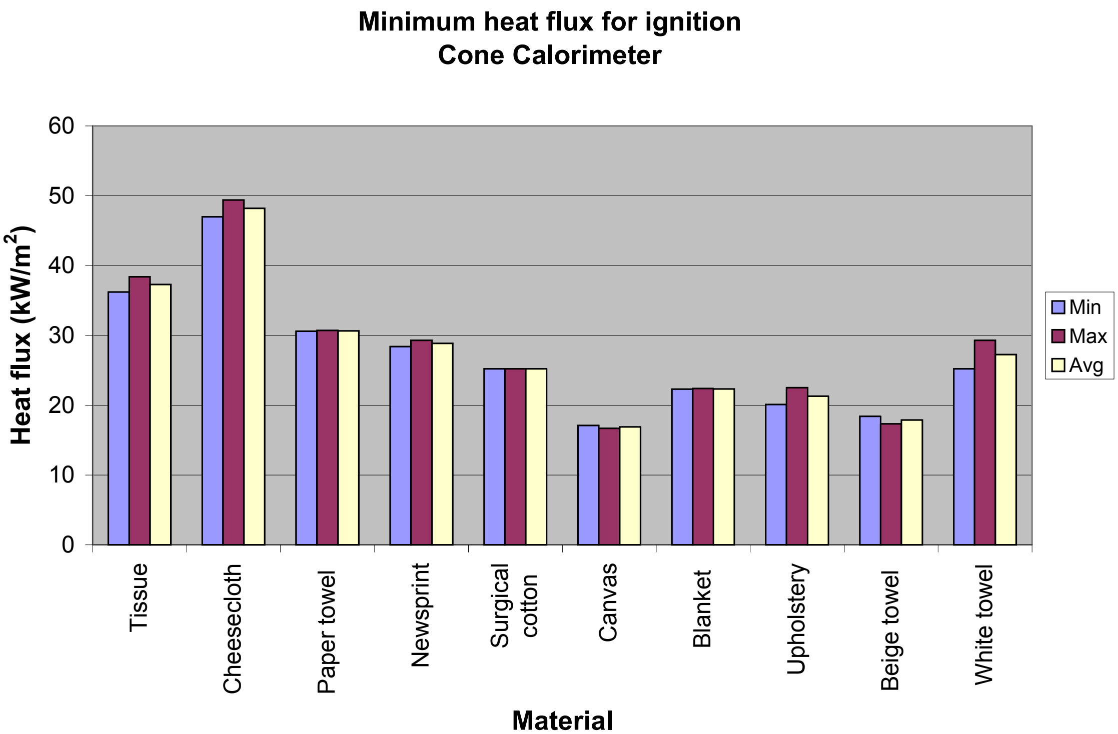

Figure 25. Minimum heat flux results for the Cone Calorimeter.

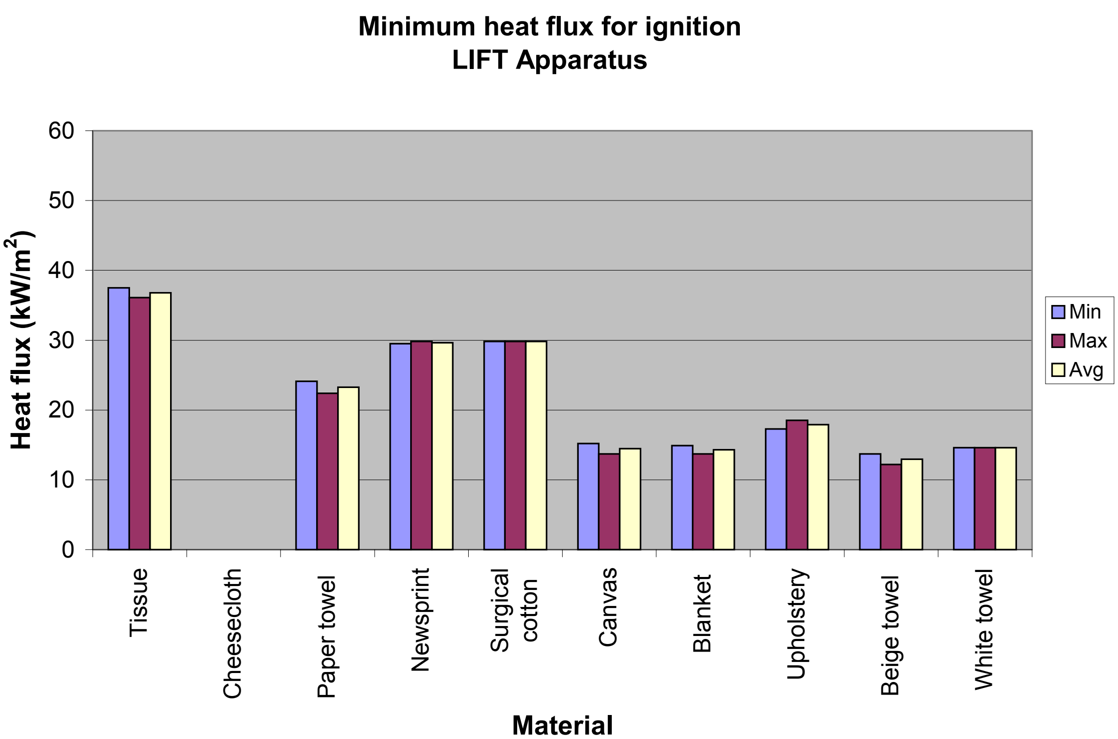

Figure 26. Minimum heat flux results for the LIFT apparatus.

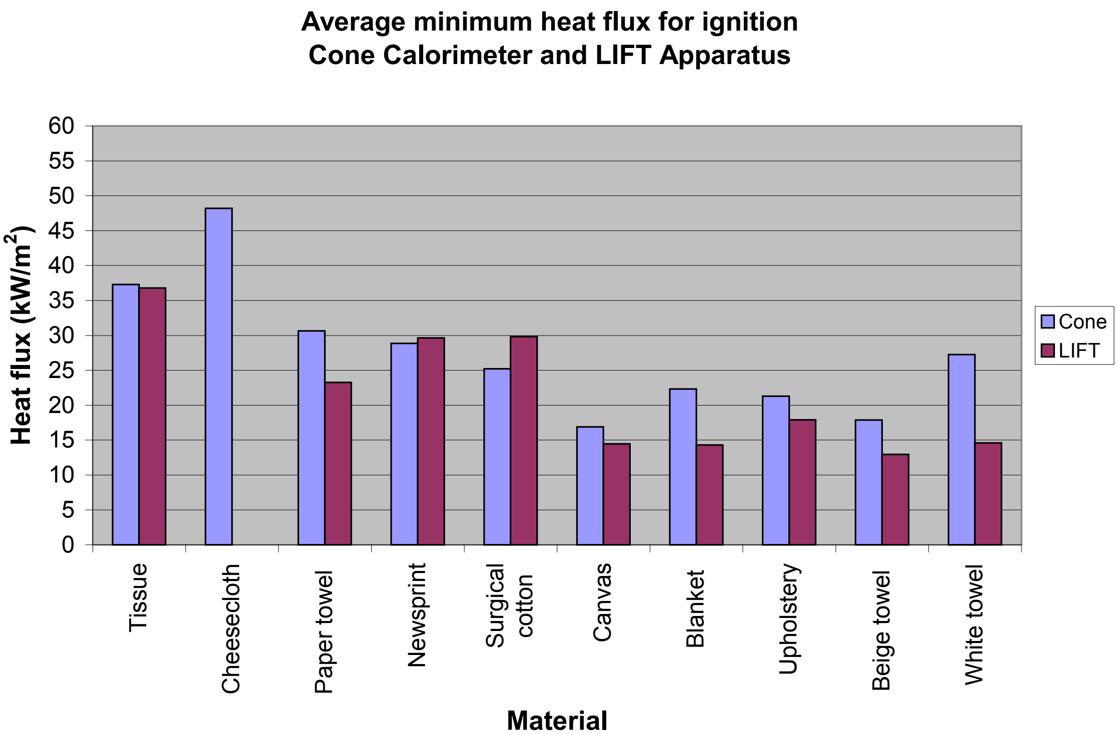

Figure 27. Average minimum heat flux data for Cone Calorimeter and LIFT Apparatus.

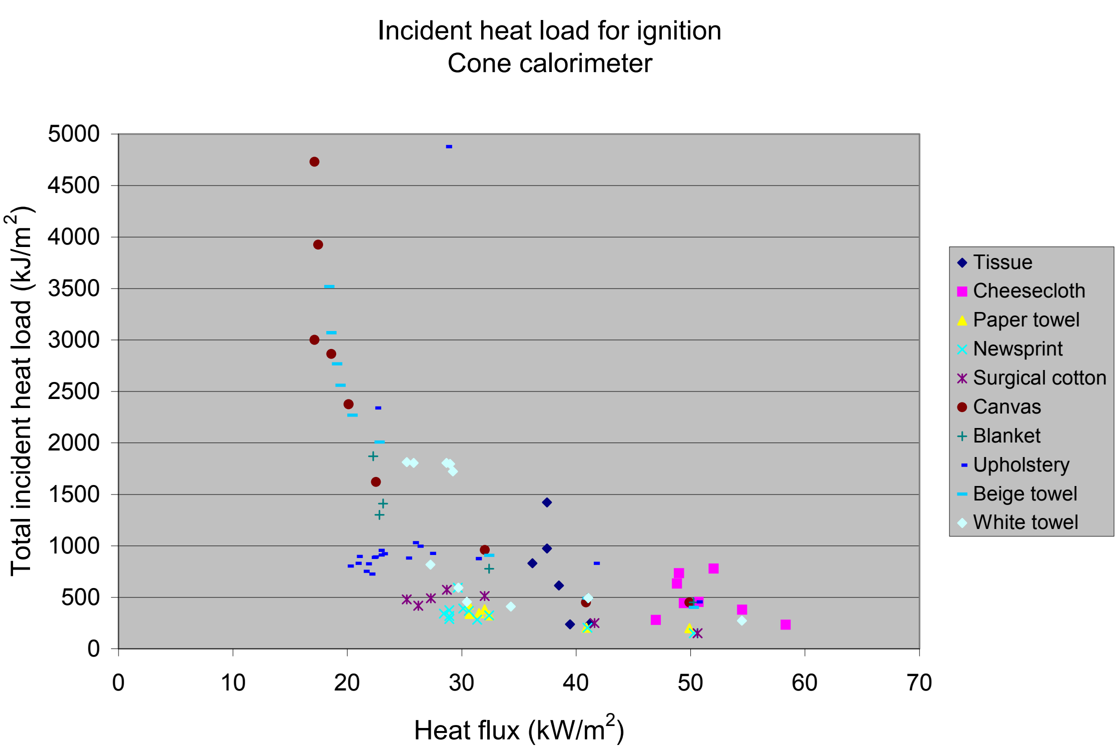

Figure 28. Incident heat load for ignition in the Cone Calorimeter.

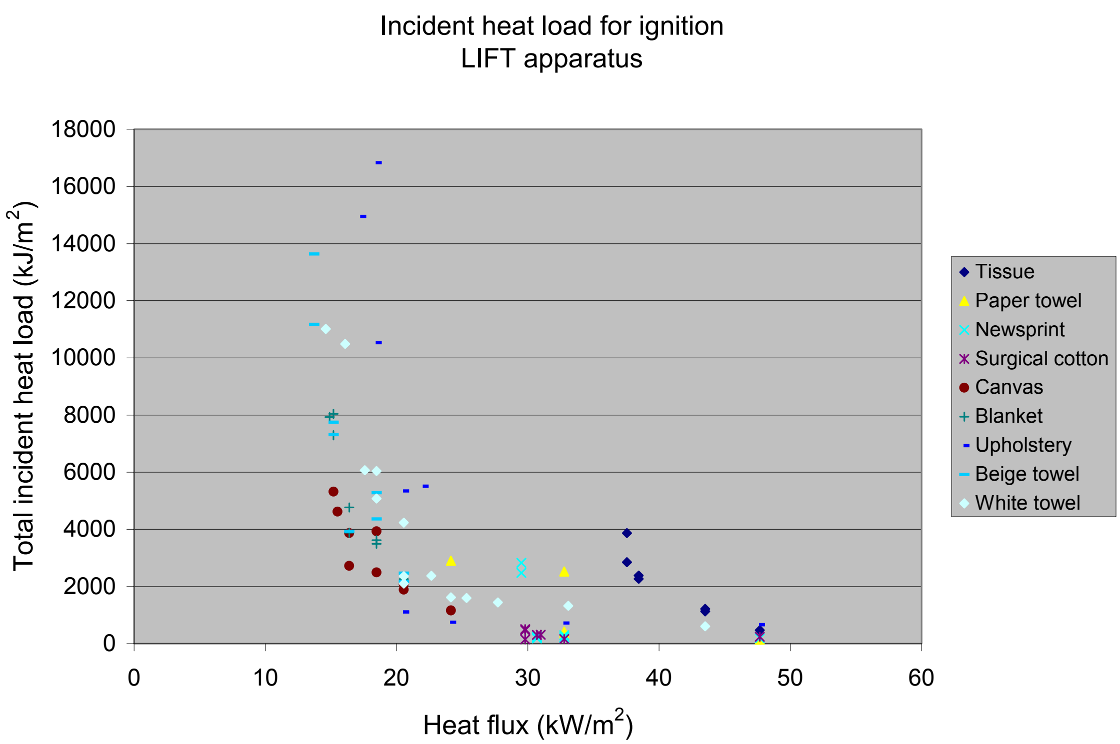

Figure 29. Incident heat load for ignition in the LIFT Apparatus.

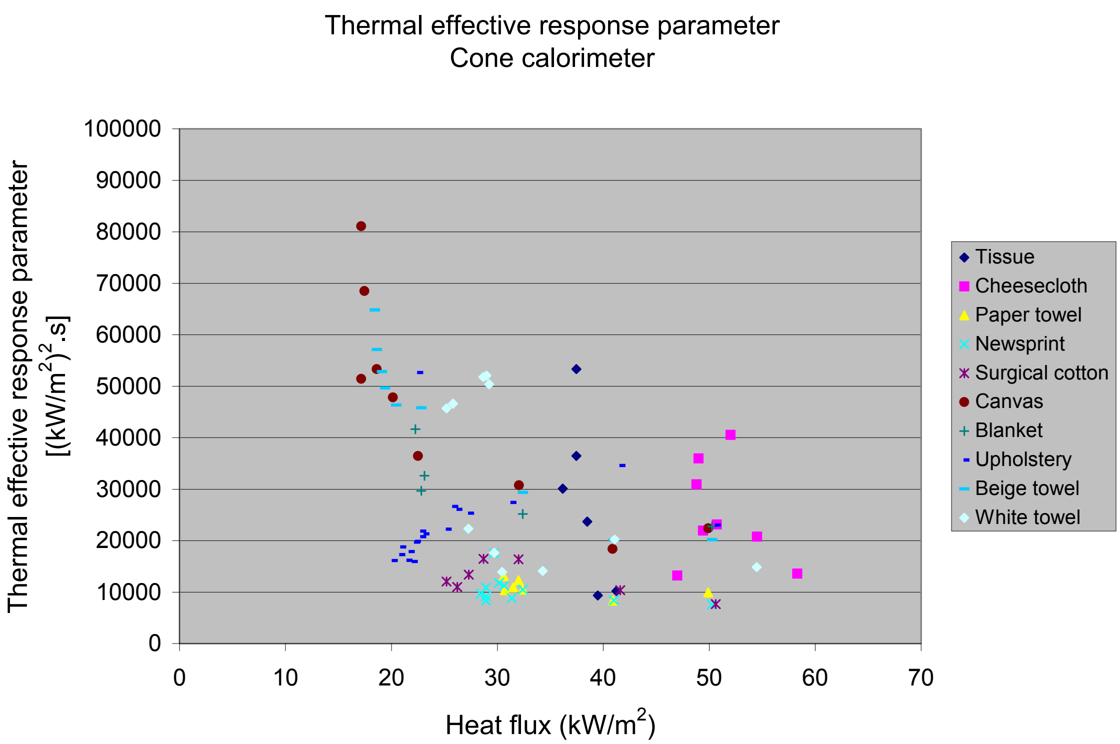

Figure 30. Thermal effective response parameter for Cone Calorimeter tests.

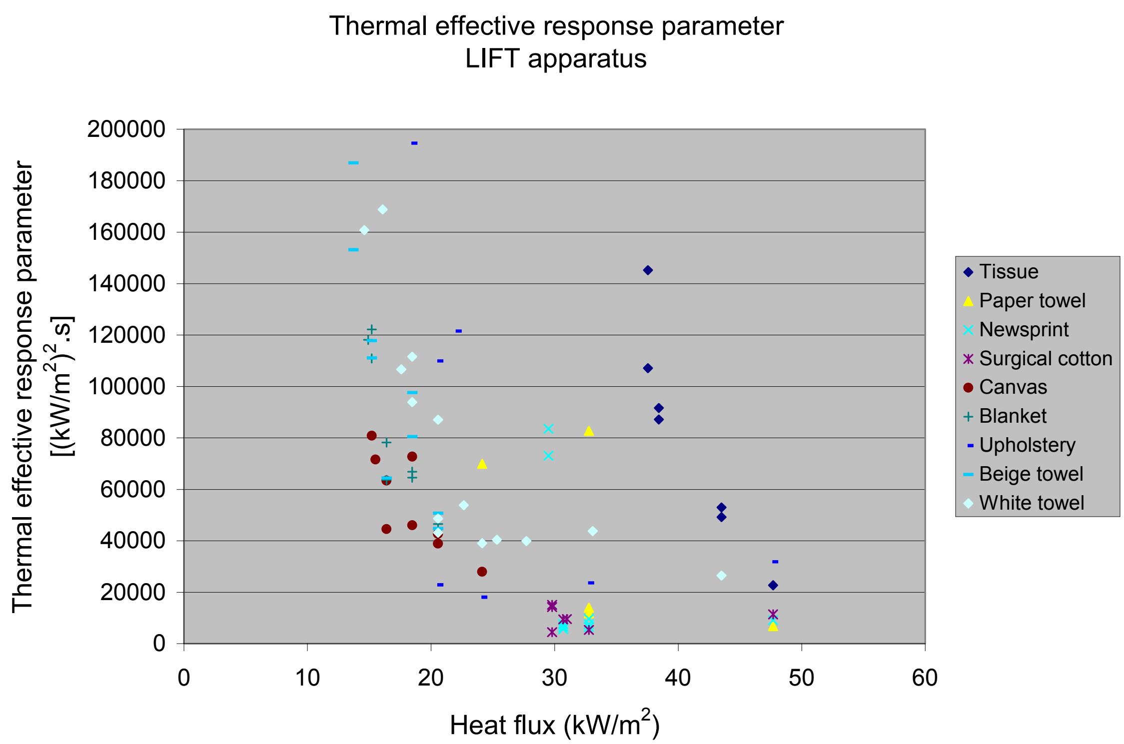

Figure 31. Thermal effective response parameter for LIFT Apparatus tests.