# Surface Temperature of Materials During Radiant Heating to Ignition

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**ABSTRACT**

Surface temperatures of nine organic combustible materials heated to flaming ignition by quartz lamp radiant heating equipment were measured without interference from reflected energy by means of a long wavelength infrared pyrometer. Temperature vs. time curves for irradiances from 0.125 to 2.5 cal/cm$^2$-sec are presented along with summary plots of surface temperatures at ignition for piloted and unpiloted ignition conditions. The factors influencing the shape of the curves and the initiation of ignition are discussed.

## INTRODUCTION

Ignition of cellulosic materials by radiant energy has been studied extensively both for fire prevention and fire starting purposes. In these studies, the parameters thought to be controlling were identified and measured as well as possible. However, some parameters, particularly surface temperatures during irradiation, are not easily measured without special equipment and techniques. Thermocouple techniques are plagued by thermal contact and conduction errors as well as direct energy absorption when exposed to incoming irradiation. Pyrometric measurements are subject to emittance errors and interference from reflected irradiation. It is not surprising, therefore, that there should be differences in the reported temperatures at ignition by various investigators. Moreover, some of the surface temperatures reported are calculated or extrapolated values.

Fons [1] in 1950 reported ignition temperature measurements with thermocouples placed in ⅜ inch diameter pine specimens at positions 0.5 and 0.667 of the radius from the center. The specimens were placed in a furnace at 1150°F (521°C) until the wood caught fire. Using transient heat flow equations for inert solid cylinders, a surface temperature of 650°F (343°C) was calculated for the instant flame appeared. This was acknowledged to be higher than the 560°F (293°C) reported by earlier investigators using finely divided fuels. It is apparent from recent studies that the use of a furnace as a source of heat in the above investigations is likely to produce a piloted ignition from the glowing walls and heating elements.

Lawson and Simms [2] in 1952 and Simms in 1959 [3] suggested that ignition might depend upon the surface of wood being brought to some critical temperature, but did not specify the temperature. However, in 1967 Simms and Law [4] reported for piloted ignition a calculated temperature of 380°C (716°F) and for spontaneous (unpiloted) ignition 545°C (1013°F).

Gardon in 1953 [5] published temperature vs. time curves for various positions including the surface of natural and also black-inked wood. Ignition temperatures were not identified, and surface temperatures were sensed with 0.025 mm diameter, spot-welded chromel P-Alumel thermocouples lightly sprung against the irradiated surface of the wood.

Alvares [6] made surface temperature measurements of blackened alpha cellulose, using an infrared pyrometer with a 3.41 micron narrow band pass filter. The arc radiation was restricted to less than 2.5 microns wavelength by a ½″ thick plexiglass window. Temperatures in the range 600-650°C (1112-1202°F) were reported at spontaneous ignition, which are higher than calculated by Simms and Law.

Koohyar [7] reported surface temperature measurements on several kinds of wood during heating to ignition. A Barnes Engineering Industrial Radiometer Model R-4D1 was used at about 75° to the normal and with a correction for reflected irradiance. Spontaneous ignition for one-sided heating was reported at 330-495°C (626-923°F), average 402°C (755°F), and piloted ignition was at 280-450°C (536-842°F), average 361°C (649°F). Two-sided heating of wood slabs gave somewhat lower ignition temperatures than one-sided heating. Over the range of incident irradiance, 0.3-0.9 cal/cm$^2$-sec, there appeared to be negligible effect of irradiance upon surface temperatures at ignition. It is of interest to note that these spontaneous ignition temperatures are considerably lower than those reported by Alvares or calculated by Simms or Fons.

Work was done at the Naval Weapons Center recently [8, 9] to provide heat flux vs. time-to-ignition data for certain materials. In obtaining the ignition data, a special long wavelength infrared pyrometer was used to identify the ignition event, but it also yielded surface temperature vs. time curves without interference from reflected energy. Because of the general interest in surface temperatures at ignition, some of these data are presented in this report.

## EXPERIMENTAL APPARATUS

Ignition tests were made with radiant energy supplied by quartz lamps which were controlled by Research, Inc., ignitron controllers. Two AU8-612B reflectors holding 15 1000-T3 quartz tube lamps each were mounted together as shown in Fig. 1 and provided with additional compressed air cooling of lamp terminals. A ¼ inch gap between the reflectors allowed sighting an infrared pyrometer normal to the specimen surface being heated.

A specimen-holding platform was placed behind an asbestos-covered steel plate with a 3″ x 3″ aperture hole. Some specimens, such as wood slabs were placed on edge about ½ inch back of the aperture hole. Other shapes of

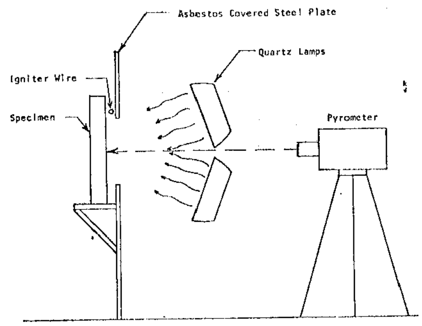


Figure 1. *Experimental test set-up.*

specimens were supported on appropriate brackets, etc., as needed. A nichrome wire was positioned across specimens ¼ inch above and ¼ inch in front of the top edge of the heated area of the specimen. This wire was connected across a Variac to provide electric current that would maintain the wire at bright red heat for the piloted ignition tests. Rising pyrolysis gases mixed with air come into contact with the hot wire and ignite when a combustible mixture is obtained. The flame flashes back to the target surface instantly. It was found impractical to place the specimen flush with the aperture plate and position the igniter wire in front of the plate, because the direct irradiation on the wire caused it to overheat and burn out.

A Hy-Cal Engineering, water-cooled Gardon gauge calorimeter was provided to monitor irradiance. It was of 30 Btu/ft$^2$-sec (8.13 cal/cm$^2$-sec) capacity with a 0-10 mv output for recording.

The pyrometer used was an IRCON Radiation Pyrometer, Model 710. This pyrometer has an indium antimonide detector and filters, making it sensitive only to wavelengths between 4.8 and 5.6 microns. Its response is in the millisecond range. The pyrometer has an output of 10 mv for full scale which covers ranges of 260-800°F, 350-1200°F, 600-2200°F and 800-4000°F (127-427°C, 177-649°C, 315-1204°C, 427-2204°C). The exceptional usefulness of this pyrometer for this work is that the radiation coming through the quartz envelopes from the tungsten filaments does not contain wavelengths longer than about 3.5 microns. The pyrometer therefore cannot "see" this radiant energy even when pointed directly at the quartz tubes. As a result, there is no interference from reflected energy from the quartz tube lamps. Thus, it is possible with this arrangement to measure surface temperatures directly without corrections except for the emittance, which has been determined to be near unity for these materials and wavelengths. However, the reflectors must be kept sufficiently cool, or there will be a longer wavelength component emitted.

A Moseley X-Y-Y′ Recorder was used as a time-base recorder for the calorimeter and pyrometer signals.

## TEST PROCEDURE

Prior to the start of a test, the Hy-Cal calorimeter was positioned on the platform and in the same plane as the specimen surface would be. The lamps were turned on with manual control and the rheostat adjusted until the desired heat flux (between 0.125 and 2.5 cal/cm$^2$-sec) was indicated on the recorder. Leaving the rheostat at the pre-setting, the lamps were turned off, and the specimen was substituted for the calorimeter. The lamps and recorder were then turned on simultaneously until the appearance of flame. If the test was for piloted ignition, the Variac would be turned on just before the lamps. It was also the practice to follow each test immediately with another calorimeter measurement to make sure the radiant heat flux had not changed during a test.

## MATERIALS TESTED

The following materials were tested with no-pre-conditioning other than storage in the air-conditioned laboratory at room temperature and 42% relative humidity for at least two months:

| | |
|---|---|
| Pine blocks | 4″ × 4″ × ¾″ |
| Pine dowels | ½″ diam. × 4″ |
| Oak dowels | ¼″ diam. × 4″ |
| Corrugated box cardboard | 4″ × 4″ × 0.16″ |
| Newspaper want-ads | 4″ × 4″ × 0.0035″ |
| White Canvas | 4″ × 4″ × 0.053″ |
| Green densely woven cotton cloth | 4″ × 4″ × 0.022″ |
| Black rubber strips | 1½″ × 6″ × ⅛″ |
| Polyurethane foam strips | 1½″ × 6″ × ⅝″ |

The first seven of the above materials are common cellulosics selected for a range of thicknesses. These include natural woods, processed wood fibers, and processed cotton fibers. The black rubber is butadiene processed for tire tread wear, while the polyurethane is a synthetic resin.

## MEASURED SURFACE TEMPERATURES

In Figure 2 are reproductions of the recorded millivolts vs. time curves from the IRCON pyrometer for corrugated box cardboard ignited with and without pilot, respectively. The pyrometer calibration is non-linear, and the rate of heating is not directly proportional to the slope. It is of interest though that the two curves agree very well until the moment piloted ignition occurred. The recorder was turned off as soon as possible after appearance of flame—probably less than a second—to avoid cluttering the paper, which was used for several tests. As shown, the unpiloted test continued smoothly, but with accelerated heating. Shortly after the change in scale, the curve became quite irregular with many rapid fluctuations due to smoke issuing from the surface. Ignition coincided with a small jump in millivolts. Ignition was easily detected visually and marked on the record. Sometimes the appearance of flame would produce a sudden large jump in millivolts, and other times the increase in millivolts would preceed the appearance of flame.

Figures 3 and 4 illustrate the surface temperature behavior in piloted and

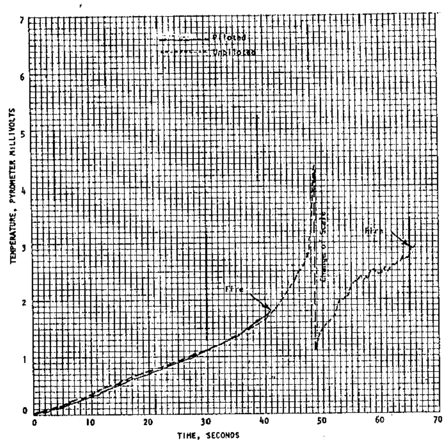


*Figure 2. Tracing of recorder curves for cardboard at 1.0 CAL/CM2-SEC.*

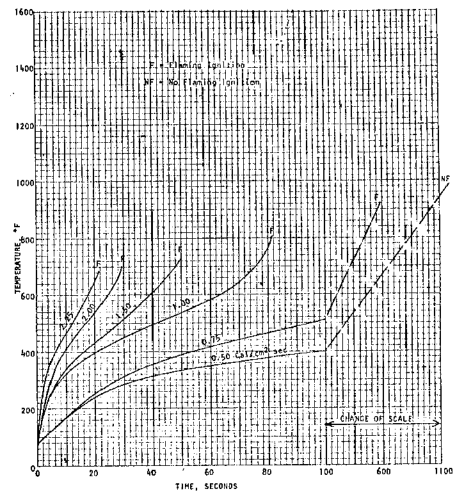


Figure 3. *Surface temperatures during piloted ignition of ¾ inch pine blocks.*

unpiloted ignition tests on ¾ inch thick ponderosa pine wood. For clarity in presentation only one typical curve for each heat flux is presented. Additional curves in each flux class are shown in Ref. 10. However, the ignition temperatures for all of the tests are plotted on the summaries of ignition temperatures vs. heat flux, as in Fig. 5. Temperature rise is rapid at first with a decreasing slope of the curve. The slope becomes steady between 450° and 500°F where scorching and charring begins. Above 600°F the slope tends to increase slightly and then again decreases above 900°F until ignition takes place. It is interesting that the specimens heated with 0.75 cal/cm²-sec flux with a pilot igniter caught fire at much higher surface temperatures than those subjected to higher heat fluxes. At a still lower flux, 0.5 cal/cm²-sec, there was no flame. It is probable that with the slow heating, most of the volatiles escaped (or did not accumulate in a combustible concentration) by the time the usual igntition range of 650-800°F (343°-427°C) was reached, and some glowing charcoal was necessary to ignite the volatiles diffusing from deeper in the specimen at 900-1060°F (482-571°C) surface temperature. With still slower heating, ignition did not occur. Unpiloted ignition occurred at higher surface temperatures than piloted ignition. As the flux was lowered in unpiloted tests, higher ignition temperatures were experienced until at 1.0 cal/cm²-sec ignition did not occur.

The ½ inch diameter pine dowels in piloted ignition tests, Fig. 6, ignited at lower surface temperatures than the ¾ inch blocks. Figure 7 shows that except for the 2.5 cal/cm²-sec test, the dowels ignited at temperatures of 850-1350°F (454-732°C) in the unpiloted tests. Figure 8 is a summary of the surface ignition temperatures vs. heat flux for the pine dowels.

All of the ¼ inch oak dowels, Fig. 9, were pilot-ignited between 550-760°F (288-404°C). However, it was surprising that flaming ignition still occurred at 690 seconds for the lowest flux of 0.75 cal/cm²-sec. One would suppose

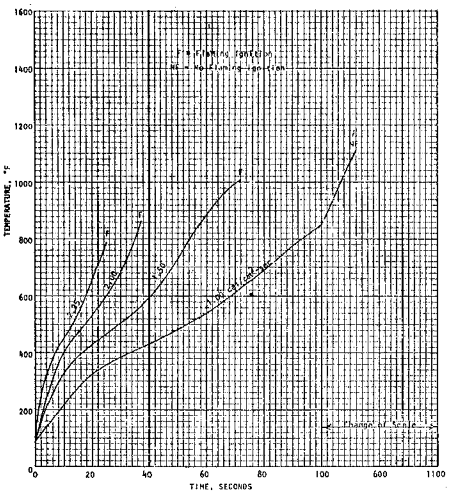


Figure 4. *Surface temperatures during unpiloted ignition of ¾ inch pine blocks.*

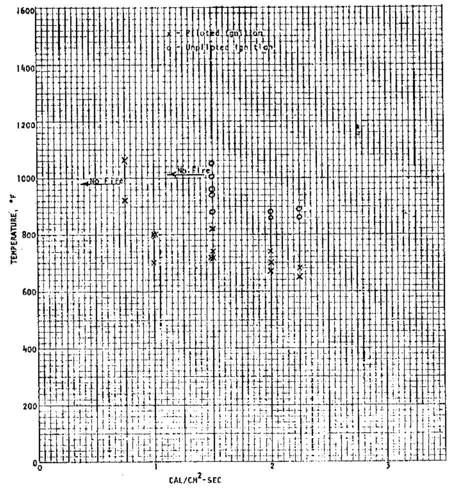


Figure 5. *Effect of radiant heat flux on ignition temperatures of ¾ inch pine blocks.*

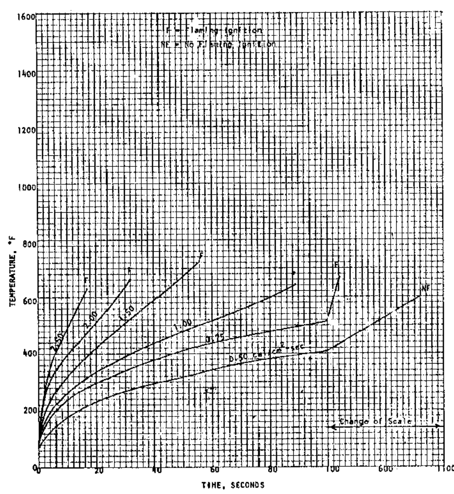


Figure 6. *Surface temperatures during piloted ignition of ½ inch pine dowels.*

that all of the volatiles would have escaped from the small dowel before then. No flaming ignition occurred in the unpiloted tests on this material, Fig. 10. These curves show a peculiar downturn after a peak of 1200-1300°F (649-704°C), which may be due to a coating of ash over the glowing charcoal. Surface ignition temperatures for the ¼″ oak dowel are summarized in Fig. 11.

The behavior of the box cardboard was noticeably different than the ¾ inch pine blocks in unpiloted ignition tests, but was similar in the piloted ignition tests, Fig. 12, 13, 14. The unpiloted tests exhibited long steep temperature rises above 700°F (371°C) and then decreasing slopes above about

*Surface*

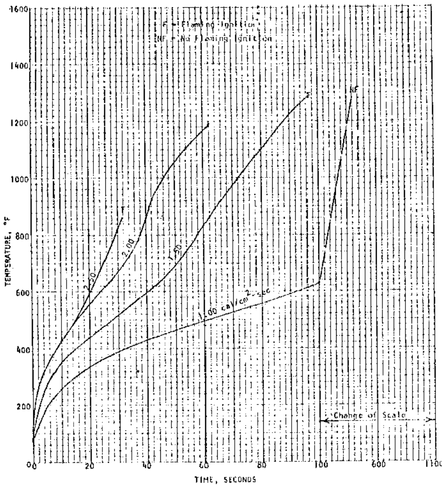


Figure 7. *Surface temperatures during unpiloted ignition of ½ inch pine dowels.*

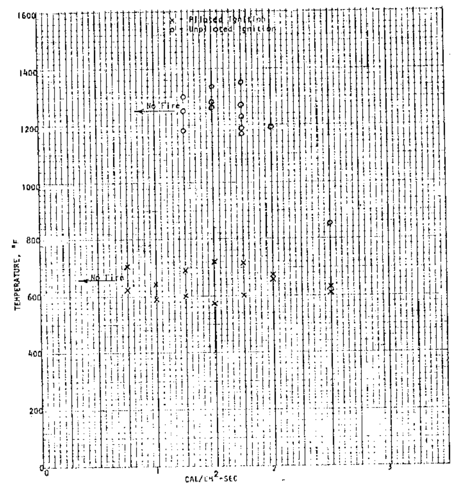


Figure 8. *Effect of radiant heat flux on ignition temperatures of ½ inch pine dowels.*

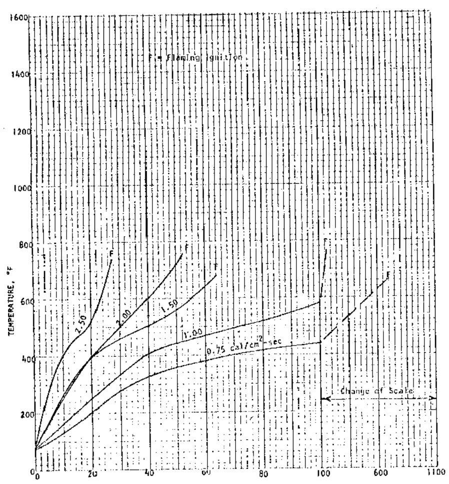


Figure 9. *Surface temperatures during piloted ignition of ¼ inch oak dowel.*

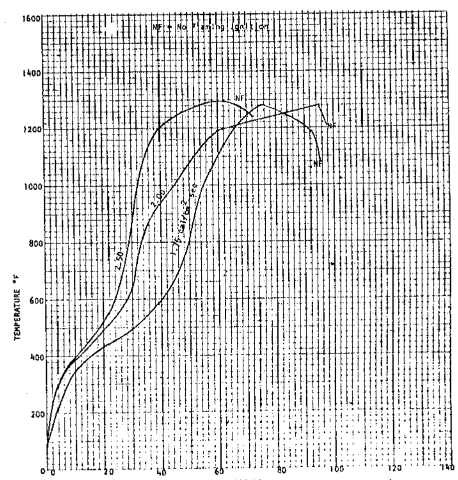


Figure 10. *Surface temperatures during unpiloted ignition of ¼ inch oak dowel.*

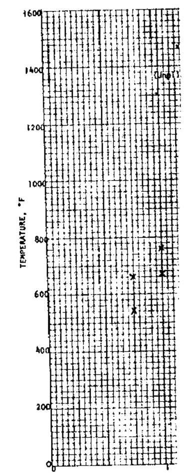

Figure 11. *on ignition te dowel.*

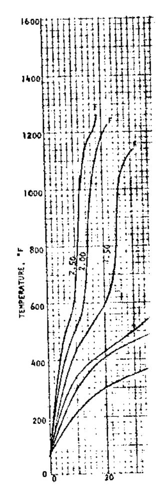

Figure 1 *ing unpilot*

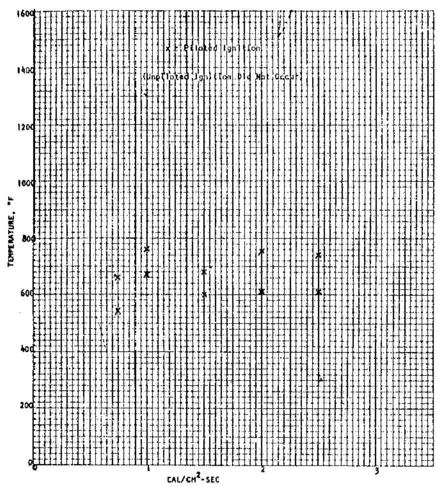


Figure 11. *Effect of radiant heat flux on ignition temperatures of ¼ inch oak dowel.*

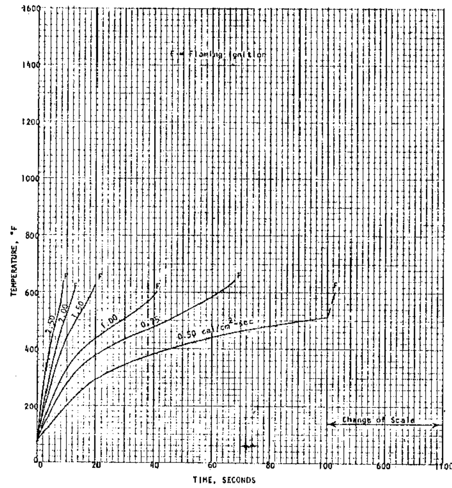


Figure 12. *Surface temperatures during piloted ignition of cardboard.*

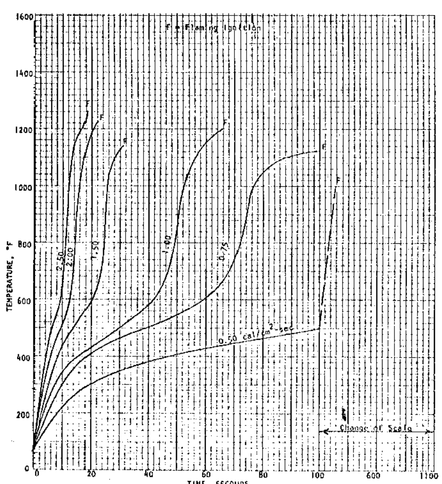


Figure 13. *Surface temperatures during unpiloted ignition of cardboard.*

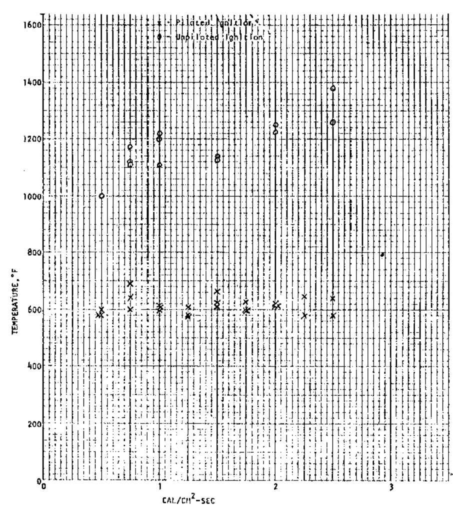


Figure 14. *Effect of radiant heat flux on ignition temperatures of box cardboard.*

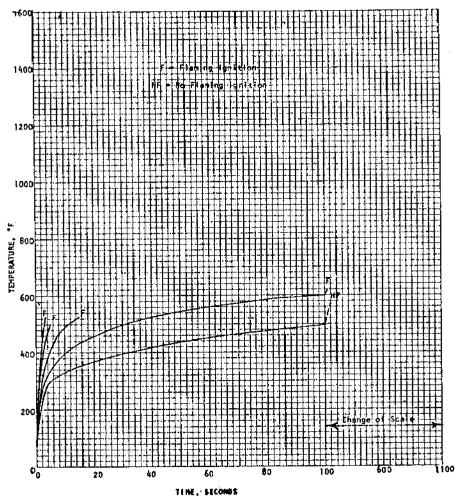


Figure 15. *Surface temperatures during piloted ignition of newspaper want-ads.*

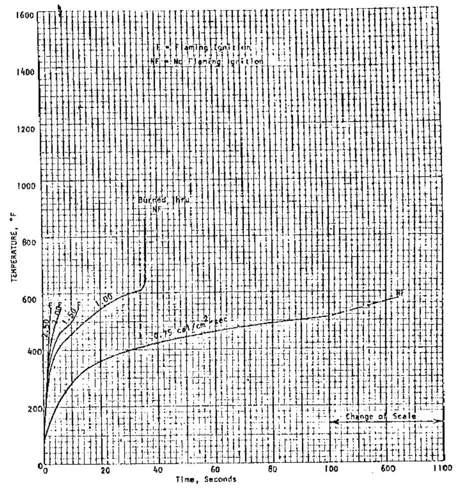


Figure 16. *Surface temperatures during unpiloted ignition of newspaper want-ads.*

1000°F (538°C) just before flaming ignition. A possible explanation of this may be that the thin outer paper layer loses all its volatiles without igniting and becomes a glowing char. By then the back side of the corrugated board and the corrugations, or "honeycomb" itself, may be emitting volatiles through holes in the front charred layer. A glowing char is present to ignite these volatiles. A contributing factor may be that the paper making process changes the structure and distribution of cellulosic matter so that volatile release is different. Of course, there is a density difference in the region of volatile production because of the manufactured air spaces under a thin cover layer, which has an effect on available volatiles and diffusion to the surface. Welker, [11], has established for many varieties of wood a relationship between density and ignition. As displayed in Fig. 14, piloted ignition surface temperatures of the box cardboard are quite constant. Unpiloted ignition temperatures show more scatter and also an up-trend with heating flux.

Figures 15, 16, 17 for newspaper (want-ads) show the peculiar ignition behavior of a very thin cellulosic material. There was very little difference between piloted and unpiloted ignition. Ignition temperatures were nearly 100°F lower than for the thicker cellulosic materials, and in addition appeared to have a down-trend with increase in heat flux.

White canvas, Fig. 18, 19, 20, followed a surface temperature trend much like the cardboard, except that there was no unpiloted flaming ignition. The green cotton material, Fig. 21, 22, 23, also appears similar to the cardboard, but at heat fluxes of 1.5 cal/cm$^2$-sec and above there is unpiloted ignition. Much more scatter of unpiloted surface temperatures at ignition is present than for piloted ignition of the green cotton material.

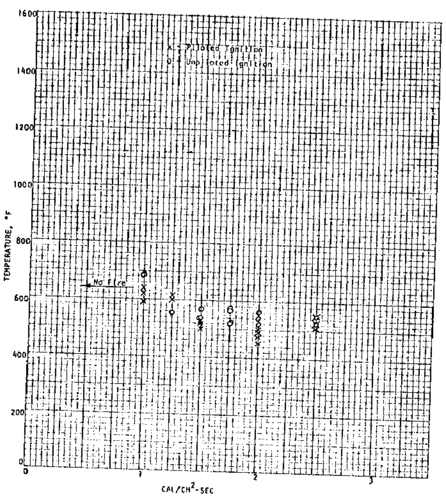


Figure 17. *Effect of radiant heat flux on ignition temperatures of newspaper want-ads.*

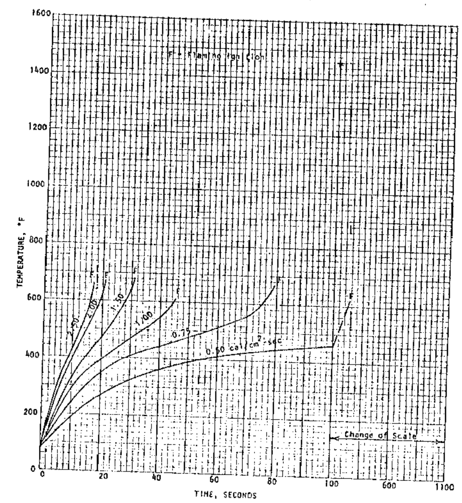


Figure 18. *Surface temperatures during piloted ignition of white canvas.*

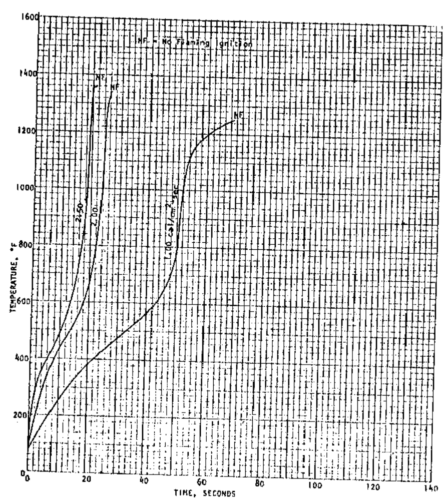


Figure 19. *Surface temperatures during unpiloted ignition of white canvas.*

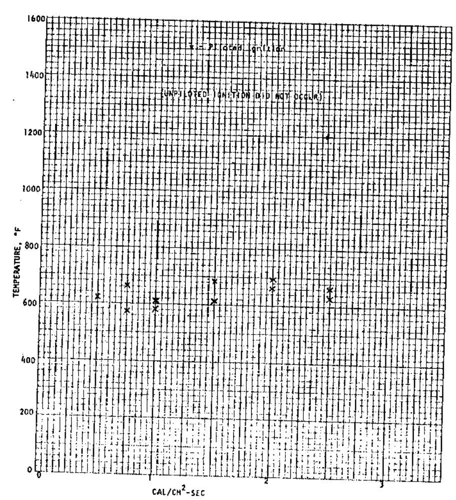


Figure 20. *Effect of radiant heat flux on ignition temperatures of white canvas.*

The ignition behavior of the rubber is shown in Fig. 24, 25, 26. Piloted ignition with heat fluxes from 0.75 to 2.0 cal/cm²-sec, takes place at about 800°-900°F (427-482°C), which is considerably higher than for cellulosic materials. However, ignition took place at 600-615°F (315-324°C) when the flux was 2.5 cal/cm²-sec, and did not take place at all for 0.5 cal/cm²-sec. Surface temperatures exceeded 1200°F (649°C) before unpiloted ignition took place.

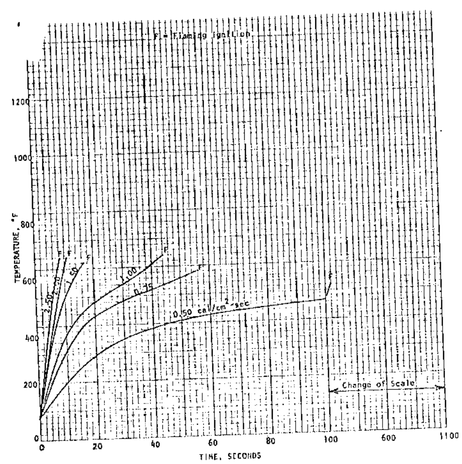

Figure 21. *Surface temperatures during piloted ignition of green cotton cloth.*

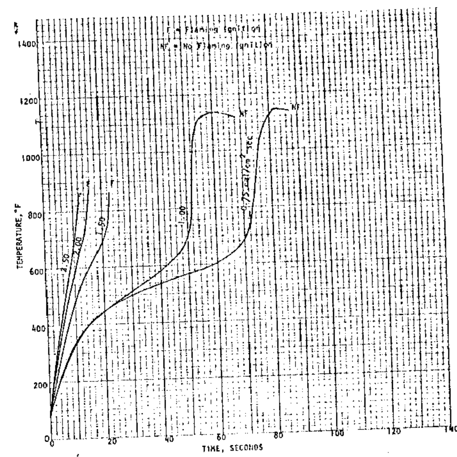

Figure 22. *Surface temperatures during unpiloted ignition of green cotton cloth.*

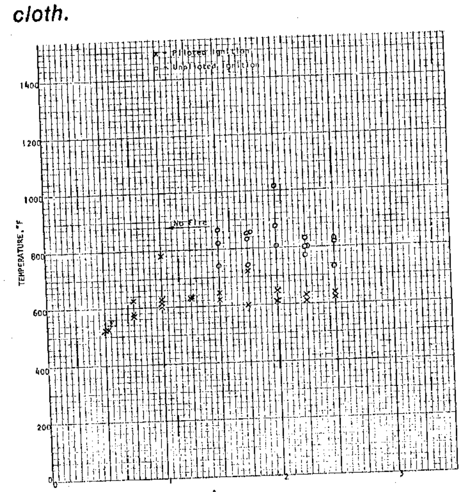

Figure 23. *Effect of radiant heat flux on ignition temperatures of green cotton cloth.*

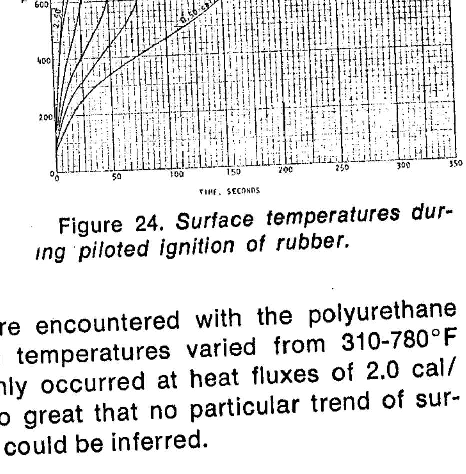

Figure 24. *Surface temperatures during piloted ignition of rubber.*

Rather erratic ignition patterns were encountered with the polyurethane foam, Fig. 27, 28, 29. Piloted ignition temperatures varied from 310-780°F (154-416°C) while unpiloted ignition only occurred at heat fluxes of 2.0 cal/cm²-sec and above. The scatter was so great that no particular trend of surface ignition temperature with heat flux could be inferred.

## DISCUSSION

It is postulated that the majority of ignitions in all the cellulosic and rubber materials of this report require a glowing ignition source. In piloted ignition

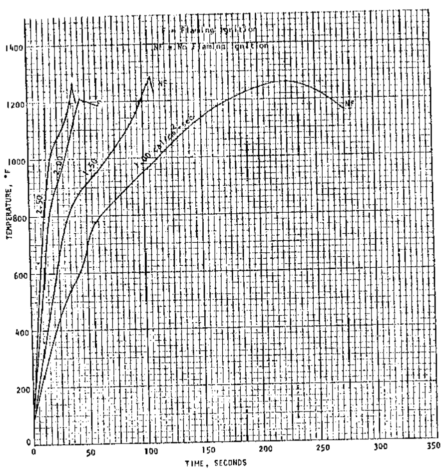


Figure 25. *Surface temperatures during unpiloted ignition of rubber.*

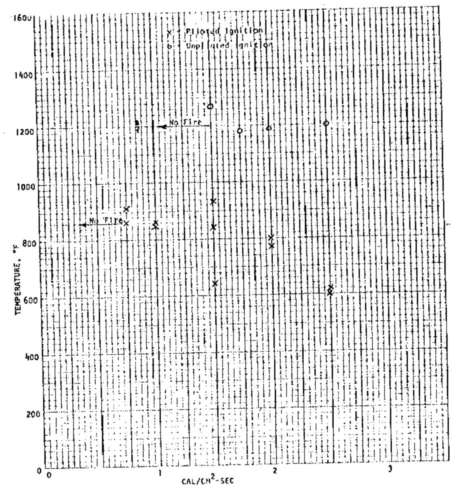


Figure 26. *Effect of radiant heat flux on ignition temperatures of rubber.*

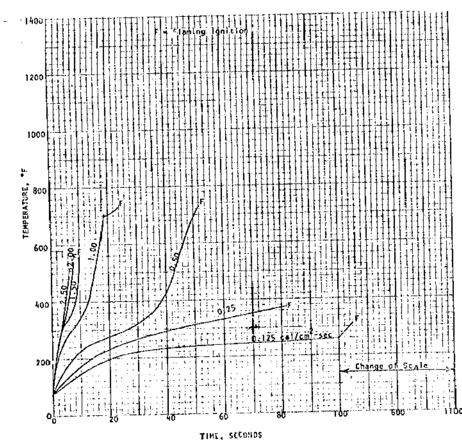


Figure 27. *Surface temperatures during piloted ignition of polyurethane foam.*

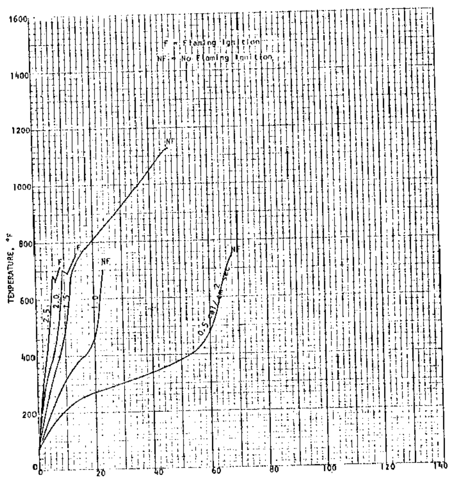


Figure 28. *Surface temperatures during unpiloted ignition of polyurethane foam.*

this glowing source is present to act when the production of volatiles is sufficient to provide a localized combustible mixture with air. In unpiloted ignition, some point on the surface must be carbonized and heated as a localized hot spot in the presence of the right volatile-air mixture. This is suggested as the explanation for the results from the unpiloted ignition of rubber. As heat is applied to the rubber surface, melting, vaporizing, and carbonization occur in that order. If the heating rate is low, melting occurs slowly, vaporization is low, and vapors are diffused as rapidly as formed, and additional melt protects the incompletely carbonized portion. So, although the rubber exhibits

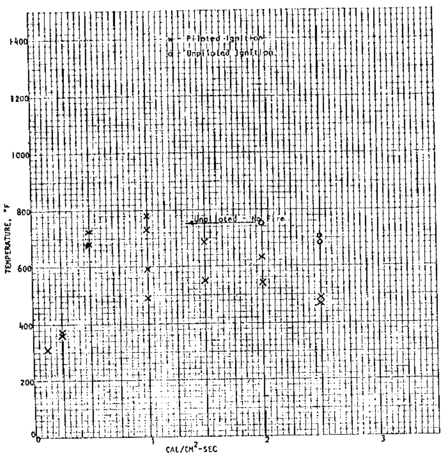


Figure 29. *Effect of radiant heat flux on ignition temperatures of polyurethane foam.*

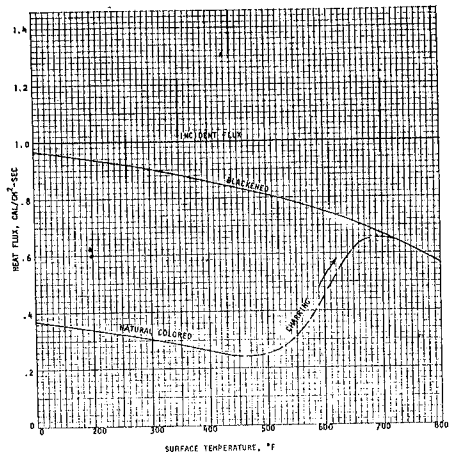


Figure 30. *Quartz lamp radiant flux retained by blackened vs. natural-colored ponderosa pine.*

a charred surface after exposure, no ignition source is produced and no ignition occurs. It might be that the rubber could be melted completely through without ever producing a glowing char. But if the application of heat is rapid, evaporation of melted rubber is almost immediate and carbonization occurs without being covered by the melt. Hot spots appear in the rough carbon surfaces produced, and vapor concentration is present. Ignition occurs at lower measured surface temperatures than at lesser heating rates because the measured surface temperatures do not record the small hot spots which may be present.

In those materials such as the ¼ inch oak dowels, in which flaming occurred long after the volatiles had escaped, the explanation is in the texture of the lignin which forms the cell walls. In oak this is thick and the cells are small. The small amount of volatile material present in the small diameter dowels is quickly driven off without the formation of a combustible mixture of volatiles and air. The lignin carbonizes and glows but without a volatile-air concentration to ignite. However, when enough carbonized particles adjacent to each other are glowing and radiating heat to each other, the heat exchange becomes exothermic and flaming occurs.

There has been considerable discussion in the literature concerning the effects of endothermic and exothermic chemical reactions during the heating and ignition of organic materials, particularly wood. Since in the present ignition tests a constant irradiance was used, the shape of the temperature vs. time curves might be expected to reveal some information about any such heat absorption or evolution. However, this is complicated by the absorption by the material of the quartz lamp radiant energy, the heat losses by the material due to re-emitted energy, and the effect of scorching and charring on that re-emittance.

It should be remembered that the radiant heat flux referred to in Fig. 3 through 29 is only the incident irradiance, and not all of it is absorbed by the natural colored materials. Figure 30, taken from [9], shows the effect on absorbed heat flux as a pine wood specimen is heated by quartz lamps with an

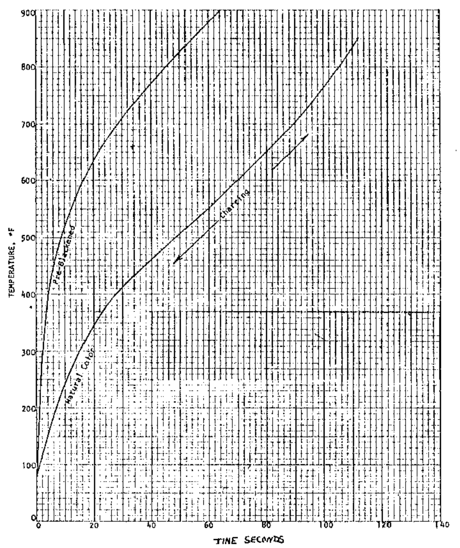

Figure 31. *Surface temperatures of ponderosa pine wood (incident flux = 1.0 CAL/CM2-SEC).*

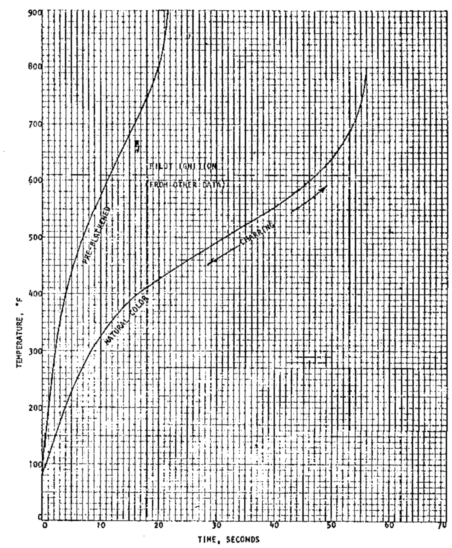

Figure 32. *Surface temperatures of box cardboard (incident flux = 1.0 CAL/CM2-SEC).*

incident flux of 1.0 cal/cm$^2$-sec. If the irradiated surface has been blackened to an emittance of 0.97 before heating, the net flux absorbed varies smoothly from 0.97 to 0.57 cal/cm$^2$-sec as the surface temperature increases from 80° to 800°F (27-427°C), due to re-radiation and convective cooling losses as the difference between surface temperature and ambient temperature increases. Tests described in [9] also indicated that natural-colored ponderosa pine has an absorptance of 0.38 for the short wavelength radiation from quartz lamps. On this basis the absorbed flux would decrease from 0.38 to about 0.24 cal/cm$^2$-sec as the surface temperature rises to 450°F (232°C). Immediately thereafter scorching and charring begins (visually observed), and the absorptance climbs rapidly until it approaches that of a pre-blackened specimen near 700°F (371°C). Upon further heating the now charred specimen would be subject to the same absorptance as a pre-blackened specimen. Thus surface effects during the heating of specimens by quartz lamp radiation complicate the temperature vs. time curves obtained.

In an attempt to reveal any heat gains or losses by the pyrolysis reactions without the masking surface reflectance effects, a pine specimen was blackened with Krylon flat black enamel before irradiation for comparison with a natural colored specimen. The results, from [9], are shown in Fig. 31. Typically, the curve for the natural-colored specimen decreases in slope due to the low absorptance and growing heat losses until about 450°F (232°C) where it straightens and then increases slope above 650°F (343°C). The blackened surface heats more rapidly and decreases slope gradually as heat losses due to temperature differential from ambient increase. It nearly straightens out again from 700°F (371°C) up. In this range of surface temperature the slopes of the blackened and natural colored speciments are nearly parallel. Figure 32 shows the same conditions for box cardboard. The fact that the blackened specimens show no further decrease in slope above 700°F (371°C)—but rather an increase—where the losses normally would decrease the heating rate even more rapidly, indicates that an exothermic reaction or oxidation is taking place.

It has been observed in other tests with heat fluxes of over 5.0 cal/cm$^2$-sec that a dip in the surface temperature vs. time curve occurs just before unpiloted ignition. No such dip was observed in any of these tests which were made at a maximum flux of 2.5 cal/cm$^2$-sec, and it is believed that the endothermic reaction present in "flash pyrolysis" is not noticeably present at slower heating rates. This conclusion is in line with that of other investigators.

Temperature measurement with the infrared pyrometer is influenced by the emittance of the target surface. The wood, cardboard, and cloth surfaces were smooth, but not polished, and may be considered diffuse reflectors. The directional reflectance was estimated by comparing the intensities of a beam of long wavelength radiation from an electric hotplate at 400°F (204°C) as reflected off the natural colored and the blackened specimens. Both gave extremely low signals on the IRCON Pyrometer compared with a direct sighting on the hotplate, indicating that these materials would re-emit energy at an emittance near unity for the relatively low surface temperatures before charring. Charring would not be expected to lower the emittance.

A comparison of average surface temperatures at ignition reported here, Table 1, with those reported by other investigators over the years is interesting. Fons [1] compared his 650°F (343°C) for ⅜ inch pine cylinders or dowels with 560°F (293°C) reported by earlier investigators who used fine fuels. If one considers Fons' ignition conditions in a furnace as equivalent to piloted ignition, his figure is in almost exact agreement with the average surface temperature of 646°F for ½ inch pine dowel in Table 1. The earlier work on fine fuels, if piloted, is also in agreement.

*Table 1. Surface Temperatures (°F) at Ignition.*

| Material | Piloted Average | Piloted Range | Unpiloted Average | Unpiloted Range |
|---|---|---|---|---|
| ¾" Pine Block | 766 | 650-1060 | 911 | 780-1050 |
| ½" Pine Dowel | 646 | 575-720 | 1219 | 850-1350 |
| ¼" Oak Dowel | 663 | 545-760 | NF | NF |
| Box Cardboard | 612 | 575-690 | 1177 | 1000-1380 |
| Newspaper | 541 | 450-640 | 558 | 520-685 |
| White Canvas | 635 | 570-695 | NF | NF |
| Green Cotton Cloth | 621 | 510-780 | 822 | 730-1015 |
| Black Rubber | 790 | 600-935 | 1208 | 1180-1270 |
| Polyurethane Foam | 561 | 310-780 | 712 | 680-750 |

Note (1) NF = No Flaming Ignition.
Note (2) The above averages and ranges are computed without regard to the variation of surface temperatures with heat flux.

The calculated temperatures of Simms and Law [4], 716° and 1013°F (380, 545°C), respectively, for piloted and unpiloted ignition, are also reasonably in agreement for wood over ½ inch thick. The work of Alvares on unpiloted ignition temperatures of alpha cellulose gave 600-650°C (1112-1202°F). This compares well with results on box cardboard, but is too high for newspaper, which may be a result of difference in thickness and therefore a variation in caloric retention due to conduction within the specimen and "other side radiation". Martin, [12], indicates that such measurements are thickness dependent until the specimen becomes semi-infinite. The temperatures reported by Koohyar [7] for ¾ inch pine blocks, 330-495°C (626-923°F), are within the range, but low for the average of piloted ignition reported here. His unpiloted or spontaneous ignition figures are decidedly lower than obtained at NWC, which may be due to a tendency toward piloted ignition by his flame curtain nearby, or to difficulties in pyrometer corrections.

When one observes the scorching and charring of a fairly large specimen area during an ignition test, it can be seen that only a few spots darken first. The dark spots then absorb energy much faster than elsewhere and therefore have a faster temperature rise. Since the IRCON pyrometer only "sees" an area about ⅛″ x ⅛″, it may or may not be looking at the spot nearest where ignition initiates. Other things being equal, it would then probably be more accurate to accept the top of the range of surface temperatures as the representative ignition temperature. There is also the equally great uncertainty of the pilot igniter being at the proper spot for the optimum condition of ignition in piloted ignition tests. It therefore appears that the scatter of ignition temperature data may exist until someone succeeds in pointing a pyrometer and pilot igniter only at the right spot in each test. The other alternative might be to test only perfectly homogeneous blackened specimens. It would also be interesting to know whether the apparent increase in ignition temperatures with decreasing irradiated area is merely due to the better chance of measuring the hottest spot. However, it does seem reasonable that a larger irradiated area would yield a larger volume of pyrolysis gases, making earlier ignition probable.

## SUMMARY

The results and experiences gained from these tests lead to the following picture of the ignition processes. As a natural colored specimen of wood, for example, is irradiated with constant flux, the surface temperature climbs at a decreasing rate towards an equilibrium temperature that is a balance between heat input and heat losses. If this equilibrium temperature is not high enough and has not penetrated the wood deeply enough to produce sufficient pyrolysis gases, no flaming ignition will occur. On the other hand, if the equilibrium temperature is within the scorching or charring range (above about 450°F or 232°C), the heat absorption rate will increase and the slope of the temperature vs. time curve will no longer decrease; it may hold steady or actually increase. When the surface temperature reaches about 650°F (343°C) at heat fluxes of 1.0 to 2.5 cal/cm$^2$-sec, pyrolysis gases are evolved at a rate

Wood

great enough to provide a flammable mixture. If a pilot igniter is present in the proper position, the mixture will begin flaming combustion.

If no igniter is present, the surface temperature will continue to rise rapidly until losses cause a decrease in climb rate. Somewhere above 700°F (371°C) exothermic energy from surface oxidation of char may compensate for the heat losses and lead to a more rapid temperature climb. During this phase of the heating, some local spot on the char may get hot enough from the irradiance plus exothermic energy of oxidation to ignite pyrolysis gases, if enough are still being evolved at this location. Then unpiloted or spontaneous ignition is result.

This picture of ignition, probably somewhat incomplete, indicates that what may appear to be a "characteristic ignition temperature" for materials is actually the resultant of several conditions necessary to produce a fire. A number of combinations of these conditions will produce a fire, and therefore the surface temperature at the instant of ignition can be expected to vary within appreciable limits.

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