

On the importance of spectrally resolved absorptivity data in fire technology

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Fire Technology

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Abstract

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The spectral absorptivity of 72 products has been measured in the wavelength region 0.3-20 μ m. Effective absorptivity for fire induced heat radiation typically lies in the range 0.75-0.95. It was found that the effective absorptivity varies significantly with the temperature of the heat source. This has some effect on the heating of a surface. The effect is more important when the absorptivity is used as input for calculations of ignition temperature and thermal inertia. It was found that the absorptivity of radiation from fires for products exposed to irradiation in the cone calorimeter decreased with increased exposure time. This is surprising since, for example, wood that is darkened when exposed to heat obviously has a higher absorptivity in the visual part of the spectrum than fresh non-darkened wood. Finally, it was concluded that none of the studied materials showed a particularly low absorptivity in the infrared region and therefore none of the products stand out as particularly good reflectors of radiation from fires. Several ideas were, however, presented for how such spectrally tailored surfaces, with low absorptivity for radiation from fires, can be produced.

Key words: spectral absorptivity, blackbody, temperature, radiative heat transfer, cone calorimeter

Sökord: spektral absorptivitet, svartkropp, temperatur, strålning, värmeöverföring, konkalorimeter

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Preface

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Abbreviations

Abbreviation	Quantity	Unit	Explanation/comment
c c ₀	specific heat speed of light	[JK ⁻¹ kg ⁻¹] [ms ⁻¹]	$c_0 = 2.99792458 \cdot 10^8 \text{ ms}^{-1}$ (exact)
Е	Irradiance	[Wm ⁻²]	Incident radiant power per unit area
F I	radiant power intensity	[W] [Wsr ⁻¹]	Radiant power per unit solid angle
h h _c	Planck's constant convective heat transfer coefficient	[Js] [Wm ⁻² K ⁻¹]	$h = 6.626 \cdot 10^{-34}$ Js $h_c \approx 13$ Wm ⁻² K ⁻¹ for conditions prevailing in the cone calorimeter [1].
h_{eff}	effective heat transfer coefficient	$[Wm^{-2}K^{-1}]$	
k	thermal conductivity	$[Wm^{-1}K^{-1}]$	
k _B L	Boltzmann's constant radiance	[JK ⁻¹] [Wm ⁻² sr ⁻¹]	$k_B = 1.381 \cdot 10^{-23} \text{ JK}^{-1}$ Radiant power per projected area
М	exitance	[Wm ⁻²]	Exiting radiant power per unit area
R_{λ}	spectral reflectance	[]	
t _{ign}	time to ignition	[s]	
T_{λ}	spectral transmittance	[]	
T_{∞}	ambient temperature	[K]	Temperature for all x at $t = 0$ s and for all t far away from the heated object $(x \rightarrow -\infty)$.
$q_e^{"}$	external irradiation	$[Wm^{-2}]$	
α	effective absorptivity	[]	
$lpha_\lambda$	spectral absorptivity	[]	
3	emissivity	[]	
φ	radiant heat flux	[W/m2]	In this report the radiating heat flux absorbed by a surface
ρ	density	[kgm ⁻³]	8 2 4
σ	Stefan-Boltzmann's constant	[Wm ⁻² K ⁻⁴]	$\sigma = 5,67 \cdot 10^{-8} \text{ Wm}^{-2} \text{K}^{-4})$

Summary

Radiation is one of the two main heat transfer processes in transporting energy from flames to a surface. The other process is convection and was not considered in this report. The spectral absorptivity of 72 products was measured in the wavelength region 0.3-20 μ m. This wavelength region contains virtually all radiation energy from a fire.

Based on the measurements, and on the theory for radiative heat transfer, the effective absorptivity for fire induced heat radiation for the different products were calculated. These typically lies in the range 0.75-0.95. It was also found that the effective absorptivity varies significantly with the temperature of the heat source. The reason for this is that the spectrum of the emitted radiation from a heat source, such as a fire, changes with temperature. This has limited effect on the heating of a surface.

The dependence of the effective absorptivity on heat source temperature is important when the absorptivity is used as input for calculations of ignition temperature and thermal inertia. Using existing models for predicting ignition temperature and thermal inertia, and correcting these models with the new information on effective absorptivity, it could be shown that the effects were significant but not very large. It was considered that the uncertainties in the model are so high that corrections for the effective absorptivity might be of minor importance compared to the other uncertainties and assumptions.

An interesting observation was that the absorptivity of radiation from fires for products exposed to irradiation in the cone calorimeter decreased with increased exposure time, that is, the absorptivity decreased when the products darkened due to heat. This is surprising since, for example, wood that is darkened when exposed to heat obviously has a higher absorptivity in the visual part of the spectrum than fresh non-darkened wood. This is an important observation since it opposes the general view that heat transfer increases with increased thermal exposure due to darkening

Finally, it was concluded that none of the studied materials showed a particularly low absorptivity in the infrared region and therefore none of the products stands out as particularly good reflector of radiation from fires. Several ideas were presented for how such spectrally tailored surfaces, with low absorptivity for radiation from fires, can be produced.

1 Introduction

A burning object, such as a sofa or a table for example, will release around one third of its combustion energy in the form of radiation. The other two thirds are released in the form of increased gas temperature. Heating of objects in the lower part of a room, such as flooring, is mainly governed by radiation. The reason for this is that the hot gases rise towards the ceiling by buoyancy and therefore do not directly participate to heat transfer near the floor. It is important to understand how much radiation different surfaces will absorb when exposed to radiation. Traditionally it is assumed that the fraction of the radiation that is absorbed by a surface, the absorptivity α is 0.9. This means that most of the radiation is absorbed by the surface and it will therefore heat up, and eventually ignite, faster than if the absorptivity had been lower. Hallman [2] observed that the ignition time strongly depends on the spectral distribution of the incident radiation. This means that a surface will heat up differently depending on how the radiation energy is distributed between different wavelengths. It is therefore important to measure the absorptivity not only as the total absorptivity but also spectrally resolved for each wavelength. Such measurements give information on the absorption of radiation from different types of heat sources. In general, surprisingly little effort has been made on finding surface materials, such as paints for example, with low absorptivity in the infrared wavelength region where most of the radiative heat transfer from fire occurs [3]. Such surfaces would heat up more slowly than other surfaces and would therefore be attractive from a fire safety point of view.

The purpose of this pilot study was to actually measure the absorptivity of several materials with fresh surfaces as well as surfaces already exposed to heat, and investigate whether the assumption of α =0.9 is correct. Another goal was to see whether it is correct to characterize the absorptivity with a single scalar value of α , or if spectrally resolved information, that is absorptivity as a function of wavelength, is generally required. Finally, the study proposes ideas for how progress can be made in developing surfaces with low absorptivity in the infrared wavelength region.

2 Theory of radiative heat transfer

Radiation from a hot surface or a hot smoke layer is characterized by its exitance, M, which is expressed in Wm⁻². This is expressed by the Stefan-Boltzmann law that gives the total exitance for a blackbody source as:

$$M = \sigma T^4 \tag{1}$$

where σ is the ,Stefan-Boltzmann's constant.

It is interesting to compare Eq. (1) with convective heat transfer, where the heat flux is expressed by:

$$\phi_{convective} = h_c \left(T_{\text{heat source}} - T_{\text{exposed surface}} \right)$$
⁽²⁾

The radiative heat transfer is proportional to the fourth power of the temperature of the heat source while convective heat transfer is directly proportional to this temperature. In other words the ratio between radiative and convective heat transfer is proportional to the cube of the temperature of the heat source. As a consequence radiative heat transfer becomes more important with higher temperatures of the flames or of the hot gas layer.

2.1 Blackbody radiation

The spectral radiant exitance from a perfect blackbody emitter is given by

$$M_{\lambda} = \frac{2\pi h c_0^2}{n^2 \lambda^5 \left[\exp\left(\frac{h c_0}{n \lambda k_B T}\right) - 1 \right]}$$
(3)

where

- *h* is Planck's constant,
- c_0 is the speed of light in vacuum,
- *n* is the refractive index, and
- k_B is Boltzmann's constant.

with units Wm⁻³ (power divided by area divided by wavelength). In this expression it is assumed that the dependence of the refraction index, *n*, on wavelength, λ , is negligible [4]. This is a correct assumption for air. Furthermore, for air the refractive index only differs from unity on the fourth decimal. Therefore we will assume *n* = 1 in this study. Expression (3) can therefore be slightly simplified to

$$M_{\lambda} = \frac{2\pi h c_0^2}{\lambda^5 \left[\exp\left(\frac{h c_0}{\lambda k_B T}\right) - 1 \right]}$$
(4)

Examples of the spectral blackbody exitance for different temperatures are given in Figure 1. The visual part of the spectrum, $\sim 0.38 \ \mu\text{m} - 0.74 \ \mu\text{m}$, is indicated with a colour spectrum. Longer wavelengths belong to the IR (InfraRed) part of the spectrum. Note that the diagram has a logarithmic y-axis and it is therefore clear that the exitance increases strongly with temperature, in accordance with Eq. (1).



Figure 1 Spectral blackbody exitance for different temperatures. The visual part of the spectrum is indicated with colours.

It is also clear from Figure 1 that the wavelength where the spectrum has its peak exitance decreases with increased temperature. This is expressed by Wien's displacement law saying:

$$\lambda_{\rm max}T = 2898 \,\mu{\rm m}\cdot{\rm K}$$

(5)

where λ_{max} is the wavelength where the exitance has its maximum for a given temperature. The radiation from the sun ($T \sim 5777$ K) has its peak around 0.5 µm which is in the green part of the visual spectrum. Fires on the other hand typically have temperatures around 1200 K or lower. This means that most of the energy in their radiation is in the IR part of the spectrum around 2 µm or higher¹. This is very important to bear in mind when absorption of radiation from fires is considered. Whether a surface looks black (high visual absorptivity) or white (low visual absorptivity) is of little importance since we can only see relatively short wavelengths, ~ 0.38 µm – 0.74 µm. In order to know the absorptivity at longer wavelengths, relevant to radiation from fires, measurements must be conducted.

¹ This is the reason why IR radiation is sometimes called "heat radiation".

2.2 Absorbed irradiation

When a surface is exposed to heat radiation we talk about irradiation. The total irradiance, E, impinging on a surface is obtained by integrating the spectral irradiance E_{λ} over all wavelengths:

$$E = \int_{0}^{\infty} E_{\lambda} d\lambda$$
 (6)

The radiant heat flux, ϕ , into a material is given by the absorptivity, α , multiplied by the irradiance. It is often assumed that α is constant for all wavelengths, e.g. $\alpha = 0.9$. However, as will be seen later α may vary significantly with wavelength and it is more appropriate to use the spectral absorptivity α_{λ} . This is one of the rationales for this study. The absorbed radiant heat flux can then be calculated as:

$$\phi = \int \alpha_{\lambda} E_{\lambda} d\lambda \tag{7}$$

If the irradiance comes from a perfect blackbody emitter the spectral distribution would be given by the exitance in Eq. (4). Real hot surfaces, or gases such as a flames for example, are not perfect blackbodies. For a real hot body the exitance is given by the blackbody exitance multiplied by the emissivity ε_{source} where the subscript "source" refers to the heat source and not to the surface receiving the radiation. The irradiance upon an absorbing surface then becomes

$$E_{\lambda} = \varepsilon_{source} M_{\lambda} \tag{8}$$

In general $\varepsilon_{\text{source}}$ depends on the wavelength. In Figure 2 a schematic geometry is given that describes the formalism in this report. Two infinite surfaces are assumed. This means that angular dependencies can be disregarded and the equations above describe total hemispherical properties. Combining Eqs. (4), (7), and (8) gives the radiant heat flux absorbed by a surface receiving radiation from a heat source as:

$$\phi = \int_{0}^{\infty} \frac{2\pi h c_{0}^{2} \alpha_{\lambda} \varepsilon_{source}(\lambda)}{\lambda^{5} \left[\exp\left(\frac{h c_{0}}{\lambda k_{B} T}\right) - 1 \right]} d\lambda$$
(9)

Hot emitting surface (e.g. flame, hot gas layer, cone calorimeter spiral) T, $\epsilon_{source,\lambda}$ Exitance $\epsilon_{\text{source},\lambda}M_{\lambda}$ Irradiance E_{λ} = $\epsilon_{source,\lambda}M_{\lambda}$ Absorbed radiant heat flux α_{λ} $\phi_{\lambda} = \alpha_{\lambda} E_{\lambda} = \alpha_{\lambda} \varepsilon_{\text{source},\lambda} M_{\lambda}$ Receiving surface (e.g. floor, wall)

Figure 2 Schematic geometry for the formalism used in this report.

2.2.1 Effective absorptivity

The effective absorptivity, α_{eff} , can be calculated for a given spectral distribution of the irradiance, i.e. for a given heat source. This is simply the ratio between the actually absorbed radiant heat flux and the impinging radiant heat flux for a given heat source, i.e. for a given temperature of the heat source. The impinging radiant heat flux is identical to the radiant heat flux that would have been received by an ideal absorber with $\alpha_{\lambda} \equiv 1$. The effective absorptivity becomes:

$$\alpha_{eff} = \frac{\phi}{\phi_{ideal}} = \frac{\int_{0}^{\infty} \frac{2\pi h c_{0}^{2} \alpha_{\lambda} \varepsilon_{source}(\lambda)}{\lambda^{5} \left[\exp\left(\frac{h c_{0}}{\lambda k_{B} T}\right) - 1 \right]} d\lambda$$

$$\int_{0}^{\infty} \frac{2\pi h c_{0}^{2} \varepsilon_{source}(\lambda)}{\lambda^{5} \left[\exp\left(\frac{h c_{0}}{\lambda k_{B} T}\right) - 1 \right]} d\lambda$$
(10)

The dependence of ε_{source} on wavelength is not considered in this study where the absorptivity of surfaces *receiving* heat radiation is in focus. Spectral properties of different heat sources will be the subject of a coming study. The discussion here is somewhat simplified since it is assumed that fires emit radiation like blackbodies, or like grey bodies. A grey body is a body emitting radiation with a spectrum with the same shape as one of the curves in Figure 1. However, for a grey body the emissivity ε_{source} is not unity, instead $\varepsilon_{source} < 1$, but still constant. For sooty flames and for black smoke layers it can be assumed that the exitance behaves similarly to a grey body. For other types of flames with less soot the deviation from a grey body can be considerable. In general measurements are needed in order to assess the exitance spectrum for a certain

fire. By assuming a constant ε_{source} in Eq. (10) this term cancels. Cancelling the other common factors gives the expression:

$$\alpha_{eff} = \frac{\int_{0}^{\infty} \frac{\alpha_{\lambda}}{\lambda^{5} \left[\exp\left(\frac{hc_{0}}{\lambda k_{B}T}\right) - 1 \right]} d\lambda}{\int_{0}^{\infty} \frac{1}{\lambda^{5} \left[\exp\left(\frac{hc_{0}}{\lambda k_{B}T}\right) - 1 \right]} d\lambda}$$
(11)

Another way to express the effective absorptivity is that it is the weighted average of the spectral absorptivity, where the weight function is the exitance spectrum for the actual heat source. Thus:

$$\alpha_{eff} = \frac{\int_{0}^{\infty} \alpha_{\lambda} M_{\lambda} d\lambda}{\int_{0}^{\infty} M_{\lambda} d\lambda}$$
(12)

which of course is identical with Eq. (11).

3 Experimental setup and method

3.1 Absorptivity measurements

Direct absorptivity measurements are very difficult and instead the reflectivity, R_{λ} , and, when relevant, the transmittance, T_{λ} , are measured. The spectral absorptivity is then calculated according to:

 $\alpha_{\lambda} = 1 - R_{\lambda} - T_{\lambda} \tag{13}$

Only a few of the tested products had any significant transmittance.

Spectra in the UV, visible and near IR region, with wavelengths in the interval $0.3 - 2.5 \mu m$ where recorded by using a Perkin Elmer Lambda 900 double beam spectrophotometer equipped with a Spectralon 15 cm diameter integrating sphere. In the thermal infrared wavelength range, with wavelengths in the interval $2.5 - 20 \mu m$, a Bruker Tensor 27, FTIR single beam spectrophotometer equipped with a 7 cm gold coated integrating sphere, is used. The principle of operation of an integrating sphere is shown in Figure 3. The figure shows a cross-section of an integrating sphere with the incident beam entering the sphere through the entry port to the left and hitting the sample (or reference) covering the sample port to the right. The light reflected from the sample surface is trapped inside the sphere and illuminates the inside wall of the sphere. This illumination intensity is seen by the detector, which then records a signal proportional to all the reflected light, including both the specular and diffuse parts. The sphere in Figure 3 is not drawn to scale.



Figure 3 Schematics of an integrating sphere used in the measurements. The integrating sphere is not drawn to scale.

There are some differences in the design of the integrating spheres for the UV - visible near IR region as compared to the IR region, but the principle of operation is the same. The UV - visible - near IR instrument is a double beam instrument whereas the infrared instrument is a single beam instrument. The integrating sphere in the IR is coated with gold, and is equipped with an internal centre mounted mirror which redirects the incoming beam to the reference and sample surface in such a way that no correction for the sample reflectance needs to be done. The measurements are always performed with a reference scan followed by a sample scan taken immediately after one another to avoid instrument drift.

Two scans are required for accurate measurements. The reference reading with a reference standard covering the sample port gives the detected signal

$$S_{ref} = AR_{ref} \tag{14}$$

where R_{ref} is the reflectance of the reference standard and A is an instrument amplification factor. When measuring the sample, this reference standard is replaced by the sample and the reading becomes

$$S_{sample} = AR_{sample} \tag{15}$$

The reflectance of the sample is obtained from the ratio

$$R_{sample} = \frac{R_{ref} S_{sample}}{S_{ref}}$$
(16)

if R_{ref} is known. For the measurements in this project, a spectralon and a gold reference surface of the same composition as the sphere wall was used in the UV - visible - near IR instrument, and IR, respectively

We can always separate the reflected light into a specular and diffuse (scattered) component. The specular part is strictly defined as light being reflected as from a perfectly smooth and flat mirror. In an integrating sphere this definition is approximated by the light leaving the sphere when the cover is removed from the specular exit port. In this project this separation was not regarded as being relevant and the reflectance was only measured as the total hemispherical value

Transmittance measurements are performed in a similar way as the reflectance measurements described above, but with the sample positioned across the beam entry port in Figure 3.

3.2 The cone calorimeter

In the Cone Calorimeter, ISO 5660-1 [5], specimens of 0.1×0.1 m are exposed to controlled levels of radiant heating. The specimen surface is therefore heated up and during normal operation an external spark ignitor ignites the pyrolysis gases from the specimen. The gases are collected by a hood and extracted by an exhaust fan. The heat release rate (HRR) is determined by measurements of the oxygen consumption derived from the oxygen concentration and the flow rate in the exhaust duct. The specimen is placed on a load cell during testing. A retainer frame covers the periphery of the specimen. Smoke production rate is measured with a laser system. In this study the cone calorimeter was mainly used to expose products to an irradiation level of 30 kWm⁻² during different levels of thermal degradation, see Section 4.3. No heat release rate or smoke production was measured. The cone calorimeter was also used to measure the time to ignition for different irradiation levels, see 6. A schematic drawing of the cone calorimeter is shown in Figure 4.



Figure 4 Schematic drawing of the Cone calorimeter, ISO 5660.

4 **Experimental results**

In total 72 different products were investigated and 285 absorptivity spectra were obtained. The reason why there are more spectra than products is that many of the products were characterized at different stages of thermal degradation, see Section 4.3. All spectra are presented in Appendix A.

4.1 Spectral absorptivities

Some selected absorptivity spectra are shown in Figure 5 to Figure 11 below. These spectra can be used for calculating effective absorptivities for different grey body temperatures according to Eq. (11), or they can be used as input for more advanced radiation calculations where actual spectral data is required. All results are presented in Appendix A. Figure 5 to Figure 11 are included here to serve as examples, and as a basis for the discussions in subsequent sections. The numbering in the graphs ("No 64..." for example) is only a dummy counter used to keep track of all the measurements and should not be considered. The indication of the effective absorptivies, α_{eff} , for different grey body temperatures is explained in subsequent sections. In many of the spectra a text like "0 s 30 kWm⁻²" is included. This means that the tested product has not been exposed to heat radiation in the cone calorimeter. In the same way the text "15 s 30 kWm⁻²" means that the product has been exposed to 30 kWm2 irradiation in the cone calorimeter during 15 s. See also Section 4.3.



Figure 5 Spectral absorptivity of a white wall paint.



Figure 6 Spectral absorptivity of a white ceiling paint.



Figure 7 Spectral absorptivity of white ABS.



Figure 8 Spectral absorptivity of white PVC.



Figure 9 Spectral absorptivity of black PVC.



Figure 10 Spectral absorptivity of plywood.



Figure 11 Spectral absorptivity of dark heat treated non-lacquered ash tree flooring.

4.2 Effective absorptivities as functions of heat source spectra

The main purpose of this part of the study is to investigate whether the effective absorptivity changes in any significant way with temperature of the grey body emitter. More specifically this is translated into different irradiation levels in the cone calorimeter [5], see also Section 3.2. One of the reasons why this is interesting is that ignition temperature and thermal inertia are often determined using theories based on measurements of time to ignition in the cone calorimeter under different irradiation levels, see Section 6.

The temperature of the conical coil in the cone calorimeter for different irradiances is tabulated in Table 1. The temperatures are average values for three thermocouples attached to different positions on the coil. The irradiance was measured with a Schmidt-Boelter heat flux gauge. It is assumed that the spectrum has the same wavelength dependence as for a perfect blackbody emitter. In other words it is assumed that the steel in the coil behaves as a grey body. This has been shown to be a reasonable assumption [6].

 Table 1 Temperatures of the conical coil for different irradiance levels in the cone calorimeter at SP.

Irradiance [kWm ⁻²]	10	25	50	75	100
Temperature [K]	674	852	1025	1153	1300

The temperature for 100 kWm⁻² (1300 K) was not determined directly in the cone but were estimated from the other results. The reason for this was that running the cone calorimeter at 100 kWm⁻² is very cumbersome. Note that it is not possible to directly use the formalism in Section 2 in order to relate the irradiation level with the temperature since the hot surface in the cone consists of a helical coil. The situation is therefore very different from the one indicated in Figure 2 and considerable efforts would be required to simulate the IR-optics of the cone calorimeter if the formalism in Section 2 should be used.

In Table 2 to Table 5 the effective absorptivities, calculated according to Eq. (11), for different products and different grey body temperatures of the heat source are given. In addition to the temperatures in Table 1 the grey body temperature of the sun, 5777 K, has been used. The reason for this is that the effective absorptivity for this grey body temperature reflects what the human eye and brain experiences as light and dark, i.e., a high α_{eff} (T=5777 K) is experienced as a dark product while a low α_{eff} (T=5777 K) is experiences as a light product. This relationship is not necessarily true for exitance spectra from heat sources corresponding to lower, more fire related, temperatures, as will be seen below.

Grey body emitter T [K]	674	852	1153	1300	5777
Cone calorimeter irradiation [kW/m2]	10	25	75	100	Sun
			$lpha_{eff}$		
Product					
Plywood	0.86	0.84	0.79	0.76	0.4
dark heat treated lacquered ash tree	0.89	0.88	0.83	0.80	0.63
flooring					
dark heat treated non-lacquered ash	0.83	0.81	0.77	0.74	0.62
tree flooring					
light lacquered ash tree flooring	0.90	0.88	0.84	0.82	0.40
light non-lacquered ash tree flooring	0.86	0.84	0.80	0.77	0.37
medium dark lacquered oak flooring	0.91	0.89	0.85	0.83	0.56
medium dark non lacquered oak	0.86	0.84	0.80	0.77	0.50
flooring					

 Table 2 Effective absorptivities for different grey body temperatures, for various wood products.

Table 3 Effective absorptivities for different grey body temperatures, for various carpets.

Grey body emitter T [K]	674	852	1153	1300	5777
Cone calorimeter irradiation [kW/m2]	10	25	75	100	Sun
			$lpha_{eff}$		
Product					
beige PVC carpet	0.92	0.91	0.89	0.87	0.60
black PVC carpet	0.93	0.93	0.93	0.93	0.92
grey PVC carpet	0.90	0.88	0.84	0.82	0.43
blue PVC carpet	0.89	0.87	0.83	0.80	0.43
pink PVC carpet	0.90	0.88	0.84	0.81	0.39
red PVC carpet	0.92	0.92	0.90	0.89	0.80
black rubber mat	0.90	0.90	0.91	0.91	0.95
grey rubber mat	0.91	0.91	0.91	0.91	0.82
beige vinyl carpet	0.91	0.90	0.87	0.85	0.51
black vinyl carpet iQ Eminent	0.93	0.93	0.93	0.93	0.94
grey vinyl carpet	0.92	0.91	0.88	0.87	0.57
white vinyl carpet	0.88	0.86	0.81	0.79	0.44
black vinyl carpet Marleyfloor	0.92	0.92	0.93	0.93	0.94
brown vinyl carpet	0.90	0.89	0.88	0.87	0.77
linoleum carpet	0.92	0.91	0.88	0.86	0.55

Grey body emitter T [K]	674	852	1153	1300	5777
Cone calorimeter irradiation [kW/m2]	10	25	75	100	Sun
			α_{eff}		
Product					
yellow top paint 7079	0.90	0.88	0.84	0.82	0.44
blue top paint 7078	0.89	0.87	0.83	0.81	0.73
white priming paint 7419	0.86	0.83	0.78	0.75	0.27
red priming paint 7808	0.90	0.89	0.86	0.83	0.71
red priming paint water	0.89	0.87	0.83	0.80	0.70
blue paint 30	0.89	0.89	0.88	0.87	0.75
black wallpaint 07	0.93	0.93	0.93	0.93	0.95
white wallpaint 07	0.85	0.83	0.77	0.74	0.26
blue wallpaint 07	0.92	0.91	0.90	0.90	0.75
red top paint 7073	0.89	0.88	0.84	0.81	0.55
white water based top paint 7590	0.87	0.84	0.78	0.75	0.25
black lacquer paint 30	0.92	0.92	0.92	0.93	0.95
white lacquer paint 30	0.86	0.84	0.79	0.76	0.26
white wall paint 7	0.84	0.81	0.75	0.71	0.24
white wall paint 20	0.84	0.81	0.74	0.71	0.23
white ceiling paint 3	0.86	0.83	0.78	0.75	0.30
white hard wall paint 40	0.87	0.84	0.78	0.74	0.23
black ceiling paint	0.92	0.93	0.93	0.93	0.95
red ceiling paint	0.87	0.84	0.79	0.77	0.70
white floor paint 000	0.86	0.84	0.78	0.75	0.24
mid gray floor paint 002	0.90	0.89	0.89	0.88	0.76
blue lacquer paint	0.90	0.89	0.88	0.87	0.74
blue lacquer paint + 8W% mica	0.90	0.89	0.88	0.87	0.75

 Table 4 Effective absorptivities for different grey body temperatures, for various paints painted on plywood.

Grey body emitter T [K]	674	852	1153	1300	5777
Cone calorimeter irradiation [kW/m2]	10	25	75	100	Sun
	$\alpha_{\rm eff}$				
Product					
white ABS	0.91	0.90	0.86	0.84	0.31
black ABS	0.92	0.92	0.92	0.92	0.94
nature acetale	0.93	0.93	0.92	0.91	0.46
clear acrylic G	0.93	0.92	0.89	0.87	0.23
opaque acrylic G	0.93	0.92	0.90	0.88	0.31
yellow acrylic G 780	0.94	0.93	0.93	0.92	0.62
brown acrylic G 901	0.94	0.94	0.94	0.94	0.94
clear acrylic XT	0.93	0.92	0.89	0.87	0.21
nature amid PA6	0.93	0.93	0.94	0.94	0.74
brown paper laminate	0.91	0.91	0.92	0.92	0.92
nature PE HD 250/300	0.93	0.93	0.93	0.93	0.62
black PE HD 250/300	0.93	0.93	0.93	0.93	0.95
yellow PE Ultra DS	0.93	0.92	0.91	0.90	0.53
clear PC	0.92	0.91	0.87	0.85	0.24
clear PC Ultra UV	0.92	0.91	0.88	0.85	0.46
brown PC 851	0.93	0.93	0.93	0.93	0.93
white PC M/M	0.91	0.90	0.87	0.85	0.33
grey PP	0.92	0.92	0.91	0.90	0.66
nature PTFE	0.84	0.78	0.70	0.66	0.10
white PVC	0.91	0.89	0.85	0.82	0.31
black PVC	0.93	0.93	0.93	0.93	0.95
grey PVC	0.91	0.90	0.90	0.90	0.88
white PVC expostandard	0.82	0.80	0.76	0.73	0.31
white PVC expo	0.82	0.80	0.76	0.74	0.30
clear PVC	0.91	0.90	0.86	0.84	0.27
nature PVDF	0.94	0.94	0.94	0.94	0.78
brown fabric laminate	0.91	0.91	0.90	0.89	0.68

Table 5 Effective absorptivities for different grey body temperatures, for various plastics and other materials.

Many conclusions can be drawn from the results in Table 2 to Table 5. One is that the effective absorptivity for products exposed to radiation from fires typically stays in the interval $0.75 < \alpha_{eff} < 0.95$. This means that all tested products absorb a large fraction of the irradiation impinging on them. By contrast, α_{eff} (T=5777 K) vary more widely between 0.25 and 0.95. This is in accordance with our knowledge that light products such as white paint reflect most of the *visual* light, see Figure 1, and therefore have a low absorptivity.

Another conclusion is that for many products the effective absorptivity actually changes with changing temperature of the heat source, that is with changing temperature of the grey body emitter. Some examples of this phenomenon are shown in Figure 12 to Figure 15.



Figure 12 Effective absorptivity for white wallpaint for different grey body temperatures of the heat source. From a fire perspective it is the change in absorptivity between the four points to the left that is interesting. The point to the right, effective absorptivity of sun radiation, is included for reference.



Figure 13 Effective absorptivity for plywood for different grey body temperatures of the heat source. From a fire perspective it is the change in absorptivity between the four points to the left that is interesting. The point to the right, effective absorptivity of sun radiation, is included for reference.



Figure 14 Effective absorptivity for white PVC for different gre ybody temperatures of the heat source. From a fire perspective it is the change in absorptivity between the four points to the left that is interesting. The point to the right, effective absorptivity of sun radiation, is included for reference.



Figure 15 Effective absorptivity for black PVC for different grey body temperatures of the heat source. From a fire perspective it is the change in absorptivity between the four points to the left that is interesting. The point to the right, effective absorptivity of sun radiation, is included for reference.



Figure 16 Effective absorptivity for dark ash tree for different grey body temperatures of the heat source. From a fire perspective it is the change in absorptivity between the four points to the left that is interesting. The point to the right, effective absorptivity of sun radiation, is included for reference.

In these figures, the four points to the left corresponding to heat source grey body temperatures T = 674 K, 852 K, 1025 K and 1153 K, respectively, are most important from a fire perspective. The point to the right, corresponding to a grey body temperature of T = 5777 K, is included for reference and corresponds to the effective absorptivity of sun radiation. This point also reflects the human conception of a product's absorptivity. The change in effective absorptivity with temperature for the four points to the left is in general largest for light products, such as white paint, white PVC, and also plywood. Black products, such as black PVC, has little or no dependence of the effective absorptivity on the grey body temperature, see Figure 15. This can be understood from the shape of the exitance curves in Figure 1, Eq. (12), and from the spectrally resolved absorptivity measurements in Section 4.1.

The fact that the effective absorptivity depends on the heat source, or rather on the temperature of the heat source, should be taken into account when, for example, the heating of a structure that is irradiated with radiation from a nearby fire is calculated. The simplest way to take this into account is to select a conservatively high value for the effective absorptivity, such as 0.90 or 0.95 for example. On the other hand the absorptivity is sometimes used in more complex calculations where it is used as an input parameter for calculating other important parameters such as the ignition temperature for example. This is discussed in Section 6 below. For this type of calculations there are no simple conservative assumptions that can be made. For example in Table 8 it is clear that the ignition temperature increases with increasing effective absorptivity. This means that if the absorptivity is overestimated, the calculated ignition temperature will become too high and the fire risks will be underestimated.

It should be noted that it is sometimes proposed that a product should be painted with carbon black in order to avoid uncertainties about the effective absorptivity. This will create a product with a well defined absorptivity similar to what is shown in Figure 15. On the other hand this means that we no longer study the original product but rather a product painted with carbon black.

4.3 Effects of thermal degradation

In this section the effect of thermal degradation on the absorptivity is studied. This is an important topic since a surface, such as a wall for example, exposed to fire will eventually start to break down due to the increased temperature. The question is whether, and by how much, the absorptivity will change in this process. If the absorptivity changes this obviously means that the heating of the surface via radiation will also change during the course of the heating process. In Table 6 the effective absorptivities for four different products are shown at different stages of the thermal degradation. The thermal degradation was achieved by irradiation of the products under 30 kWm⁻² in the cone calorimeter for different periods: 0 s, 15 s, 30 s, 60 s, and 120 s. The effective absorptivities are calculated according to Eq. (11) assuming a grey body temperature of 1153 K. It is observed that the effective absorptivities in general *decrease* with increasing thermal degradation.

Table 6 Effective absorptivity (assuming a grey body heat source temperature of 1153 K) for four different products as function of time in the cone calorimeter. The irradiation level in the cone calorimeter was 30 kWm⁻².

Exposure time [s] @ 30 kWm ⁻²	0	15	30	60	120
Product					
plywood	0.79*	0.80**	0.78*	0.74**	0.68*
dark heat treated non-lacqured ash tree flooring	0.77	0.76	0.77	0.74	0.70
white ceiling paint 3	0.78	0.77	0.77	0.74	0.73
white ABS	0.86	0.85	0.83	0.83	0.82

* Average value for four specimens.

** Average value for three specimens.

It is rather counter-intuitive to our experience that a material that is exposed to heat eventually becomes darker and darker. However, it should be emphasized that the human eye only perceives a small short-wavelength part of the spectrum, see Figure 1. The change in effective absorptivity for greybody radiation from a 1153 K heat source mostly depends on wavelengths to the right of the visual spectrum in Figure 1 (longer wavelengths). Actually, if the effective absorptivities for the same products and exposure times as in Table 6 are calculated for a grey body radiation from a 5777 K heat source (the sun) the absorptivities indeed increase with increased exposure time. This is in agreement with our experience that a plywood surface is darker if it is carbonized than if it is not carbonized. In Figure 17 to Figure 20 the absorptivities for IR and for visible light are plotted for the four products.



Figure 17 Effective absorptivities for plywood as a function of exposure time at 30 kWm⁻² irradiation in the cone calorimeter. The absorptivities were calculated according to Eq. (11) and grey body temperatures of 1153 K ("IR" in the graph) and 5777 K ("visible") in the graph.



Dark heat treated non-lacqured ash tree flooring

Figure 18 Effective absorptivities for ash tree flooring as a function of exposure time at 30 kWm⁻² irradiation in the cone calorimeter. The absorptivities were calculated according to Eq. (11) and grey body temperatures of 1153 K ("IR" in the graph) and 5777 K ("visible") in the graph.



Figure 19 Effective absorptivities for white ceiling paint as a function of exposure time at 30 kWm⁻² irradiation in the cone calorimeter. The absorptivities were calculated according to Eq. (11) and grey body temperatures of 1153 K ("IR" in the graph) and 5777 K ("visible") in the graph.



White ABS

Figure 20 Effective absorptivities for white ABS as a function of exposure time at 30 kWm⁻² irradiation in the cone calorimeter. The absorptivities were calculated according to Eq. (11) and grey body temperatures of 1153 K ("IR" in the graph) and 5777 K ("visible") in the graph.

The decrease of effective absorptivities for a grey body temperature relevant to fires (1153 K) is a general feature of all tested products, see Appendix A. The mechanism behind this behaviour has not been investigated in this study. The effect for radiative heat transfer to surfaces is that the it might decrease by ~ 10 % from the onset of heating to the point when the surface is completely carbonized and catches fire. This has a relatively small effect on fire spread but it is an important observation since it opposes the general

White ceiling paint 3

view that heat transfer increase with increased thermal exposure due to darkening. Once again we need to consider the fact that what we appreciate as darkening is the change in absorptivity in the narrow visual wavelength region of Figure 1. In the IR wavelength region, where most of the radiative transfer from fires take place, the surfaces in general gets lighter, and not darker, with increased thermal exposure.

4.4 The dependence of absorptivity on temperature

In this study the absorptivities have only been measured at room temperature (~ 23° C). It can be assumed that absorptivity does not change significantly with temperature for dielectric materials since there is no physical mechanism that would give such a dependence. This is an interesting subject for future studies, but in this project the temperature dependence has been assumed to depend only on the blackbody radiation spectrum being shifted at higher temperatures. Even for conducting materials such as steel it has been found that the temperature dependence of the absorptivity is very weak, at least for temperatures up to ~ 350° C [6]. Only for some semi-conducting materials do we expect a significant temperature dependence on the absorptivity due to increased filling of the conduction band with increased temperature, but neither conducting nor semi-conducting surfaces have been characterized in this study.

It can therefore be assumed that the increasing temperature of surfaces which occurs in a fire situation does not disqualify the measurement data presented here. The absorptivities do however depend indirectly on temperature via the thermal degradation. This is discussed in Section 4.3.

5 **Possibilities for spectrally tailored surfaces**

None of the products tested in this study exhibit a particularly low absorptivity in the IR-region. It would obviously be very attractive if surfaces could be tailored in such a way that they have a low absorptivity in the IR-region while at the same time as they can have any arbitrary spectrum, that is colour, in the visible part. Typically all opaque non-metallic materials have absorptivities above 0.5 for wavelengths longer than 2 μ m, see Appendix A. In order for a surface to have a lower absorptivity it needs to have a metallic-like behaviour. This condition is in conflict with the common esthetical perception for how for example walls, floors and furniture should appear in homes and offices.

There are a number of different potential mechanisms, for how a surface can have any arbitrary colour in the visual part of the spectrum while it has a low absorptivity in the IR-part. Surprisingly little has been made in this field and it is considered worthwhile to further evaluate the potential of the ideas presented above. Some of the methods presently being investigated are discussed below.

5.1 Metallic mesh on arbitrary surface

One idea is to use any material, with arbitrary colour in the visual part of the spectrum, and cover it with a finely divided metal where the particle size is such that the surface becomes metallic, and thus reflecting, for IR but non-metallic for the visual part of the spectrum. This mechanism can be understood by an analogy to the grid in a microwave oven. The characteristic size of the holes and metallic parts of the grid is much smaller than the wavelength of the microwaves, which is around 12 cm. This makes the entire grid act as a metallic reflector that reflects the microwaves back into the oven. On the other hand the grid's characteristic size, that is the hole size, is much larger than the wavelengths of the visible light. This is why we can see through the holes in the grid.

5.2 Thermochromic layer on arbitrary surface

A thermochromic material is a material that changes its optical properties at a certain temperature. This is an alternative to the finely divided metal in Section 5.1. An example is vanadium dioxide that is transparent at lower temperature but becomes metallic, or rather conductive, at 68 °C. This material is used in smart windows [7] where it acts to block sun radiation when the window gets hot, that is in excessive sunshine. A temperature of 68 °C is, however, too high a transition temperature and the vanadium dioxide is therefore doped with tungsten or magnesium which yields a lower transition temperature. For window applications this transition temperature is important in order to make the smart windows useful. The process of creating a well-defined transition temperature is relatively cumbersome and puts some limitations on this technique. For fire protection applications the situation should be much simpler, however. Whether the transition occurs at 29 °C or 68 °C is not critical for the general ability to decrease fire spread. The important thing is that the transition occurs at a reasonably low temperature. It should be pointed out that once the layer becomes conductive it has changed its optical properties even in the visual part of the spectrum. This has the advantage that the minor part of the radiation from the fire that is in the visual part of the spectrum is also reflected. The disadvantage is that if the surface gets hot for some reason other than a fire, such as a nearby toaster for example, this could result in local discolouration of the wall. Luckily, however, the thermochromic effect is reversible and once the toaster is switched-off the appearance of the wall will go back to its original.

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5.3 IR-reflecting pigments

Pigments that reflect IR-radiation exist and have been proposed for use in paints to reduce temperatures in buildings during summertime and also as a way to reflect radiation from fires [3, 8, 9]. Another attempt has been to formulate coatings with tailored IR properties for military camouflage applications [10, 11]. Several metallic based pigments exist that have low absorptivity in the IR but at the same time do not affect the visual colour of a paint. It should be pointed out, however, that a paint not only consist of pigments but also of binders and fillers. Most of these absorb IR and the usefulness of an IR reflecting pigments inside the binder can therefore be limited. Solutions for transparent binders have been proposed [9] but it is not clear if such paints can attain visually acceptable appearances for indoor use.

5.4 Metallic coatings

Various metallic colours such as nickel black [12] and black chrome [4, 13] actually have a high inherent absorptivity in the visual part of the spectrum and a low inherent absorptivity in the IR part. These colours are, however, not necessarily acceptable for indoor use for esthetical reasons. They have mainly been used for solar energy collection. Nevertheless recent work has shown that solar collectors can be made more visually appealing than has been the case traditionally. 6

The dependence of T_{ign} calculations on absorptivity

The purpose of this section is to study the importance of the absorptivity in derivation of ignition temperature and thermal inertia, $k\rho c$. Ignition of solids is normally limited by the time required to heat up the solid to a temperature where the production of pyrolysis gases is high enough to produce a fuel molar fraction that is higher than the lower ignition limit. The times for mixing and for the flammable mixture to actually proceed to combustion, once in contact with a pilot ignition source, are typically much smaller than the time required to heat up the solid to the required pyrolysis temperature [14]. Therefore the analysis in this section will focus on the heat transfer to and from the surface as well as the conduction inside the solid.

Torero [15] gives a rigorous and critical treatment of ignition theories for solid materials. Other sources are, for example, Babrauskas[1], Janssens [16], and Quintiere [14] where procedures for how to extract values of T_{ig} and thermal inertia, kpc, are also presented.

6.1 Dependence of T_{ign} calculations on total absorptivity

A commonly used technique to evaluate ignition temperature and thermal inertia of materials is to measure the time it takes for a specimen to ignite in the cone calorimeter as a function of level of irradiation. This is a simplified theory where the specimen is assumed to be completely inert. A short summary of the theory is given below. More details on the background of the equations can be found in Babrauskas [1].

The method used here were suggested by Janssens [16, 17]. This method assumes that the materials are thermally thick, meaning that there is a 1-dimensional temperature gradient into a semi-infinite specimen. For the analysis of the results a system of three equations is solved. These equations are presented below without further explanations. The equations are:

Equation for heat flux equilibrium at critical heat flux:

$$\alpha_s q_{cr} = h_c \left(T_{ign} - T_{\infty} \right) + \alpha_s \sigma \left(T_{ign}^4 - T_{\infty}^4 \right)$$
⁽¹⁷⁾

The critical irradiation level \dot{q}_{cr} is defined as the point where a linear extrapolation of q vs. $t_{ign}^{-0.55}$ crosses the x-axis, that is, the q-axis, see Figure 21.

Janssens' equation for thermally thick materials

$$\dot{q} = \dot{q}_{cr} \left[1 + 0.73 \left(\frac{K\rho C}{h_{eff}^2 t_{ign}} \right)^{0.55} \right]$$
(18)

Definition of effective convective coefficient:

$$h_{eff} = \frac{\alpha_s q_{cr}}{\left(T_{ign} - T_{\infty}\right)} \tag{19}$$

These equations are solved for T_{ign} and $K\rho C$ numerically, using Kelvin and not °C as the unit for temperature.

Experimental results for a PVC carpet [18] and for white ABS are presented below.

6.1.1 PVC-carpet

Table 7 Time to ignition, t_{ign}, as a function of irradiation level for a PVC carpet tested in the cone calorimeter [18].

Irradiation, <i>q</i> [kWm ⁻²]	Time to ignition, <i>t_{ign}</i> [s], PVC-carpet
7.5	*
10	168
15	110
25	38
35	26
50	12
75	7

* No ignition



Figure 21 Transformed ignition time vs. irradiance in the cone calorimeter for a PVC carpet [18].

Using the surface absorptivity to 0.9 and the convective heat transfer coefficient to 0.013 kWm⁻²K⁻¹, as proposed by Janssens [16], and solving Eqs. (17) to (19) numerically² gives $T_{ign} = 278$ °C and $K\rho C = 6.11 \cdot 10^5 \text{ J}^2 \text{m}^{-4} \text{s}^{-1} \text{K}^{-2}$. As seen from the results in Table 2 to Table 5, and in Appendix A, the effective absorptivities typically vary between 0.7 and 0.9. The corresponding results are shown in Table 8.

² For the PVC-carpet \dot{q}_{\min} instead of \dot{q}_{cr} was used in the numerical solution. \dot{q}_{\min} is the average value of the highest irradiation level for which no ignition takes place and the lowest irradiation level for which ignition takes place. The reason for using \dot{q}_{\min} instead of \dot{q}_{cr} here is that it has been found empirically that more realistic predictions of T_{ign} is found if \dot{q}_{\min} is used when this is substantially larger than \dot{q}_{cr} .
	$\alpha_{\rm eff}=0.7$	$\alpha_{eff}=0.8$	$\alpha_{\rm eff}=0.9$
Ignition temperature, T_{ign} [°C]	262	273	278
Thermal inertia, $K\rho C [J^2 m^{-4} s^{-1} K^{-2}]$	4.19·10 ⁵	$5.04 \cdot 10^{6}$	6.11·10 ⁵

 Table 8 Ignition temperatures and thermal inertias for a PVC-carpet [18] calculated using different absorptivities.

As can be seen in Table 8 the variation in T_{ign} is relatively small when α_{eff} is varied within the relevant limits. The variation in thermal inertia is however on the order of 30 %.

6.1.2 White ABS

Table 9 Time to ignition, t_{ign} , as a function of irradiation level for white ABS tested in the cone calorimeter.

Irradiation, <i>q</i> [kWm ⁻²]	Time to ignition, <i>t_{ign}</i> [s], white ABS
15	*
20	255
25	165
35	70
60	22

* No ignition



Figure 22 Transformed ignition time vs. irradiance in the cone calorimeter for white ABS.

Using the value 0.9 for the absorptivity and the convective heat transfer coefficient 0.013 kWm⁻²K⁻¹ gives $T_{ign} = 312$ °C and $K\rho C = 6.67 \cdot 10^5 \text{ J}^2\text{m}^{-4}\text{s}^{-1}\text{K}^{-2}$. From Table 5 it is clear that 0.9 is indeed a relevant value for the absorptivity of white ABS. If the thermal degradation is taken into account it is found in Figure 20 that the absorptivity drops a few percent almost immediately after the onset of irradiation. Therefore a sensitivity analysis in the range $0.86 \le \alpha_{\text{eff}} \le 0.90$ was performed and the results are presented in Table 10.

	$\alpha_{\text{eff}}=0.86$	$\alpha_{\text{eff}}=0.88$	$\alpha_{\text{eff}}=0.90$
Ignition temperature, T_{ign} [°C]	307	309	312
Thermal inertia, $K\rho C [J^2 m^{-4} s^{-1} K^{-2}]$	6.35·10 ⁵	$6.55 \cdot 10^{6}$	6.67·10 ⁵

Table 10 Ignition temperatures and thermal inertias for white PVC using different absorptivities.

Again it is found that the variation in T_{ign} is relatively small.

It can be concluded that when Eqs. (17) - (19) are solved for T_{ign} the deviation of the true absorptivity from the conventional value of 0.9 has a relatively small impact on the T_{ign} result.

6.2 T_{ign} as calculated with absorptivity as a function of irradiation level

In Section 6.1 it was found that the calculations of T_{ign} is relatively insensitive to the value for the absorptivity, as long as it is kept within reasonable uncertainty limits. There is, however, another aspect of how the absorptivity, or rather the spectral absorptivity, can affect these calculations. In Section 4.2 it was described how the effective absorptivity varies with varying grey body temperature of the heat source. Since the different irradiation levels in the cone calorimeter are achieved by varying the temperature of the conical coil this means that α_{eff} will differ for the different measurement of ignition time. If this is corrected for, when plotting the graph, the equation for the linear interpolation will change and thereby the entire numerical calculation of T_{ign} and $k\rho C$ will be affected. This effect is investigated for white ABS below.

Table 11 contains the same experimental data as Table 9 and three columns have been added. The second column contains the α_{eff} for the different irradiations levels as obtained from interpolation of the information for white ABS in Table 5. The third columns contains the same α_{eff} but normalized to one for the lowest irradiation level. The fourth column in Table 11 contains the irradiation levels corrected for the varying α_{eff} .

cone calor infecter.				
Irradiation, <i>q</i> [kWm ⁻²]	αeff	Normalized αeff	Corrected radiant heat flux [kWm ⁻²]	Time to ignition, $t_{ign}[s]$
15	0.909	1	15	*
20	0.903	0.993	20	255
25	0.900	0.990	25	165
35	0.892	0.981	34	70
60	0.872	0.959	58	22

Table 11 Time to ignition, t_{ign} , as a function of irradiation level for white ABS tested in the cone calorimeter.

* No ignition

A new graph with the corrected irradiation levels on the x-axis is shown in Figure 23. Clearly the equation for the linear trend line has changed as compared with Figure 22.



Figure 23 Transformed ignition time vs. corrected irradiance in the cone calorimeter for white ABS. The data points and trend line for the corrected irradiances are shown with filled markers and a bold line, respectively. The data points and trend line for the uncorrected irradiances are shown with non filled markers and a weak line, respectively.

Using the value 0.9 for the absorptivity in Eqs. (17) - (19) but with the changed trend line in Figure 23 the results changes from to $T_{ign} = 312$ °C and $K\rho C = 6.67 \cdot 10^5 \text{ J}^2\text{m}^{-4}\text{s}^{-1}\text{K}^{-2}$ to $T_{ign} = 318$ °C and $K\rho C = 5.93 \cdot 10^5 \text{ J}^2\text{m}^{-4}\text{s}^{-1}\text{K}^{-2}$. The results are summarized in Table 12.

Table 12 Ignition temperatures and thermal inertias for white ABS calculated using different non corrected and corrected irradiation levels, see also Table 11.

	non corrected	corrected
Ignition temperature, T_{ign} [°C]	312	318
Thermal inertia, $K\rho C [J^2 m^{-4} s^{-1} K^{-2}]$	6.67·10 ⁵	$5.93 \cdot 10^{6}$

It should be pointed out that the use of Eqs. (17) - (19) to determine the ignition temperature and the thermal inertia is a quite simplistic approach taking advantage of several doubtful assumptions [15]. Furthermore, it is a reasonable assumption that the heat transfer coefficient will change with changed irradiation level. Therefore there are many unknown factors affecting the calculations of ignition temperature. One conclusion of this section is that the varying spectral absorptivity actually will change the results obtained from Eqs. (17) - (19). Another conclusion is that it is not known if this effect is significant compared to other uncertainties with the simplified ignition theory. It is suggested that the algorithm for calculating T_{ign} and $K\rho C$ should be improved before such effects as the varying absorptivity for different irradiation levels is considered.

7 Conclusions

It has been found that the effective absorptivity varies significantly with the temperature of the heat source. The reason for this is that the spectrum of the emitted radiation from a heat source, such as a fire, changes with temperature. This has a limited effect on the heating of a surface. This dependence of the effective absorptivity on heat source temperature is, however, important when the absorptivity is used as input for calculations of ignition temperature and thermal inertia. Using existing models for predicting ignition temperature and thermal inertia, and correcting these models with the new information on effective absorptivity, showed that the effects were significant but not very large. It was considered that the uncertainties in the model are so high that corrections for the effective absorptivity might be of minor importance compared to the other uncertainties and assumptions.

An interesting observation was that the absorptivity of radiation from fires for products exposed to irradiation in the cone calorimeter decreased with increased exposure time, that is the absorptivity decreased when the products darkened due to heat. This is surprising since for example wood that is darkened when exposed to heat obviously has a higher absorptivity in the visual part of the spectrum than fresh non-darkened wood. This is an important observation since it opposes the general view that heat transfer increase with increased thermal exposure due to darkening

Finally, it was concluded that none of the studied materials showed a particularly low absorptivity in the infrared region and therefore none of the products stand out as particularly efficient reflectors of radiation from fires. Several ideas were presented for how such spectrally tailored surfaces, with low absorptivity for radiation from fires, can be produced. Surprisingly little has been made in this field and it is considered worthwhile to further evaluate the potential of the suggested ideas.

Appendix A Results

The order of the spectras are approximately the same as the order in Table 2 to Table 5 in Section 4.2. The numbering in the graphs ("No 64..." for example) is only a dummy counter used to keep track of all the measurements and should not be considered. The use of the effective absorptivities for different grey body temperatures is explained in Sections 2.2.1 and 4.2. In many of the spectra a text like "0 s 30 kWm⁻²" is included. This means that the tested product has not been exposed to heat radiation in the cone calorimeter. In the same way the text "15 s 30 kWm⁻²" means that the product has been exposed to 30 kWm⁻² irradiation in the cone calorimeter during 15 s. See also Sections 3.2. and 4.3.


































































































































































































































0 [∟]

Wavelength [µm]




























































References

- 1. Babrauskas V, Ignition Handbook: Principles and Application to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science, Fire Science Publishers, 2003.
- 2. Hallman J, Ignition characteristics of plastics and rubber. University of Oklahoma, 1971.
- 3. Ensminger RI, in *Pigment Handbook*, T.C. Patton, Editor. 1988, John Wiley & Sons.
- 4. Modest MF, Radiative Heat Transfer. 2 ed, Elsevier Science, 2003.
- 5. ISO 5660-1:2002 Reaction-to-fire tests Heat release, smoke production and mass loss rate Part 1: Heat release rate (cone calorimeter method), 2002.
- 6. Paloposki T, Liedquist L, Steel Emissivity at high temperatures. NT Technical Report, TR 570, 2006.
- Karlsson-Ottosson U (2009) Smarta fönster blir smartare. Ny Teknik, <u>http://www.nyteknik.se/nyheter/innovation/forskning_utveckling/article587375.e</u> ce
- 8. Bendiganavale AK, Malshe VC, Infrared Reflective Inorganic Pigments, *Recent Patents on Chemical Engineering*, 2008; 1: 67-79.
- 9. Berdahl PH, US Patent 5811180 Pigments which reflect infrared radiation from fire. 1998, The Regents of the University of California: Place.
- 10. Brady RF, Wake LV, Principles and formulations for organic coatings with tailored infrared properties, *Progress in Organic Coatings*, 1992; **20**(1): 1-25.
- 11. New pigment opens unimaginable possibilities; http://www.yki.se/en/media/news/Sidor/090831.aspx.
- 12. Tabor H, Harris J, Weinberger H, Doron B, Further studies on selective black coatings, *United Nations Conference on New Sources of Energy*, Rome, 1961.
- 13. Edwards DK, Nelson KE, Roddick RD, Gier JT, Basic studies on the use and control of solar energy. University of California, 1960.
- 14. Quintiere JG, fundamentals of fire phenomena, John Wiley & Sons ltd, 2006.
- 15. Torero JL, Flaming Ignition of Solid Fuels, in *SFPE Handbook of Fire Protection Engineering*, P.J. DiNenno and C.L. Beyler, Editors. 2008, National Fire Protection Association.
- 16. Janssens ML, Piloted Ignition of Wood: A Review, *Fire and Materials*, 1991; **15**: 151-167.
- 17. Janssens ML, Fundamental Thermophysical Characteristics of Wood and The Role in Enclosure Fire Growth. University of Gent, Gent, 1991.
- 18. Hjohlman M, Försth M, Axelsson J, SP Report 2009:08 Design fire for a train compartment. SP Technical Research Institute of Sweden, 2009.

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