IGNITION PERFORMANCE OF NEW AND USED MOTOR VEHICLE UPHOLSTERY FABRICS[†]

Michael Spearpoint[*1], Stephen M. Olenick[2], Jose L. Torero[3] and Thomas Steinhaus[4]

[1] Dept of Civil Engineering, University of Canterbury, Christchurch, New Zealand

[2] Combustion Science & Engineering, Inc., Columbia, Maryland, USA

[3] School of Engineering and Electronics, The University of Edinburgh, Edinburgh, EH9 3JL, UK

[4] DVS Risk Service GmbH, Bonn, Germany

ABSTRACT

This paper examines the standards for fire safety in transport systems and in particular the test method for the flammability of materials within passenger compartments of motor vehicles. The paper compares data from ignition tests conducted in the Cone Calorimeter and the FIST apparatus with tests conducted using the FMVSS 302 horizontal flame spread apparatus. Ten materials were selected as representative of those used as seat coverings of private and commercial passenger vehicles. The time to ignition of new and used materials subject to exposure heat fluxes between 20 kW/m^2 and 40 kW/m^2 was measured. The results from the ignition tests were analyzed using thermally thick and thermally thin theoretical models.

The critical heat flux for sustained piloted ignition was determined from the time to ignition data using the thermally thin approach. Derived ignition temperatures from both the thermally thick and thermally thin methods were compared with measurements using a thermocouple attached to the back surface of materials in selected tests. The flame spread rates in the FMVSS 302 apparatus were determined and a comparison was made between the performance of the materials in the flame spread apparatus, the Cone Calorimeter and the FIST. The results suggests that a critical heat flux criterion could be used to provide an equivalent pass/fail performance requirement to that specified by the horizontal flame spread test although further testing is needed to support this.

[†] This research was undertaken at the University of Maryland, Dept. of Fire Protection Engineering, USA.

[*] Corresponding author, michael.spearpoint@canterbury.ac.nz

NOMENCLATURE

A area, [m^2]

B burn (flame spread) rate, [m/s]

c specific heat capacity, [J/kg.K]

d distance, [m]

Gr Grashoff number, [-]

δ thickness, [m]

h heat transfer coefficient, [W/m^2.K]

k thermal conductivity, [W/m.K]

l length, [m]

m mass, [kg]

q heat flux, [W/m^2]

ρ density, [kg/m^3]

Re Reynolds number, [-]

T temperature, [°C] or [K]

t time, [s]

σ Stefan-Boltzmann constant, [5.68 x 10^{-8} W/m^2.K^4]

V volume, [m^3]

w width, [m]

Subscripts

∞ ambient

c convective

cr critical

ig ignition

e external

s surface

Superscripts

$(\;)''$ per unit area

$(\dot{\;})$ per unit time

1. INTRODUCTION

There are many forms of passenger transportation currently in regular use (ships, trains, aircraft, buses, cars etc.) all of which contain a certain amount of combustible material. In an effort to make new vehicles more attractive, comfortable and to decrease their weight, designers use a range of plastics and fabric materials.

In the various modes of ground transportation the degree of fire hazard is similar [1]. In general, there is an apparent ease of egress and the vehicles may spend a large proportion of their time on the surface. Nevertheless, many vehicle fires occur in post-crash/collision situations where egress may be limited. For example, a survey of fatalities in vehicle fires in the UK in 1987 showed that 53 of 77 deaths occurred in crashes or collisions [2].

Although the majority of fires in ground-based transportation originate in the motive power equipment, it has been reported that many fires originate in the passenger compartment. Goldsmith [3] found that around 30 to 40 percent of all vehicle fires occurred in the interior (the trunk and passenger compartment). Accidental fires often occur as a result of general carelessness with items such as smoking materials and cigar lighters. Thus, the fire performance of interior fabrics of passenger compartments is one factor in the overall fire safety of a vehicle that needs to be considered during its design and whilst in use.

It has been estimated [4] that a passenger car in the US in 1970 contained around 2.5 m^2 of woven fabric, 4.2 m^2 of carpeting, and 8.4 m^2 of fabric coated with vinyl. Although estimates for more modern cars have not been obtained for this work, it would seem likely that these values are typical although the actual material may be different. Fabrics used in the compartment of a passenger vehicle have many performance requirements including tensile strength, tear resistance, flexibility, wear resistance and dielectric sealing behavior. Thus, the fire performance is only one factor for the selection of a fabric that needs to be considered by a design engineer. Finally, the fire performance of a fabric needs to be considered over the life of the vehicle in which it is to be used. Interior materials are tested when they are new but the effect of aging on the fire performance of these materials is unknown.

2. TEST METHODS AND REGULATIONS

Under ideal conditions, test methods should provide the engineer with properties inherent to the material that could be used not only to rank materials based on their fire performance, but these properties could also be used to model and predict fire growth. In reality, current testing methodologies provide information that, independent of its use, carries significant uncertainty [5]. The uncertainty stems from many sources among which it is important to highlight, the complex behavior of the material, the errors associated with the test protocol and those errors intrinsic to the data interpretation methodology. A reasonable way to reduce the uncertainty is by utilizing multiple test methods and interpretation methodologies in such a way that the combined results provide a clearer picture of the behavior of the materials.

Examining the test methods and regulations for the determination of the flammability properties of interior transportation material in general and seating materials of automobiles in particular, it was clear that there is essentially only one test method used around the world, which is the Federal Motor Vehicle Safety Standard (FMVSS) number 302 [6].

A standard to regulate and test the flammability of interior transportation material is based on the concept of limiting the fire risks by using materials in the interior of the vehicle which are difficult to ignite and have a low flame propagation velocity. This would allow sufficient time for the passengers to exit the vehicle safely in the event of a fire emergency.

As a response to the 1966 National Traffic and Motor Vehicle Safety Act, the US implemented the Federal Motor Vehicle Safety Standard (FMVSS) 302 in 1972 to reduce the fire risks of cigarettes and matches impinging on interior fabrics of a vehicle by specifying a minimum standard that must be complied with.

Although this standard represented only a United States regulation, it had a worldwide effect. Taking the case of Germany, an immediate reaction was observed in which all car manufacturers, which exported cars to the United States, had to fulfill this new US standard. Due to this fact, they equipped all of their cars with materials according to the US standard. In 1980, the German Institute for Normation released the DIN 75200 standard, which was almost identical to the US standard FMVSS 302.

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Since 1972, the United States FMVSS 302 standard has also transformed into the international standard ISO 3795, while international regulatory incorporation was completed in November 1995 in the "Directive 95/28/EC of the European Parliament and of the Council of 24 October 1995". Even though there are national differences, normally represented by the exact values of the measured flame spread rate for determination of when a material passes or does not pass the test, the FMVSS 302 method is always the basis for those tests and has become a de-facto international standard.

Thus for road passenger vehicles there is essentially only one standard test method for interior materials used throughout the world. Although this test gives a method for excluding particularly unsafe materials from being used, the test provides only limited data that might be useful to a design engineer.

In this study, the results from the FMVSS 302 method are contrasted with those of two more commonly accepted flammability tests, the Cone Calorimeter (ASTM-E-1354) and the LIFT (ASTM-E-1321). The LIFT uses large samples (180 mm x 180 mm for ignition and 800 mm x 180 mm for flame spread) which can lead to problems with ensuring that fabrics remain attached to the surface. Thus a small scale variant, the FIST [7], originally developed to test materials to be used in spacecraft, was used here. The FIST will be described in detail later but its main advantage is the reduced scale, since it uses samples 25 mm x 25 mm.

3. MATERIAL SELECTION

3.1 Preamble

The provisions of the FMVSS 302 test require that the interior materials of passenger vehicles, and in this case seat fabrics, are tested with or without the backing seat material depending on whether the fabric is attached or not. Thus the FMVSS 302 test is both a component and a composite test that appears to lack a certain degree of consistency. Consider seats consisting of two similar fabrics on similar foam interiors but where one fabric is attached in some way to the foam and the other is not. In such a case, the attached fabric and foam would be tested as a composite but the unattached fabric and foam would be tested individually. The performance of the individual components may be different to the composite but in both cases the end use will be a composite arrangement.

For the ignition experiments, all materials were tested as components but in a composite arrangement. That is, the test materials were removed from any backing foam but were tested in contact with a non-combustible ceramic fiber blanket substrate. Prior to testing, the selected materials were conditioned for at least 48 hours in an oven at 40 ºC and dried using anhydrous sodium silicate.

Where necessary, the materials were identified by visual inspection, observing their burning behavior (smell, flame and smoke characteristics, residue formation), and by performing other identification tests [8]. Table 1 details the materials used in the tests where the nominal thickness was obtained using a digital vernier in which the height of any fibre tufts were included in the measurement.

Material ID number	Estimated age [years]	Nominal thickness [mm]	Specific mass, $\rho.\delta$ [kg/m^2]	Description
Used materials				
1	19	1.4	0.74	Leather with possibly a treated top surface
2	23	2.4	0.67	Nylon or nylon/olefin blend with a latex back-coat
3	~12	2.4	0.43	Acrylic material
4	24	1.1	0.85	PVC with a light-weight woven fabric backing
5	Unknown but at least 15 yrs old	1.1	0.87	PVC with a medium-weight woven fabric backing
6	20	0.7	0.53	PVC with a heavy-weight woven fabric backing. The material was stiffer than Materials 4 and 5 and may have lost a large proportion of its plasticisers
7	~5	1.9	0.58	Nylon pile on an artificial backing material with a thin latex back-coat
New materials				
8	-	1.1	0.77	PVC laminated onto a light-weight cotton knit
9	-	1.6	0.42	Olefin (as labeled by the supplier) with a latex back-coat
10	-	4.6	0.76	Olefin with a back-coat

-       not applicable

Table 1. Details of the new and used materials.

3.2 Used vehicle seat materials

Eight materials were obtained from used seats representative of those found in private vehicles currently or previously in use in the United States. Samples were taken from the horizontal portion of the drivers seat where practical. The age of the material was estimated from the approximate age of the vehicle assuming the seat fabric was not replaced during the vehicle's life.

3.3 New vehicle seat materials

Three materials used in seat construction were obtained from a manufacturer. The materials are specifically used in buses and coaches rather than private motor vehicles. The number and size of samples provided were limited which reduced the total number of ignition tests that could be performed compared with the used automobile seat materials.

4. TEST METHODS AND PROCEDURES

4.1 Cone Calorimeter tests

The Cone Calorimeter [9] is a standard apparatus for measuring the ignition and burning characteristics of materials. A truncated cone shaped electric heater is used to impose an external incident heat flux $\dot{q}_e''$ onto the surface of a test sample. An electric spark igniter can be used to initiate piloted ignition and the time to ignition t_{ig} is recorded by the operator. The apparatus uses a load cell to measure mass loss rate per unit area and oxygen consumption calorimetry is used to obtain the rate of energy release per unit area. For this study only the time to ignition was relevant and thus no calorimetry measurements were made.

The materials were cut into 100 mm by 100 mm samples and mounted inside the test frame backed with layers of ceramic fiber blanket. During exploratory tests it was found that several samples tended to curl up towards the cone heater thereby affecting the time to ignition measurements thus a wire grid was used to retain the sample in position. Samples of each material were tested in the horizontal orientation at heat fluxes of 20 kW/m^2, 30 kW/m^2 and 40 kW/m^2.

The sample was inserted under the heater and the stop-clock started. The spark igniter was immediately positioned over the sample and observations were made, including whether the sample flashed prior to ignition and whether the sample deformed in any

way. The time to sustained ignition (i.e. where flaming continued for at least 10 seconds) was recorded.

The time at which the sample ceased flaming was also noted. Recording the time at which flaming ceased was subject to operator interpretation. Initially, at the point of ignition, samples would ignite over the complete surface of the material. However, as the test continued, the flames would recede so that many samples would continue to flame only around the edges where the sample was protected by the metal retainer frame. This edge flaming could continue for a considerable length of time but was not characteristic of the burning of the sample as a whole. Thus the time to flame out was taken to be once the characteristic burning had ceased rather than once every small flame had disappeared. For a number of selected tests, a thermocouple was positioned on the back surface of the sample to obtain a measure of the ignition temperature of the material. The thermocouple consisted of a 0.813 mm (0.032") diameter Type-K sheathed sensor. The thermocouple was attached as best as possible to the approximate center of the sample. It was assumed that having the thermocouple on the back would give a reasonable measure of the ignition temperature given the thickness of the samples and for most of the samples it was impractical to locate a thermocouple close to the top surface as a result of the thinness and form of the materials tested.

The ignition temperature measurements using the thermocouples were conducted at the low heat fluxes (20 kW/m^2) to allow sufficient time for the heat to penetrate the thickness of the material prior to ignition. The measurements using the thermocouple were complicated by the fact that the samples would sometimes alter in structure or physically deform whilst being heated. This may have resulted in the thermocouple bead becoming detached from the back surface of the material. Furthermore, if the thermocouple shifted position due to the deformation of the sample, it may have moved to an area of the sample shielded from the direct thermal radiation by the grid.

4.2   FIST tests

The FIST apparatus, or the Forced Ignition and Spread Test, is a modified LIFT [10] apparatus that is designed for micro-gravity use. The FIST was designed to allow testing of smaller samples and under conditions where buoyancy can be neglected. The FIST protocols follow closely those of the LIFT and allow two options, natural convection tests or forced flow tests. The latter is mostly used in the absence of gravity. The results from

the FIST have been shown to compare very well with those of the LIFT for a multiplicity of materials. The description of the FIST, the validation process, and the protocols used can be found elsewhere [11, 12, 13]. A brief summary of the test method and protocols is provided as follows.

The FIST consists of 2 test procedures, the ignition test and the flame spread test. An ignition test consists of a small sample, 25 mm by 25 mm, placed into the sample slide cold. An electrical radiant panel imposes a constant external heat flux onto the sample surface, and an electrically powered pilot is placed above the sample. Once the sample reaches its pyrolysis temperature, its volatiles are released. The volatiles mix with the surrounding air and eventually this mixture will attain flaming ignition. This time to flaming ignition is the ignition delay time.

The flame-spread test is conducted slightly differently. A longer sample, 100 mm by 25 mm is placed into the sample holder. The sample holder is then placed in front of the radiant panel, but this time, the igniter is not turned on immediately. First, the sample is allowed to reach its thermal equilibrium under the distributed heat flux from the radiant panel. Once the sample reaches thermal equilibrium, the igniter is turned on, inducing ignition. The flames then spread downwards, and the flame spread rate can be recorded. A relationship between the flame spread rate and the external heat flux can be found as well as a curve fit for the effect the flame has on spread (the parameter Φ) [14]. The focus of this study though was to examine the ignition properties of transportation materials and so the FIST was only employed in its ignition mode.

The FIST (Figure 1) is simply a smaller version of the LIFT apparatus. The FIST consists of 6 radiant heaters to deliver the external heat flux to the sample. The sample holder is designed to hold 3 samples, each 40 mm by 40 mm. A shield is in place to ensure that only one sample is exposed to the external heat flux, and that the others stay cold as per the LIFT procedure protocol. Kanthal wire is used as the igniter to guarantee a high enough temperature. The samples are installed vertically.
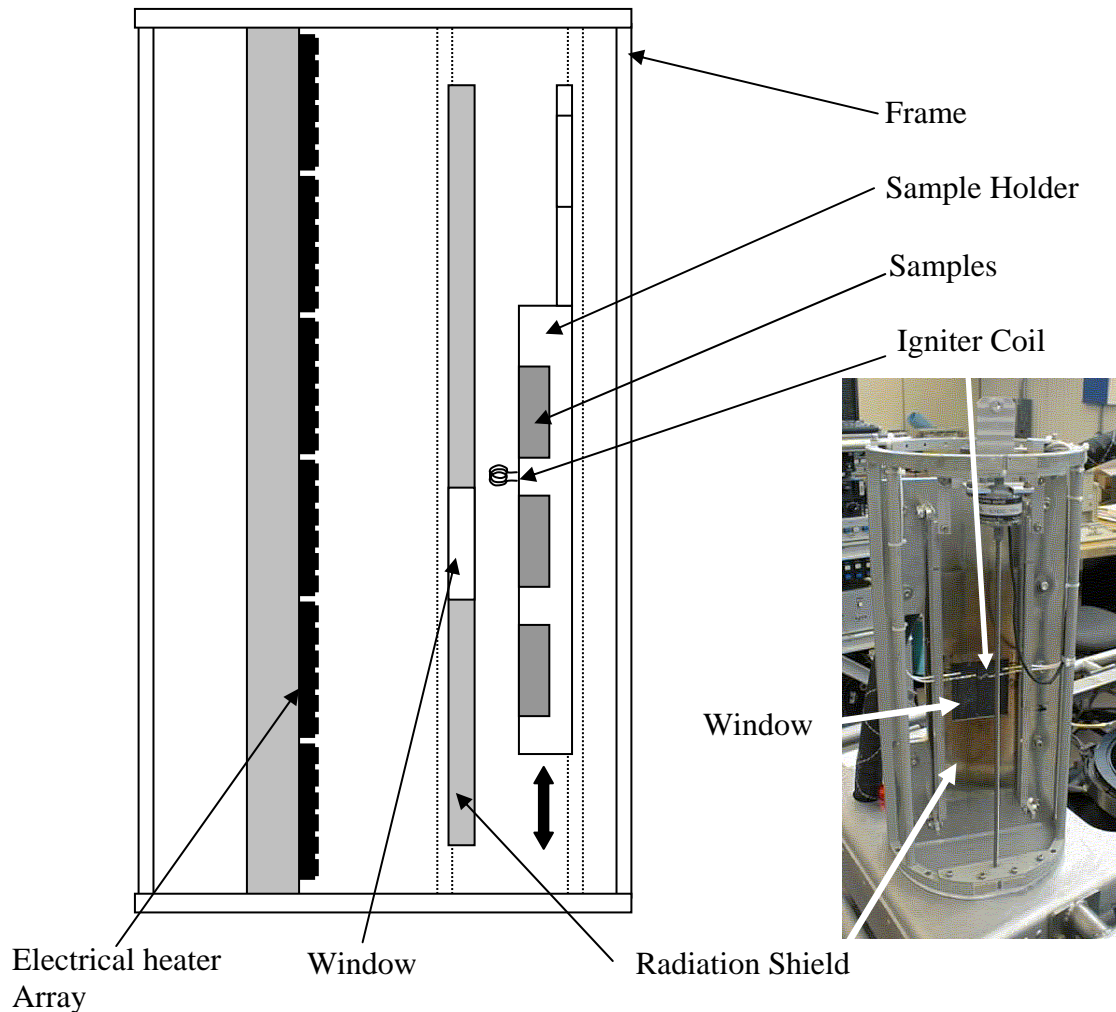
Figure 1. The FIST apparatus.

The sample holder is first loaded with a sample. Since the tests conducted in this project were carried out on the ground and not in micro-gravity, there was no reason to use more than one sample per sample holder. In micro-gravity conditions, the number of tests per holder needs to be maximized thus three samples are used per holder. The sample holder consists of a front plate, fiberglass sample holding area piece, a fiberglass-backing piece, and a metal handle backing piece.

The sample was cut to the required size of 40 mm by 40 mm, and backed with ceramic fiber blanket until the total thickness of the composite was 12.7 mm. The sample card was then loaded into the sample slides, and moved to the bottom of the FIST, where the sample could be protected from the radiant heat flux by the shield. The sample was then

moved in front of the radiant heaters, and the stop-clock was started. The igniter was turned on immediately and the sample could attain a state of flaming ignition at which point the stop-clock would be stopped. If no ignition occurred, the test was terminated when it was determined that no further useful data and observations could be obtained.

Six tests were conducted for each material, two at 40 kW/m^2, two at 30 kW/m^2 and two at 20 kW/m^2, and for each test the ignition delay time was recorded, as well as basic observations.

4.3   FMVSS 302 horizontal flame spread tests

Eight of the materials (2 new, 6 used) tested in the Cone Calorimeter and the FIST were also tested in the FMVSS 302 horizontal flame spread apparatus. The two remaining materials were not tested since insufficient amounts were available. Initially the tests were conducted following the requirements of the standard as closely as possible. All materials were tested without any backing and were exposed to the burner flame for the required 15 seconds. Subsequent to the 15-second flame exposure tests, those materials that did not exhibit any flame spread were exposed to a continuous flame, although not required by the standard. The flame was held in position until either flame spread was achieved or it was clear that no flame spread would occur.

5.   ANALYSIS

5.1   Approach

Interpretation of ignition delay times to obtain reliable information is not trivial for thin materials such as the ones used for this study. The insulating substrate due to its low thermal conductivity transfers little heat away from the sample, nevertheless does represent a heat sink that needs to be accounted. Quintiere [15] suggests that in such an arrangement, the fabric can be considered as a thermally thin material (Figure 2a) where heat losses to the substrate are small. Babrauskas [16] also considers this arrangement to be physically and thermally thin but notes that other researchers have found this may not always be so. Depending on the type of fabric, the thermo-physical properties of the substrate and the thermal contact between them, the arrangement may lead to significant heat transfer from the sample to the substrate (Figure 2b). Two extreme scenarios will be studied here, that of a thermally thin sample perfectly insulated on one side and that of a thermally thin sample that is thin enough that represents no resistance for the heat that is

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then directly imposed on the insulation behind. The insulation will be treated as a semi-infinite solid. The real conditions will not correspond to either of these scenarios, because the sample does have a thermal capacity, thus will absorb heat, nevertheless, including the sample in the analysis will require full knowledge of its thermal properties. These properties, and their evolution with temperature, are unknown and are the purpose of the test. The utility of this analysis is that it provides the two extreme conditions, one where no heat goes to the insulation and one where all the heat goes to the insulation. The experimental results should fall somewhere in between.
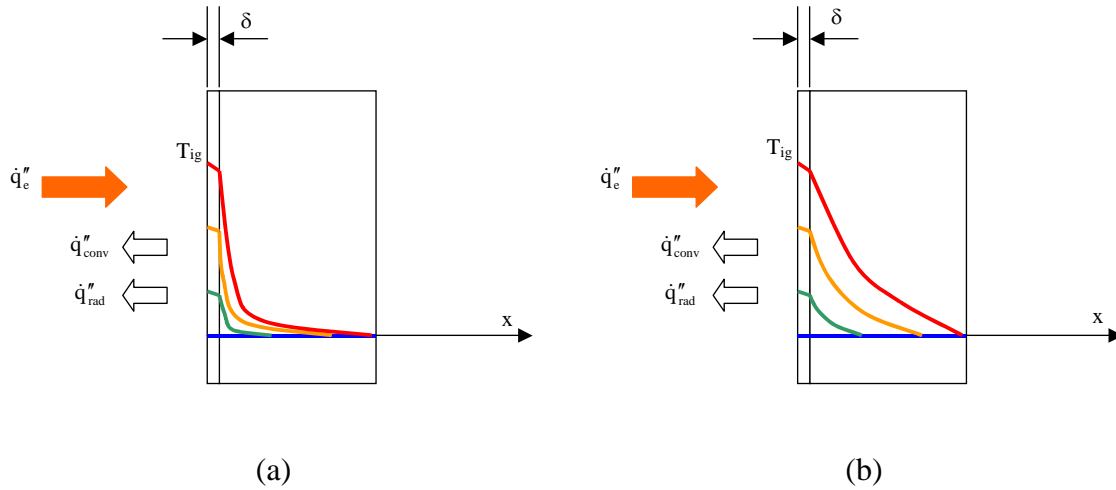

(a)   (b)

Figure 2. Heat transfer characteristics through the thin fabric to the substrate; (a) thermally thin (b) thermally thick.

5.2 Thermally thin sample with no heat losses to the back

In this case it is assumed that the substrate acts as a layer of inert, low-conductivity insulation therefore ignition is controlled solely by the fabric. Quintiere [15] suggests that the time to ignition of such a thermally thin material can be given by

$$\frac{1}{t_{ig}} = \left(\dot{q}_e'' - \dot{q}_{cr}'' \right) \frac{1}{\rho c \delta} \frac{1}{\left(T_{ig} - T_\infty \right)} \tag{1}$$

It is important to note that equation (1) assumes that through the integrity of the heating process, surface heat losses are constant at its maximum value where the surface temperature is the ignition temperature. This assumption is not unreasonable since

initially the temperature increases rapidly and therefore throughout most of the heating period the temperature is close to the ignition temperature.

To obtain the critical heat flux required for ignition $\dot{q}''_{cr}$, the data was plotted in the form of $1 / t_{ig}$ against $\dot{q}''_e$ and the critical heat flux obtained from the intercept along the x-axis of a linear extrapolation through the data.

The critical heat flux obtained by this analysis is only an approximate value as a result of the simplifications made by the theory. However, the results are sufficient and the values for the critical heat flux give a relative measure for the different materials examined. If it is assumed that $\dot{q}''_{cr}$ is given by

$$\dot{q}''_{cr} = \sigma(T_{ig}^4 - T_\infty^4) + h_c(T_{ig} - T_\infty), \tag{2}$$

then the ignition temperature T_{ig} can be found. The solution to Equation (2) is found by iteration.

5.3 Sample of negligible thermal capacity semi-infinite solid backing

For this case, it is assumed that because δ is very small, it can be neglected when solving the energy equation

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} \tag{3}$$

When this equation is solved for the ignition temperature (T_{ig}) and the ignition time (t_{ig}), the thermal inertia ($k\rho c$) of the insulation appears in the solution. On the other hand, the boundary condition at the interface between the fabric and the air is given by the fabric, so that

$$-k\frac{\partial T}{\partial x}\bigg|_{x=0} = \dot{q}''_{net} \tag{4}$$

where k is the thermal conductivity corresponding to in-depth conduction (the resistance for heat to go in) which can still be assumed to be that of the insulation and therefore is consistent with Equation (3). In contrast, $\dot{q}''_{net}$ is given by the following energy balance

$$\dot{q}''_{net} = a\dot{q}''_e - \dot{q}''_{rad} - \dot{q}''_{conv} \tag{5}$$

where a is the absorptivity of the fabric. The radiation term is commonly expressed as

$$\dot{q}''_{rad} = \varepsilon\sigma(T_S^4 - T_\infty^4) \approx h_r(T_S - T_\infty) \tag{6}$$

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since $h_r = \varepsilon\sigma(T_S^2 + T_\infty^2)(T_S - T_\infty)$, so it is a property of the fabric because the emissivity (ε) is a property of the fabric. Again, the value for the radiative heat transfer coefficient (h_r) can be assumed to be a constant because most of the time is spent close to the ignition temperature, therefore by substituting $T_s = T_{ig}$, a constant radiative heat transfer coefficient for each material is obtained.

The convective losses are dependent on a correlation of the flow that is a function of $Gr^{1/4}$ and $Re^{1/2}$, which can be assumed to be a constant and independent of the fabric so $\dot{q}''_{conv} = h_c(T_S - T_\infty)$ [11].

The solution for the ignition time will correspond to the time that the surface attains the ignition temperature and since the surface is the fabric, then the ignition temperature is that of the fabric. However the time is obtained by solving Equation (3) so the thermal inertia that appears in Equation (7) is that of the insulation.

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{k\rho c}}\frac{a\dot{q}''_e}{(T_{ig} - T_\infty)} \tag{7}$$

The absorptivity (a) is that of the fabric and the ignition temperature, as was discussed earlier, is that of the fabric. By using the known thermal inertia for the insulation (typically when $T_s = 340$ ºC then $k = 0.068$ W/m.K, $\rho = 64$ kg/m^3, $c = 800$ J/kg.K thus $k\rho c = 3056$ W^2.s/m^4.K^2), then the slope of the plot of $1/t_{ig}^2$ against $\dot{q}''_e$ gives

$$\frac{a}{(T_{ig} - T_\infty)} \tag{8}$$

It is generally not necessary to know the absorptivity of a material in order to accurately and realistically measure the radiant ignitability of a specimen provided the heater in the apparatus has emission characteristics roughly similar to those of real fires [5]. The Cone Calorimeter and the FIST use similar electrical heating elements and are both likely to be representative of real fires. In addition the absorptivity approaches unity as the material starts to degrade [5], therefore assuming unity value for the absorptivity, the ignition temperature can then be estimated.

5.4 Numerical solution

Despite the strong simplifications, the solution to Equation (3) provides an estimate of the energy that is transferred to the insulation and thus the heat-flux into the insulation at the

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onset of ignition can be used to calculate a corrective factor for the ignition temperature established from equation (1). This can be done by providing an analytical solution to equation (3) as done by Long et al. [11] or by using a simple transient, one-dimensional finite difference heat conduction calculation. The later method was preferred here because it does not imply further assumptions. The temperature boundary condition at the back of the sample holder was assumed to be ambient.

A sample set of results corresponding to Material No. 5 is presented in Figure 3. It can be noted that due to the low thermal conductivity, the in-depth heat flux increases initially with time, after a few seconds surface heat losses become dominant, and the in-depth heat flux begins to decrease and eventually will reach steady-state conditions. In contrast, the net heat-flux follows the expected decaying trend until it reaches a negligible value and steady state can be assumed. The temperature will thus increase until the net heat-flux becomes zero, after which the surface temperature will not vary any further. The asymptotic value of the in-depth heat flux calculated can then be used to correct $\dot{q}''_{cr}$ in equation (2) and obtain a more accurate ignition temperature.
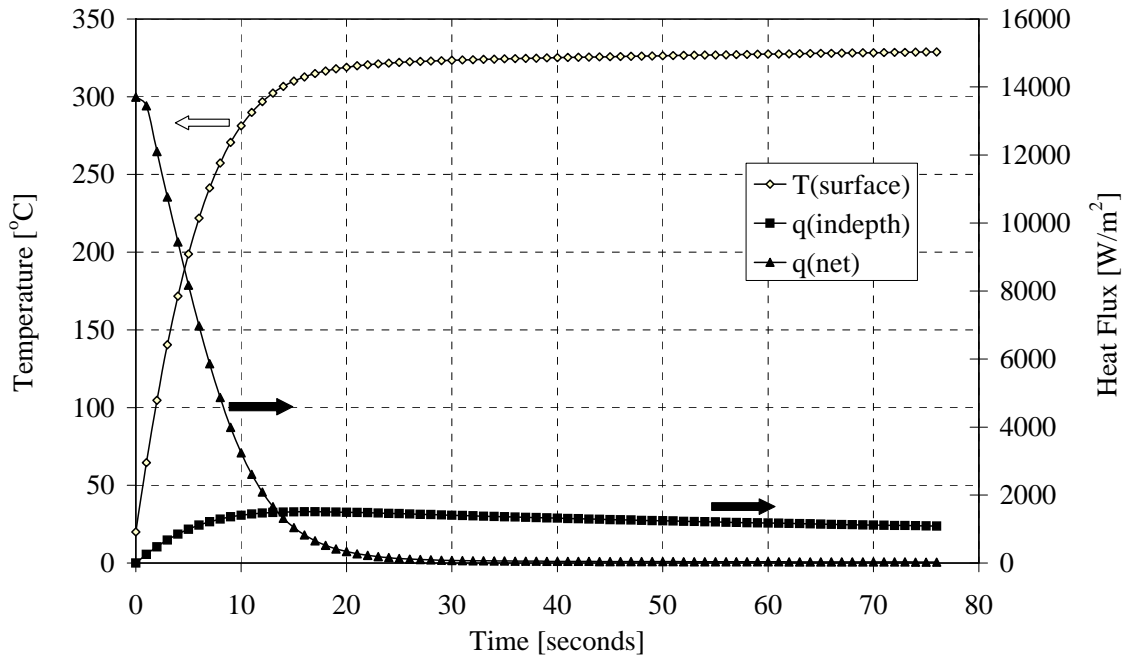

Figure 3. Evolution of the surface heat flux and temperature for Material No. 5.

6. RESULTS

6.1 Cone Calorimeter and FIST tests

A total of 59 ignition tests were conducted in the Cone Calorimeter and 57 tests in the FIST. Figure 4 shows typical results from the Cone Calorimeter and the FIST plotted with the vertical axis corresponding to both thermally thin and semi-infinite solid coordinates. For illustration, results are presented for a used and a new material. Similar results were obtained for all other materials studied. It can be noticed that the expected linear correlation can be established using either solution, in theory corroborating the validity of both assumptions. In reality, Figure 4 only shows that a linear fit to the data is in most cases possible. The data for the FIST and the Cone Calorimeter seems to provide similar results although the line fit through the thermally thin solution gives different slopes for each test apparatus.
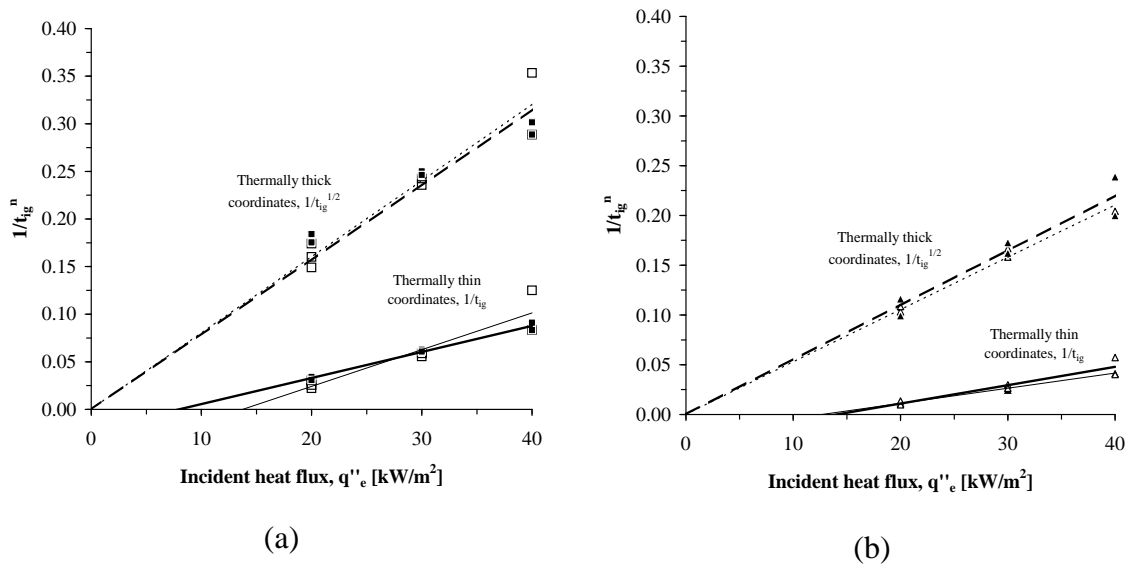

Figure 4. Typical ignition results plotted in thermally thick and thermally thin coordinates; (a) Used material 5; (b) New material 10. FIST - solid symbols; Cone Calorimeter – open symbols.

For the FIST experiments it was observed that most of the materials would melt and drip significantly, and since the FIST holds the sample vertically instead of horizontally, sometimes the sample would deform out of place which would influence the ignition delay time. Unlike the Cone Calorimeter, the FIST did not utilize a grid to hold the sample in place and with no grid in place and the sample in the vertical position, the

sample could melt completely out of the holder. This did cause some discrepancy between the results from the Cone Calorimeter and the FIST.

It is important to note that these differences are not mentioned with the objective of establishing criteria of quality between tests but to highlight the sources of uncertainty. As mentioned before, the grid used in the Cone Calorimeter reduces sample displacement, nevertheless the heat capacity of the grid has an unavoidable effect on the energy balance at the surface and thus on the ignition delay time. The debate between horizontal and vertical testing for ignition delay times has been present for decades. Horizontal testing allows a better study of liquids or materials that will undergo melting, dripping or significant deformation. Nevertheless, the flow structure is complex, thus the relative location of the pilot has a significant impact on the result [17]. Furthermore, the unstable nature of the plume magnifies external variables such as geometrical effects [18]. These specific problems are minor when the configuration is vertical and natural convection leads to a stable boundary layer to be formed.

6.2   Thin theory critical heat flux

Experimental values for the minimum heat flux for ignition by the use of bracketing were unobtainable due to the lack of sufficient material. The critical heat flux for ignition for each material tested in the Cone Calorimeter and the FIST was obtained by using the thermally thin material analysis. Figure 5 summarizes and compares these critical heat fluxes for each material. The critical heat flux for ignition cannot be obtained using the semi-infinite solid solution since the assumptions leading to equation (7) will break down as the external heat flux approaches the critical values. A different solution is then valid and it is generally recommended to use empirical values instead of extrapolations to the data [10].
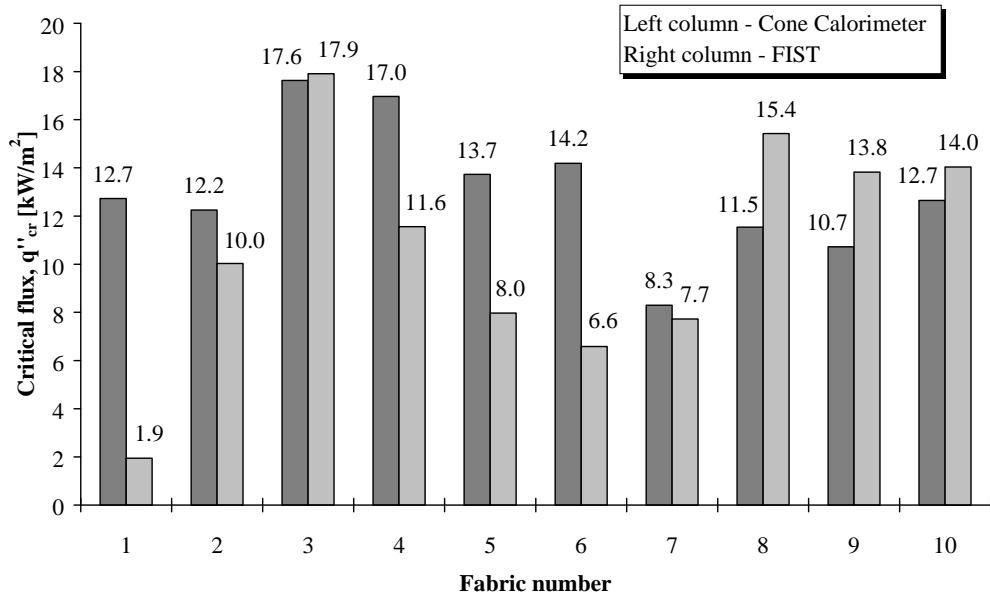
Figure 5. Summary of critical heat fluxes obtained in the Cone Calorimeter and the FIST assuming a thermally thin approach.

Figure 5 shows significant differences between the two test procedures. For most used materials, the Cone Calorimeter seems to provide higher critical heat fluxes. The opposite seems to be true for the new materials. Material 3 seems to be the only one where this trend was not followed. Detailed observation of the experiments showed that the only clear conclusion that could be drawn was that deformation is enhanced in the FIST. For vertical samples, deformation will lead to accumulation of fuel at the bottom of the sample leading to areas where the fuel was in greater proximity to the heater, thus receiving larger heat fluxes than those established by the calibration. Thus those materials where deformations were more significant showed shorter ignition delay times with the FIST. Not coincidentally, most of the used materials showed larger deformation.

6.3   Ignition temperature

The ignition temperature for each material was obtained by solving Equation (2) for the thermally thin approach using the critical heat fluxes given previously and also by using the semi-infinite solution. The convective heat transfer coefficient was taken to be 18 W/m^{2}K [19] for the Cone Calorimeter and 24 W/m^{2}K [20] for the FIST. Figure 6 also shows experimental values obtained using thermocouples between the sample and the

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insulation. The corrected values that incorporate heat conduction into the insulation are also presented.

Figure 6 shows a comparison between the different measured and calculated temperatures. The calculated values are clearly divided into two groups, the higher temperatures are obtained using the thermally thin approach. Unrealistically low temperatures are calculated for most cases when using the semi-infinite approach. The correction results in a systematically lower temperature, nevertheless the correction is generally of the order of 20 to 30$^\mathrm{o}$C, which is small when compared to the scatter of the data. For Materials 1, 2, 5 and 6 the measured temperature lies between the Cone Calorimeter and FIST predictions and for Materials 9 and 10 the measured temperatures are slightly below the predictions obtained from the test apparatuses.
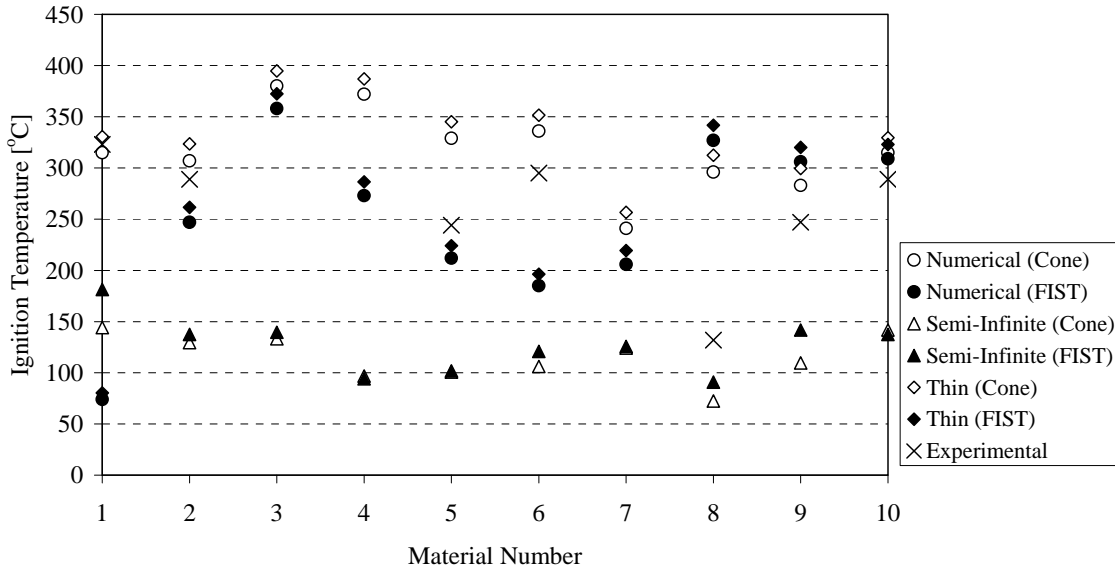

Figure 6. Comparison of the average measured ignition temperatures with the calculated ignition temperatures using the semi-infinite solid solution, the thermally thin calculation and the thermally thin with correction for in-depth heat conduction into the insulation approach.

The exceptions to the above statement are for Materials 1 and 8. The predicted ignition temperature using the thermally thin approach for Material 1 in the FIST is significantly lower than that from the Cone Calorimeter and that measured by the thermocouple. The reason for this discrepancy was due to the sample deforming out of the FIST apparatus during the tests which consequently affected the ignition times. For Material 8, the

ignition temperatures obtained in the Cone Calorimeter and the FIST using the thermally thin approach are considerably greater than recorded by the thermocouple. It appears that for this material, the thermally thick approach is more appropriate.

6.4 FMVSS 302 test

Table 2 shows the results from the FMVSS 302 tests and it can be seen that three materials ignited and exhibited flame spread with the 15-second flame. Another material achieved flame spread with the continuous flame and four materials did not exhibit any flame spread.

Material number	15 s flame			Continuous flame		
	Flame spread distance	Flame spread time	Flame spread rate	Flame spread distance	Flame spread time	Flame spread rate
	d	t	B	d	t	B
	[m]	[min:sec]	[m/s]	[m]	[min:sec]	[m/s]
Used materials						
1	-	-	-	n/a	n/a	n/a
2	0.100	02:52	0.00058	n/a	n/a	n/a
3	-	-	-	-	-	-
5	-	-	-	0.200	08:01	0.00042
6	-	-	-	-	-	-
7	0.115	02:40	0.00072	n/a	n/a	n/a
New materials						
9	0.060	00:32	0.00188	n/a	n/a	n/a
10	-	-	-	-	-	-

- : no flame spread

n/a : no test data available

Table 2. Flame spread results from the FMVSS 302 tests.

It might be expected that all the materials (at least in their original form) obtained and tested in this study had passed the FMVSS 302 test. This may not have been the case where vehicles were manufactured prior to 1972 (the year that the standard was introduced). Examination of the horizontal flame tests conducted for this study showed that Material 9 failed the test since its burn rate of 0.00188 m/s was greater than the specified 0.0017 m/s. This appears to be a surprising result since this was one of the new materials tested and it would have been assumed that the new materials were more likely to have been able to pass the test.

It is important to note that a good correlation between the ignition temperatures predicted using that thermally thin approach and the Cone Calorimeter test data was obtained with the flame spread performance. The materials that sustained flame spread were those three where the predicted ignition temperatures were the lowest. In contrast, the rate of spread was not greater for those materials with the lowest ignition temperatures. The performance of Material 5 with a continuous flame could not be linked to any of the previous results.

7. RANKING ANALYSIS

The analysis of the time to ignition data suggests that a thermally thin approach can be used to characterize the ignition performance of the fabric materials when backed with a non-combustible ceramic fiber substrate.

A comparison of the performance of the seven used materials in the Cone Calorimeter and the FIST is presented here. The critical heat fluxes of each material were ranked in ascending order (i.e. the lowest critical heat flux was ranked first etc.). Comparing the ranking performance of the used materials in the Cone Calorimeter and the FIST (Figure 7) it is evident that there is some degree of agreement between the two test apparatuses. Three of the seven materials are equally ranked however two of the four remaining materials (Materials 2 and 6) have a ranking difference of greater than 3.
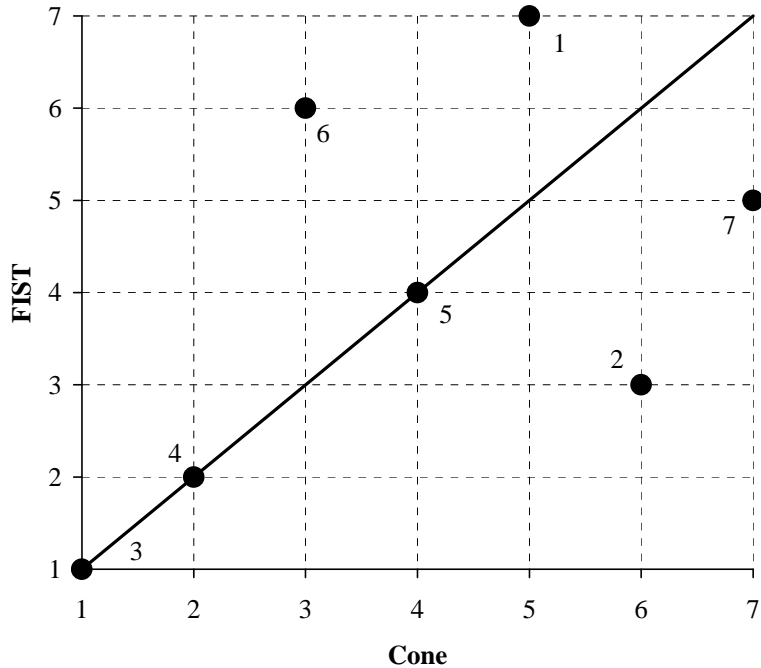
Figure 7. Comparison of critical heat flux rankings of used vehicle materials from the Cone Calorimeter and the FIST.

For the comparison of the performance of the used materials in the Cone Calorimeter/FIST and the horizontal flame spread apparatus only those materials available for the horizontal flame spread were considered. It is clear that the ranking of the horizontal flame spread tests has no method to differentiate between materials that exhibit no flame spread whereas the Cone Calorimeter and FIST use data that can be ranked. This limitation in the ranking of the horizontal flame spread data is evident in this analysis.

As indicated in the previous section, comparison of the Cone Calorimeter and horizontal flame spread ranks shows that a reasonable correlation between the ignition temperature and the propensity to spread can be seen for materials 2 and 7 where the test conditions were the same. Material 5 spread under different conditions and thus cannot be compared. Despite this correlation, no consistent ranking can be obtained between the three tests. Clearly FMVSS 302 corresponds to a more complex scenario that includes more variables than just ignition. This is an important observation since this test is intended to represent a criterion for ignition.

Further examination of the results show that both the Cone Calorimeter and the FMVSS 302 apparatus ranked Material 7 last among the used materials. The critical heat flux obtained from the Cone Calorimeter for this material was 8.3 kW/m^2. Furthermore, it was found that Material 9 failed the FMVSS 302 apparatus test and its critical heat flux in the Cone Calorimeter was determined as 10.7 kW/m^2. All of the other materials tested in the FMVSS 302 passed and had critical heat fluxes above 11 kW/m^2. It will be tempting to set an equivalency between the two tests where a threshold of 11 kW/m^2 could be established as a common pass/fail criterion. This will be inappropriate due to the limited number of test results presented here, but also because there are no physical arguments to support such an equivalency.

With only a limited number of new materials available for this study, it was not possible to perform a meaningful comparison between the fire performance of used and new materials.

8. CONCLUSIONS

- Currently there is a single test method used internationally for the fire flammability of materials used in the passenger compartments of many types of vehicle. The test method has some limitations and is only intended to provide a minimum performance standard, and therefore lends itself to be complemented by other test methods that would provide more information than a pass/fail criterion.

- Time to ignition data measured in the Cone Calorimeter and the FIST can be used to determine the ignition temperature of the materials.

- The behavior of the sample and the insulating backing introduces significant uncertainty to the interpretation of the data. Thermocouple measurements of the ignition temperature compared reasonably well with the derived values using a thermally thin approach. A semi-infinite solution that ignores the thermal capacity of the sample under predicts the ignition temperatures for all of the materials studied with the exception of Material 8, showing that some materials could conform to these assumptions.

- The ignition performance of materials tested in the Cone Calorimeter and the FIST show similar characteristics both in terms of properties obtained and relative ranking.

Nevertheless, for these particular materials, the experimental configuration of the FIST seems to lead to greater uncertainty.

- A correction for heat losses through the insulation provides only a marginal improvement to the results. The improvement is well within the experimental error.

- No direct correlation between the ranking of the Cone Calorimeter, the FIST and FMVSS 302 could be discerned. However, materials with the lowest predicted ignition temperature using the thermally thin approach were found to exhibit sustained flame spread in the FMVSS 302 test.

- The FMVSS 302 is intended to be a test that identifies the ignitability of materials to be used in vehicles. These tests have demonstrated that for materials characteristic of vehicles, there is no correlation between conventional ignition tests and the FMVSS 302 test.

- Horizontal flame spread tests using the FIST might show a better correlation with FMVSS 302, nevertheless, this study did not consider that comparison since it escaped the objectives of the test.

9. ACKNOWLEDGEMENTS

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