



Fire behaviour of plastics for electrical applications

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Abstract

To determine the fire resistance of materials for low-voltage switchgear and controlgear appliances, the glow wire test is widely used throughout the European Union as described by IEC standards. This approach to fire hazard assessment is criticized by experts in fire science as well as rescue services and insurance companies. To determine if the glow wire and other bench-scale test methods can assure that the criteria of a basic fire risk assessment are met, a set of 10 materials from the European market for low-voltage switchgear and controlgear was tested by different methods. As classification tests, the glow wire tests and 50 W vertical test methods were employed. It was investigated if heat release based methods, the cone calorimeter test and the pyrolysis combustion flow calorimeter, might contribute to the definition of better standards. An approach to vertical cone calorimeter testing is discussed.

The information gained of the materials' fire behaviour by the various test methods shows clear deficiencies in the currently employed fire hazard assessment according to IEC standards. Short-term modifications and alternative approaches for a better fire hazard assessment are proposed. In addition, an evaluation of the single burning item apparatus as a test-bench for full-scale tests is given.

Key words: fire hazard assessment, bench-scale tests, electrical fire, heat release, switchgear, controlgear, glow wire test

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Summary

The fire hazard posed by polymeric materials which find use as enclosures for electrical appliances are nowadays assessed by bench-scale test methods that employ overheated wires or small flames. Within the IEC standardization scheme, the glow wire test is the recommended tool for testing end products or parts of low-voltage switchgear. In parallel, the scientific community developed heat release based bench scale tests which are extensively applied to study the fire behaviour of polymeric materials. The most prominent example is the cone calorimeter test (ISO 5660-1) and recently, a micro-calorimetric method, the pyrolysis combustion flow calorimeter emerged as a promising technique.

In this study, the ignitability and combustion behaviour of a set of ten materials that were supplied by a number of leading manufacturers of low-voltages switch-gear on the European market was assessed using the methods named above. The materials were formulations based on the polymers: high density polyethylene (HDPE), high impact strength polystyrene (HIPS), low density polyethylene copolymer (LDPE-co), polyamid 66 (PA), polycarbonate (PC), polycarbonate-acrylonitrile butadiene styrene (PCABS), polypropylene (PP), polyvinylchloride (PVC) and unsaturated polyester (UP). All but one formulations contained flame-retardents and all but one formulation were thermoplastic materials. A set of fire safety criteria was formulated in order to evaluate if the information gained from the bench-scale test methods can ensure the right selection of materials for a safe operation of the equipment.

The tests of the materials with the glow wire method (IEC 60695-2-12 and -13) showed that this test method alone cannot ensure that a sufficient level of fire safety is met. The test is biased by a changing contact area between the glow wire and the material, even for identical materials tested at different temperatures and thicknesses. Melt flow and sample deformation was for all cases tested a beneficial process that led to a withdrawal of material from the heat source and extinguishment. Therefore the conclusion drawn cannot be expected to apply to a wider fire hazard assessment. It was shown that the ranking obtained by the test does not give sufficient information on the flammability of the materials. A simple method is described that allows determining the materials with the worst performance. Used in such way, the glow wire test might be used as a first step to take decisions on further testing. The glow wire should however not be used as the single criteria for a fire risk assessment.

Testing with a 50 W vertical flame (IEC 60695-11-4 and -10) showed that several of the materials tested underperformed in this test, which is not generally required for certification of low voltage switchgear in Europe. 5 materials did not reach a qualification, 3 materials were ranked V-2 and one material V-0. A further material has a suspected V-0 ranking but samples could not be prepared in a satisfying manner. The evaluation concentrated thus on the V-2 class of materials. The V-2 class accommodates materials of widely different inherent flammability as extinguishment might occur due to that the flaming part falls from the specimen. Therefore, materials with a high inherent flammability and strong melt flow are considered equal to materials with considerably lower inherent flammability which might yield a miniscule flaming droplet. This classification can therefore not be considered as suitable to make decisions on fire safety. Conclusion on the V-0 class of material behaviour could not be drawn as there were too few such materials. In terms of a fire risk assessment, the lack of information on deformation and mechanical integrity given by the small flame test points out a need for complementary tests.

Both calorimetric test methods were successful in identifying the least flammable and most flammable materials. Further a measure of the worst case heat release is given, along with the smoke and carbon oxide levels that might be expected. Thereby, important information is gained that gives a much wider perspective for decision making for a fire safety assessment. As both calorimeters use very high external heat fluxes to force combustion, information on ignitability and extinguishment by a small flame source or over-heated wire cannot be drawn using today's methods of data evaluation. The impact of flame inhibiting additives is smaller in the calorimetric methods than in the small scale bench test. Especially the pyrolysis flow combustion calorimeter does not yield such information. Therefore, no ranking of seven of the ten materials with intermediate to low performance was obtained by using the calorimetric methods.

Vertical cone calorimeter measurements could be used to identify the materials that could withstand a high thermal impact without melt flow and with limited deformation. Such experiments are however very difficult to conduct on liquefying materials. These difficulties are discussed in some detail. The potential for pool fire formation can however be determined. A comparison to horizontal cone calorimeter measurements can be very useful to identify where the horizontal measurements might not apply well to real life applications with vertical orientation.

The single burning apparatus was evaluated as a test bench for full scale test for future research projects. The design of the apparatus allows an easy and realistic installation of switchboard on the mock-up walls. Smoke gases can be handled and the heat release rate measured should ignition result in fire propagation that spreads to the whole apparatus. Due to the erratic behaviour of melting materials, many different ignition scenarios need to be evaluated. The design of a suitable electrical ignition source remains to be the principal challenge.

In the sections Conclusions and Future work, recommendations for improvement of bench scale fire testing methods for both the short and long term are given. The results of this study show a clear demand for a better exchange of information between fire testing laboratories and appliance designers. New standard protocols ought to give very comprehensive performance levels that inform the designer about the material's limit of fire resistance and about the consequence of failure of the materials at question.

Sammanfattning

Brandrisken med polymera material i höljen till el-apparater utvärderas i nuläget med enkla småskaliga laboratoriemetoder där en glödtråd eller en liten låga utgör antändningskällan och där informationen från provningen är av typen godkänd/icke-godkänd. Inom IEC-regelverket används glow-wire metoden för tester på slutprodukter och delar av kopplingsdosor för lågspänningsapplikation. Parallellt används avancerade kalorimetriska laboratoriemetoder baserade på mätning av värmeutveckling allt mer inom forskarvärlden för att studera brandegenskaperna hos polymera material. Den mest välkända av dessa metoder är konkalorimetern (ISO 5660-1) och nyligen har en lovande mikrokalorimetermetod tagits fram.

De ovan nämnda metoderna har i denna studie applicerats för att studera antändnings- och förbränningsbeteendet för en serie av tio olika polymera material som tillhandahölls av på den Europeiska marknaden ledande tillverkare av el-kopplingsdosor. De undersökta materialen var formuleringar baserade på följande polymerer: hög-densitet polyeten (HDPE), låg-densitet polyeten sampolymer (LDPE-co), polyamid 66 (PA), polykarbonat (PC), polykarbonat-akrylonitril butadien styren (PCABS), polypropylen (PP), polyvinylklorid (PVC) och en omättad polyester (UP). Samtliga material förutom ett var flamskyddade och endast ett av materialen var en hårdplast. En uppsättning brandtekniska kriterier ansattes i studien för att utvärdera om de enkla laboratoriemetoderna ger tillräcklig information för ett riktigt materialval för en säker produkt.

Provningar med glow-wire metoden (IEC 60695-2-12, 13) visade att denna metod ensam inte kan garantera att en tillräcklig brandsäkerhet erhålls. Testresultaten påverkas starkt av förändringar i kontaktytan mellan glödtråden och provmaterialet genom smältning och deformation av materialet och kan ge tveksamma resultat. Detta gäller även för identiska material provade med varierad tjocklek och varierad temperatur. Smältning och deformation var i samtliga fall resultatmässigt till fördel för det provade materialet då det ledde till ett materialflöde bort från glödtråden och att materialet slutligen självslocknade. Med anledning av detta kan inte några långtgående slutsatser om brandsäkerhet dras av testresultaten. Provningarna visade att rankningen från glow-wire testen inte gav tillräcklig information om materialens brandbeteende. En enkel metod beskrivs med vilken man kan identifiera materialen med de sämsta brandegenskaperna. Använd på detta sätt kan glow-wire metoden vara ett första steg för att lägga grund för fortsatta provningar. Det är helt klarlagt att glow-wire metoden inte skall användas som enda kriterium för en brandriskbedömning.

Provningar med en 50-W vertikal liten låga (IEC 60695-11-4 and -10) visade att flera av de testade materialen gav dåliga testresultat. Man bör tillägga att denna provningsmetod inte normalt krävs i Europa för kopplingsdosor för lågspänningsapplikation. 5 av materialen visade på testresultat under metodens rankningsgräns, 3 material fick den lägsta rankningen V-2, ett material fick den högre rankningen V-0 och ytterligare ett bedömdes vara ett V-0 material. Utvärderingen av provningarna fokuserade på mellanskiktet, V-2 materialen. Denna klass av material består av material med stor spridning i brandegenskaper, då materialet kan slockna under provningen genom att den brinnande nedre delen av provkroppen smälter av och separeras från huvuddelen av provkroppen. Därför kan ett mycket brännbart material med ett högt smältflöde bedömas likvärdiga med ett avsevärt mindre brännbart material som endast ger upphov till en liten brinnande droppe. När det gäller klassen V-0 material så kan man inte dra några slutsatser från provningsresultaten då antalet sådana material som ingick i undersökningen var allt för litet. Slutsatsen är att provningsmetoden inte ger generell tillämpbar information för en helhetsbedömning av ett materials brandsäkerhet. Detta beror till stor del på att provningsresultaten inte ger någon information om ett materials mekaniska integritet och

deformation vid kontakten med den lilla lågan och detta pekar på ett behov av kompletterande provningar.

De två kalorimetriska metoderna som ingick i undersökningen kunde båda tydligt identifiera de minst brännbara och de mest brännbara materialen. Metoderna ger mått på maximal och total värmeavgivning och från konkalorimetern får man också information om producerad rök och huvudsakliga förbränningsgaser. Denna mer omfattande information ger en betydligt bättre grund för en utvärdering av en produkts brandsäkerhet. Då båda kalorimetrarna exponerar provmaterialet för ett konstant högt värmefflöde ger metoderna begränsad information om antändningsegenskaper vid exponering för en liten låga eller en överhettad el-ledning. Med ett speciellt provningsförfarande och resultatutvärdering för konkalorimetern kan man dock få information också om låga antändningsenergier. Effekterna från flaminhibitorer är mindre vid provningar med de kalorimetriska metoderna jämfört med de enkla småskaliga laboriemetoderna. Mikrokolorimetern ger i princip inte någon information alls om effekterna från flaminhibitorer. Därför kunde man inte separera brandegenskaperna tillfredställande för material med dåliga till medelgoda resultat, vilket var 7 av de 10 testade materialen.

Konkalorimeterförsök med provkroppens yta exponerad i vertikal position användes för att identifiera material vilka kunde klara en hög värmeexponering utan att rinna och deformeras. Den här typen av experiment är svåra att utföra på smältande material och dessa svårigheter diskuteras i rapporten. Men ett materials potential för att rinna och orsaka en poolbrand kan utvärderas med metoden. En jämförelse med normala konkalorimeterförsök med provytan exponerad i horisontell position kan vara värdefullt för att klargöra relevansen av de normala mätningarna för applikationer med vertikal orientering.

SBI-apparaten utvärderades för användning vid fullskaliga experiment med kopplingsdosor i framtida forskningsprojekt. SBI-uppställningen tillåter en enkel och realistisk montering av kopplingsdosan på en av uppställningens obrännbara väggar. Rök-gaser från försöket samlas upp och värmeavgivningen från en mer omfattande brand i dosan kan mätas med SBI-apparatens analysystem. Då ett smältande material många gånger beter sig på ett icke förutsägbart sätt krävs det att ett större antal antändningsscenarier utvärderas. Också utformningen av en lämplig elektrisk antändningskälla återstår att ta fram.

Baserat på den här genomförda undersökningen ges rekommendationer avseende de enkla småskaliga laboriemetoderna, både i ett kort och i ett långt perspektiv. Studien visar tydligt på ett behov av bättre informationsutbyte från brandtest av material till designarbete med slutprodukten. Nya standarder och kravspecifikationer bör ge mer omfattande krav på materialprestanda, vilket också skall informera produktutvecklaren om materialets brandtekniska begränsningar och om konsekvenserna av en eventuell brand i materialet.

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1 Introduction

On the issue of fire safety, considerable confusion reigns amongst the principal actors on the market for low voltage switchgear and controlgear in Sweden. The Swedish rescue services, backed by insurance companies, point out that current standards, which are essentially based on the glow wire test and small test flames, do not provide a reliable level of safety. Tailor made solutions for different sectors of industry, e.g. agriculture, are being defined in order to balance the acceptable risk for the insurer and the need of coverage for the users. Whilst statistical evidence on the extent of the problem is scarce, empirical evidence has been provided that a number of products can be ignited with ease resulting in uncontrolled fires. Rescue services are naturally interested in a reduced use of materials that pose such a threat and demand a higher level of safety for the users of the appliances.

There is considerable uncertainty among producers of low voltage switch and controlgear whether the performance criteria set to the product by current IEC standards are sufficient, given the limited information obtained by applying the prescribed test methods. A standard that represents a good level of safety and allows innovative design is sought after. Designers often lack insight into fire safety issues and rely merely on the classification given by today's bench scale tests. This requires however that there is an absolutely reliable result from these tests, which gives freedom of design once the right material choice is made. Recent studies have shown that this is far from true [1]. The industry further has an interest in positive discrimination from inferior products by means of reliable tests. Global marketing of products fosters a demand for all-in-one solutions to meet the requirements on the European and American market. Common experience is however that good performance in one test does not necessarily ensure the same outcome in another test.

In summary, demands from all the actors point toward a common interest that is the improvement of the test methods used to determine the fire hazard posed by materials that are widely-used for the products in question. This study addresses these demands by evaluating both state-of-the-art bench scale test that are widely used and more recent test methods that emerged in the scientific community. The former are the glow wire test and vertical flame test. The latter are heat release based methods, the cone calorimeter and pyrolysis combustion flow calorimeter. For this purpose, a sample of 10 materials that find widespread use in low-voltage switchgear and controlgear was selected with the help of an industrial consortium that stands for a very significant share of the European market. Most fire safety concern results from the use of thermoplastic materials that by definition tend to deform and flow when subjected to abnormal heating. Naturally, this study's focus lies on this type of material. The enclosure of the appliance is often the part which stands for most of the thermoplastic material by volume and weight. Simultaneously, fire safety standards put on the enclosure material are the lowest. Therefore the study puts special emphasis on polymeric materials used for enclosures. This work has been inspired by a recent study performed for products on the American market [2,3]. One significant difference between both sets of materials is the more widespread use of brominated flame retardants in the U.S. This difference and the incidents reported by rescue services led us to investigate both materials and bench-scale test performance for the European market.

1.1 Purpose of the study

The purpose of this study is to contribute to finding an answer to the following questions: What information is provided by classifying the materials with the bench scale tests that are currently applied? What information is not provided? What is the potential benefit of more recent, heat release based test methods that emerged in the scientific community for regulatory purposes? Can fire safety criteria for low-voltage switchgear appliance be met by a materials selection approach?

We want to give a comprehensive picture of what information is gained from the various materials tests and show the tests' limitations. Thus, we hope to prevent safety illusions and foster the development of innovative testing and design solutions that overcome the undeniable limitations given by many materials within a certain price-range.

The study provides data on the performance of a small but widely used sample of materials from the European market of low voltage switchgear and controlgear appliances.

1.2 Fire safety criteria

As the basis of an evaluation of test methods for fire risk assessment, the criteria for the evaluation should be clearly stated. The following criteria were formulated by Babrauskas and Simonson [1] for electrical appliances. They shall serve as a basis for this study.

- Electrical components of the appliance should be designed as to minimize the possibility of overheating and starting a fire.
- If an electrical fault occurs and leads to overheating and fire, effective barriers or enclosures must be provided so that the fire will not propagate and ignite external objects.
- If the appliance has combustible external parts, small external ignition sources impinging on the appliance must not cause a large flaming fire.

In addition to these criteria, the toxicity of gases evolving from a burning appliance must be considered. The above criteria being fulfilled, there should be no concern about toxicity, as fire propagation will be limited and the fire contained. As many of today's appliances do not meet all the above criteria, the issue needs to be addressed.

The concern of this study is the fire safety of enclosure materials for low-voltage switchgear and controlgear. A few particularities that are important to the current form of IEC standards shall be commented in brief. The general rules for constructional performance requirements state that [4]: "Parts of insulating materials which might be exposed to thermal stresses due to electrical effects, and the deterioration of which might impair the safety of the equipment, shall not be adversely affected by abnormal heat and by fire." To ensure that this holds, the standard proposes to use either the glow wire test or the hot wire ignition and, where applicable, arc ignition tests. The latter both test are not considered here as will be explained in the limitations given below. The conditions for the glow wire test are further specified as: "Parts of insulating materials necessary to retain current-carrying parts in position shall conform to the glow-wire tests of 8.2.1.1.1 at a test temperature of 850 °C or 960 °C according to the expected fire hazard. [...] Parts of insulating materials other than those specified in the previous paragraph shall conform

to the requirements of the glow-wire test of 8.2.1.1.1 at a temperature of 650 °C.” Allowing tests to be made “on any parts of identical material having representative cross-section” and the clause “Alternatively, the manufacturer may provide data from the insulating material supplier to demonstrate compliance with the requirements.” effectively allows the glow wire test to be used for materials only in stead of testing the end product. No other reference to fire testing is made in the general rules.

The enclosure material is by definition not retaining current carrying parts. As such, it is not the first material to fulfill the role of a fire barrier. However, it cannot be excluded that the enclosure material is subjected to abnormal heat from live parts. This is the obvious reason to use the glow wire test for such materials within IEC regulation. The proximity of the enclosure material to the live parts in today’s highly compact devices makes the exposure to a small flame a likely scenario. For instance, many materials that full-fill today’s most stringent requirements, a glow wire flammability of 960 °C and V-0 rating or better, may produce a small to medium size flame as long as the material is in direct contact with the overheated conductor or an electrical arc. This totally justifies the scenario of an open flame applied to the enclosure for a short time. Limited oxygen access within the enclosure is an important factor. However, the electrical source of the heat produced leads to the persistence of flames even in oxygen-depleted environment. Hence, the enclosure should not be easily ignited to self-sustaining burning by small flames, should contain such flames within the apparatus and not spread flames to the surrounding by burning droplets.

Limitations:

The scope of this study excludes other scenarios where the device can be rightly regarded as a victim of fire. Such scenarios would be a burning trash bin underneath the device, or the contribution of the device to the development of a room fire which originates from other sources such as furniture. Toxicity could not be addressed within this study, due to limited resources. As the current state of the art of materials testing is the focus of this study, design criteria of the appliances are not considered.

As this study concerns fire testing standards for electric equipment, it may surprise that no standard was included that simulates arc ignition. It was evaluated whether the high current arc ignition (HAI) test should be included in the study. The test has a reputation as being non-reliable and was never widely accepted in the fire science community. Performing tests with the HAI on the one and only instrument available in Sweden would have consumed almost half the budget of this project. Correspondence with Underwriters Laboratories Inc. (USA) revealed that a new apparatus using direct current is being developed. [5]. Likewise, the hot wire ignition test (HWI) was not considered in this study as a withdrawal of this standard is considered by the responsible technical committee TC89 of IEC due to problems with the repeatability of the test method.

1.3 Methodology

Results and discussion within this study are mainly organized into three sections. The first section examines bench scale test as defined by IEC standards, the glow wire test and 50 W vertical flame test. The second section is concerned with heat release based methods, the horizontal cone calorimeter test and the pyrolysis combustion flow calorimeter. A third section presents an adapted version of the vertical cone calorimeter test that was used to study the materials flow behavior under fire conditions. To separate facts from wider conclusions, each section describing standardized tests is clearly subdivided into a mere report of the measured data, followed by a critical discussion of

the significance of the obtained data. Additionally, a short evaluation of the single burning apparatus as a test bench for full scale testing in future research projects is given. All testing has been conducted on state-of-the-art equipment strictly respecting the standards. Any deviation from the standard protocol is highlighted.

2 Experimental methods

A description of the materials and test methods is given in this section. Glow wire testing, vertical flame testing, cone calorimeter testing and thermal imaging were performed at SP Fire Technology facility in Borås (Sweden). Pyrolysis combustion flow calorimetry and thermal gravimetric measurements were conducted at Bundesanstalt für Materialprüfung in Berlin (Germany).

2.1 Material properties and processing

Table 1-1 provides an overview of the processing methods used to produce flat sheets from the materials that were tested. In most cases processed materials were provided by the industry consortium supporting this study. In a few cases the processing was performed by a compounding company with broad experience of the materials.

Table 1-1: Materials and processing methods used.

| Material | Process | Comment |
|-----------------|----------------------|---------------------------------|
| HDPE | Compression molding | |
| HIPS | Injection molding | Blend of two PS grades |
| LDPE-co | Compression molding | |
| PA | Injection molding | |
| PC | Injection molding | |
| PCABS-1 | Flat-sheet extrusion | |
| PCABS-2 | Injection molding | |
| PP | Compression molding | |
| PVC | Compression molding | Material intended for extrusion |
| UP-GF | Compression molding | Insufficient form filling |

Specimens for the cone calorimeter, vertical flame and glow wire test were using a band saw and any particles were removed from their edges.

A few selected properties of the materials studied are presented in Table 1-2.

Table 1-2: Selected material properties.

| Material | Polymer resin | Principle flame retardant | Tensile modulus (GPa) | Density (kg m⁻³) | Dielectric strength (MV m⁻¹) | Area of application |
|-----------------|---|--|------------------------------|------------------------------------|--|--|
| HDPE | High-density polyethylene | metal hydroxide | ~ 1 | - | - | Enclosures |
| HIPS | High-impact Polystyrene | low amount of halogen. FR & probably metal hydroxide | 2-3 | 1000 | - | Enclosures |
| LDPE-co | Polyethylene copolymer | non-halogenated FR | < 0.5 | 1200 | - | Flexible parts of enclosure, Cables, Plugs |
| PA | Polyamide 66 | non-halogenated, nitrogen-compound FR | 5-7 | 1300 | - | Enclosures |
| PC | Polycarbonate | not known | 2-3 | 1200 | 16-20 | Enclosures |
| PCABS-1 | PC & Acrylo-Butadiene-Styrene | probably phosphorus | 2-3 | 1200 | 31-35 | Conduits |
| PCABS-2 | PC & Acrylo-Butadiene-Styrene | none | 2-3 | 1200 | 26-30 | Enclosures |
| PP | Polypropylene | metal hydroxide | < 1 | 1300 | - | Flexible parts of enclosure, Cables, Plugs |
| PVC | Polyvinylchloride | chlorine in polymer | 2-3 | 1500 | 16-20 | Electrical conduit |
| UP-GF | Unsaturated polyester, glass fiber reinforced | halogenated FR | 8 - 10 | 1700 | 10 - 15 | Enclosures |

2.2 Glow wire test for materials (IEC 60695-2-12 and -13)

All tests were conducted according to IEC 60695-2-12 and IEC 60695-2-13. A short description of the test method and details on sample handling and calibration are given below.

In a glow wire test a 4 mm thick nickel/chromium (80/20) wire, bend to 1 cm radius, is heated to a given temperature in the range 650 °C to 960 °C. It is pressed on the front surface of the specimen with a slight force of 1 ± 0.2 N. The glow wire is applied for 30 s at equal current supply without compensation for the temperature decrease or increase at the glow wire tip (the temperature change was observed to vary with as much as ± 100 °C for the specimens tested). The glow wire tip is allowed to penetrate the sample with a maximum displacement of 7 ± 0.5 mm from the specimen front surface. After 30 s the glow wire is withdrawn. The time to ignition and time to extinguishment are recorded. A paper indicator is placed 200 mm underneath the glow wire and it is recorded whether or not flaming droplets ignite the paper indicator.

Two indices are defined that describe the performance of the material, i.e. Glow wire ignition temperature and the Glow wire flammability temperature [6,7]:

Glow wire ignition temperature (GWIT)

The temperature which is 25 K (30 K between 900 °C and 960 °C) higher than the maximum temperature of the tip of the glow-wire which does not cause ignition of a test specimen of given thickness during three subsequent tests. Ignition is defined as a flame that persists for longer than 5 s.

Glow wire flammability temperature (GWFI)

The highest test temperature, during three subsequent tests for a test specimen of a given thickness, at which one of the following conditions are fulfilled:

- a) flames or glowing of the test specimen extinguish within 30 s after removal of the glow-wire and there is no ignition of the wrapping tissue placed underneath the test specimen;
- b) there is no ignition of the test specimen.

Sample preparation and conditioning:

All specimens were cut from compression or injection molded plates 1.5 and 3 mm thick. All specimens were stored at room temperature and 50 % relative humidity for at least 48 h before testing.

Calibration:

Temperature calibration with a silver foil and a control of the contact force were performed. In addition to requirements in the standard the time for the temperature of the glow wire to cool from 960 to 600 °C was recorded. For the instrument used here, this time amounted to 51 s. This number can vary between different equipments, and might have some influence on the results.

2.3 50 W Vertical flame test (IEC 60695-11-4 and -10)

All tests were conducted according to IEC 60695-11-4. This IEC standard corresponds to the American standard UL 94. A short description of the test method and details on sample handling and calibration are given below.

A 50 W flame is applied to the lower end of a specimen measuring 125x13x1.5 and 125x13x3 mm³ respectively. The duration of the flame application is 10 s, after which the afterflame time t_1 is recorded. If the specimen extinguishes, the flame is applied for a further 10 s and the afterflame time t_2 and the afterglow time t_3 are recorded. The specimen is placed 30 cm above a cotton pad. Whether or not the cotton indicator is ignited by flaming droplets affects the classification which is given in Table 1-3.

Table 1-3: Vertical burning categories according to IEC 60695-11-10 [8].

| Criteria | Category | | |
|--|----------|---------|---------|
| | V-0 | V-1 | V-2 |
| Individual test specimen afterflame time (t_1 and t_2) | < 10 s | < 30 s | < 30 s |
| Total set afterflame time t_f for any conditioning | < 50 s | < 250 s | < 250 s |
| Individual test specimen afterflame plus afterglow time after the second application ($t_2 + t_3$) | < 30 s | < 60 s | < 60 s |
| Did the afterflame and/or afterglow progress up to the holding clamp? | No | No | No |
| Was the cotton indicator pad ignited by flaming particles or drops? | No | No | Yes |

Sample preparation and conditioning:

All specimens were cut from compression or injection molded plates 1.5 and 3 mm thick. All specimens were stored at room temperature and 50 % relative humidity for at least 48 h before testing. A second set of specimen was conditioned at 70 °C for $7 \times 24 = 168$ h and cooled to room temperature in a dessicator with dry air before testing. The PCABS2 specimens were only 120 mm long in stead of 125 mm.

Calibration:

The burner calibration was checked with the copper block method described in IEC TS 60695-11-4 [9].

2.4 Cone calorimeter (ISO 5660-1)

All horizontal cone calorimeter tests were conducted according to ISO 5660-1. A brief description of the method is given below, together with the specific test conditions used and details on sample handling and calibration. A detailed discussion on the interpretation of the results from a cone calorimeter test is given in conjunction with the presentation of the results in section 3.2.1.

In the cone calorimeter a sample with a 10x10 cm² surface area, typically a few millimetres thick, is exposed to a uniform heat flux in the range of 20 to 90 kW/m² [10]. The cone heater used to impose the heat flux is shown in Figure 1-1. Thermoplastic specimens typically ignite within the first minutes of the experiments and the major part of the organic material is consumed as the cone heater maintains the heat flux even as the sample burns. The heat released from a burning object is for the wide majority of materials proportional to the amount of oxygen that was consumed [11]. The cone calorimeter uses this principle to calculate the heat released by the material through measuring the oxygen level in the combustion gases. Other gas analysers determine the carbon monoxide and dioxide production and a laser device measures how much light is absorbed by the smoke produced. A cone calorimeter from Fire Testing Technology (United Kingdom) was used.



Figure 1-1: Sample compartment of the cone calorimeter.

Sample preparation and conditioning:

Compression or injection moulded plates of 3 mm thickness were tested. All samples were conditioned at room temperature and 50 % relative humidity for more than 48 h before testing.

Test conditions:

An external heat flux of 35 kW m⁻² was applied. Triplicate measurements were performed.

Calibration:

Gas analyzer, smoke detector, heat flux and C-factor calibration was performed on each day of testing.

2.5 Pyrolysis Combustion Flow Calorimeter

The principles of the test method and the test procedures used are described below. A detailed discussion on the interpretation of the results from a pyrolysis combustion flow calorimeter test is given in conjunction with the presentation of the results in section 3.2.2.

The Pyrolysis Combustion Flow Calorimetry (PCFC) uses a pyrolyser to heat up a small amount (1 - 5 mg) of sample with a constant heating rate ranging from 1 to 4 °C s⁻¹ in a nitrogen atmosphere [12]. The volatile degradation products from the sample are then mixed with oxygen and further heated in a combustor to complete oxidation. The oxygen consumption is measured and used to determine the heat release. This measuring principle aims at simulating polymer combustion, where degradation usually takes place in an oxygen-deprived pyrolysis zone and the gases then mix with air at the sample surface to form a flame. The heat measured by the complete oxidation of the pyrolysis gases is the maximum amount of energy a flame on the material might provide for self-sustained propagation of a fire.

Sample preparation and conditioning:

3 ± 0.02 mg samples were cut from plates or pellets of the material with a scalpel to cubic shape. A microbalance was used to determine the weight of the sample before and immediately after the experiment. As the HIPS material was delivered as a blend of two pellets, both types of pellets, denoted HIPScl and HIPSw were tested.

Test protocol:

A heating rate of 1 °C s⁻¹ was used for all experiments. Faster heating rates are desirable. The variation in gas flow due to the gas evolution from the sample could however not be compensated for by the newly designed apparatus. Therefore, measurements at higher heating rates with faster degradation were not found to be reliable. The combustor was heated to a temperature of 900 °C. The gas flow rate was 100 ml min⁻¹. Duplicate to quadruplicate measurements were performed.

2.6 Thermogravimetric analysis

Thermogravimetric analysers are used to heat up samples with a defined heating rate whilst measuring the sample mass. Heating rates usually lie within 1 to 20 °C min⁻¹. The mass loss from the sample is an indicator for the temperature range and magnitude of degradation processes. By measuring the difference between sample temperature and furnace temperature, heat consuming (endothermal) or heat producing (exothermal) degradation processes can be distinguished (simultaneous differential analysis).

Sample preparation and conditioning:

10 ± 0.25 mg samples were cut from compression moulded or injection moulded plates with a scalpel to cubic shape.

Test protocol:

A heating rate of 10 °C min⁻¹ was used for all experiments. The furnace was flushed with nitrogen at a rate of 30 ml min⁻¹. A Mettler Toledo TGA/SDTA 851e was used for all experiments.

2.7 Vertical cone calorimeter

The vertical cone calorimeter is a modified version of the cone calorimeter test according to ISO 5660-1. The specific test configuration used here was developed for the purpose of this project and is shown in Figure 1-2. A sheet of material, $100 \times 100 \times 3 \text{ mm}^3$ in size, was exposed to a constant heat flux. The sample was only supported at the edges so that sample deformation and flow were not prevented. This non-supported and isolated arrangement of the specimen intends to mimic the outer shell of an electrical apparatus. Deformation, flow and flame spread over the vertical surface can be studied qualitatively. A 1 cm long needle flame was placed as a pilot flame 5 to 10 mm above the rim of the specimen holder. The tray used to catch the molten material was made of non-combustible Monolux board (density $680 \pm 50 \text{ kg m}^{-3}$, 9.5 mm thick) and was placed 10 cm underneath the lower edge of the sample holder. The heat release rate, the mass loss of the sample in the sample holder and the mass gain on the catch pan were recorded.

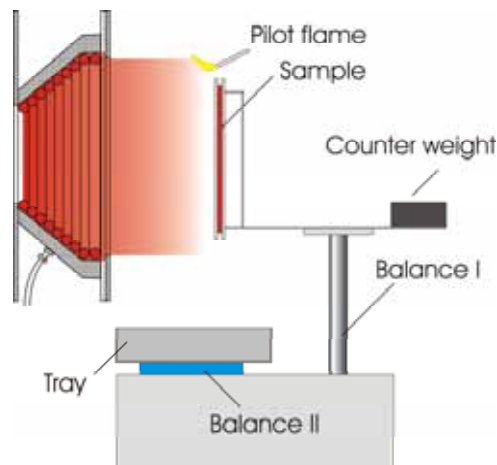


Figure 1-2: Schematic of the vertical cone calorimeter setup.

Sample preparation and conditioning:

Compression or injection moulded plates of 3 mm thickness were tested. All samples were conditioned at room temperature and 50 % relative humidity for more than 48 h before testing.

Test conditions:

External heat fluxes of 25 and 35 kW m^{-2} were applied. Two to four measurements were performed per sample type.

Calibration:

Gas analyzer, smoke detector and C-factor calibration was performed on each day of testing.

2.8 Infrared imaging

A FLIR Thermacam A40 (FLIR Microsystems, Sweden) infrared camera was used to acquire infrared videos of glow wire and vertical flame tests (Figure 1-3). The camera was operated with a measuring range of either room temperature to 500 °C or 300 to 800 °C. As the emissivity was not known for the various materials used in this study, all temperatures are reported as black-body temperatures. They do therefore not represent the actual surface temperature; a qualitative picture of the temperature distribution only is obtained. Degradation of the specimen further leads to a change in emissivity during the experiment, adding to the uncertainty. A valuable discussion of these effects was given by Kleinheinz et al. [13].



Figure 1-3: Infrared equipment used in this study.

2.9 Single burning item apparatus (SBI)

The single burning item (SBI) apparatus (EN 13823 [14]), was used as a test bench for the experiments with a full-size electrical appliance box. The SBI apparatus is normally used for classification tests of building materials according to the requirements given in the European classification standard EN 13501-1 [15].

The SBI test facility consists of a test room with the test apparatus (see Figure 1-4). The main parts of the apparatus are the trolley with the frame for mounting the sample material and the burner, and the smoke exhaust system with measurement equipment for heat release rate (by oxygen consumption method) and smoke obscuration.

The test room has an inner height of (2.4 ± 0.1) m and an inner floor length of (3.0 ± 0.2) m in both directions. The material for test is mounted in a corner configuration (see Figure 1-4) with the left wing with a size of $1.0 \text{ m} \times 1.5 \text{ m}$ and the right wing with a size of $0.5 \text{ m} \times 1.5 \text{ m}$. In an EN 13823 test the 30 kW burner are impinging on the material in the corner and heat release, smoke, flame spread and dripping are assessed [14].

The enclosures used for fire testing were installed on the left wing at a distance of 30 cm from the top and 30 cm from the corner where both wings meet. As ignition sources, a small burner with a premixed methane-air flame with a flame height of 2 cm and methamine pills (Stock code 788-141, James H. Hail, UK) were used. As a larger ignition source, a blow torch with 3 kW power (Powerjet burner with Ultramapp gas bottle, Sievert AB, Sweden) was employed.

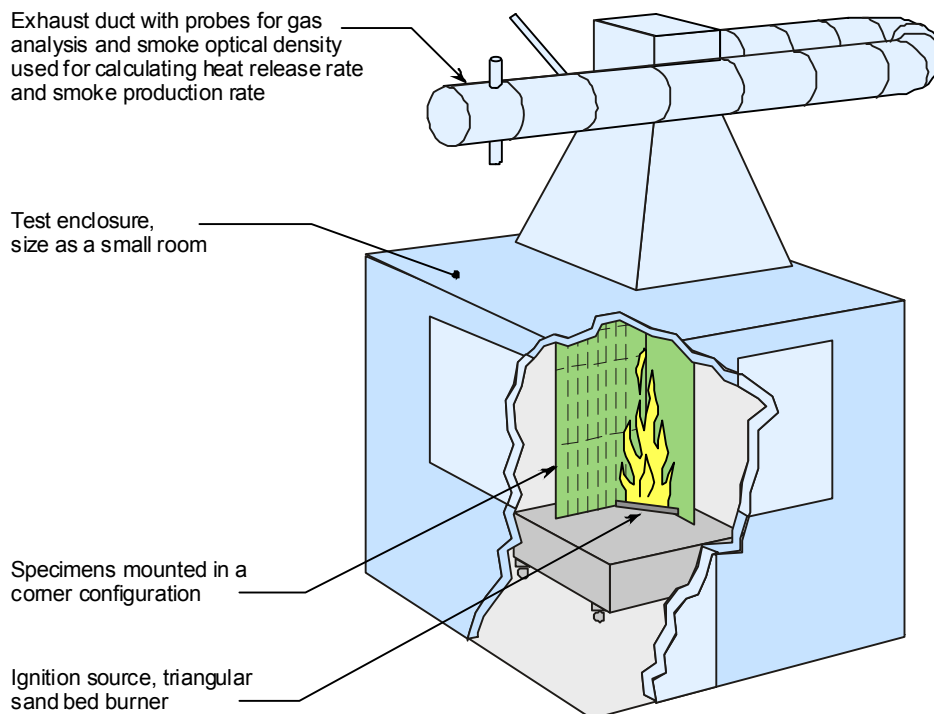


Figure 1-4: The SBI test facility (EN 13823).

3 Results and discussion

The results from both classification and heat release rate tests are reported and discussed in this section. First, an overview of the test results of the glow wire test and vertical flame test is given. The applicability of the information obtained with regards to the fire safety criteria will be evaluated. In a similar manner, the data from the heat release based test is first objectively reported, followed by a discussion of their value for the fire risk assessment.

3.1 Classification tests

The measured results for all materials in the standard bench scale tests are reported below. A discussion of the results will be given together with an evaluation of the test methods in the end of this section.

3.1.1 Glow wire test for materials

The glow wire temperatures measured for all materials are given in Figure 3-1 and Table 1-4.

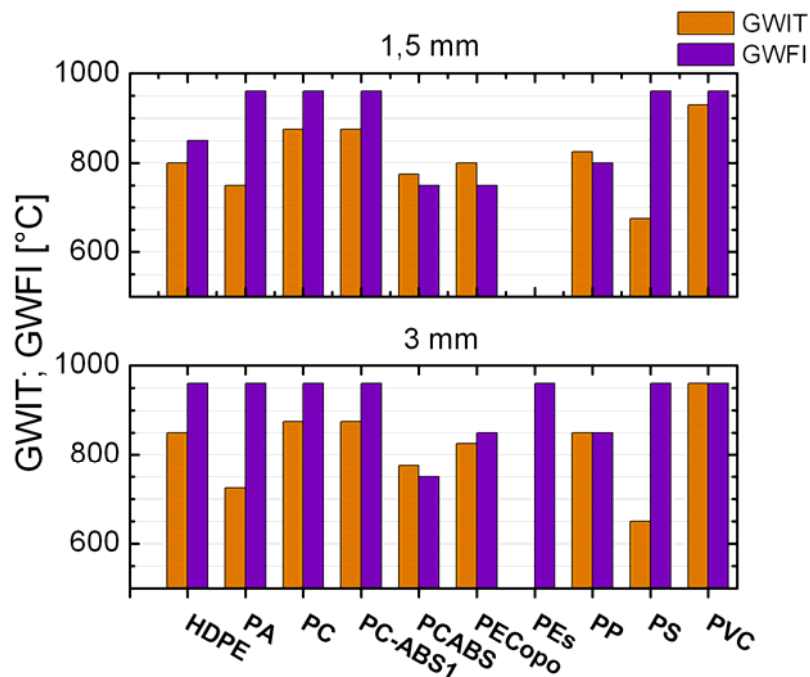


Figure 1-5: Results of the glow wire test. Glow wire ignition temperature (GWIT) and glow wire flammability index (GWFI) for specimens 1.5 and 3 mm thick.

An important observation was that none of the specimens failed the test criteria due to ignition of the wrapping tissue by flaming droplets. Overall, the wrapping tissue was ignited only once during all testing.

Table 1-4: Summary of glow wire test results.

| | Thickness mm | GWFI °C | GWIT °C | (GWFI-GWIT) °C | Observation |
|---------|-----------------|------------|------------|-------------------|-------------|
| HDPE | 1.5 | 850 | 800 | 50 | p |
| | 3 | 960 | 850 | 110 | |
| HIPS | 1.5 | 960 | 675 | 285 | g,d,p |
| | 3 | 960 | 650 | 310 | |
| LDPE-co | 1.5 | 750 | 800 | -50 | p |
| | 3 | 850 | 825 | 25 | |
| PA | 1.5 | 960 | 750 | 210 | g,p |
| | 3 | 960 | 725 | 235 | |
| PC | 1.5 | 960 | 875 | 85 | g,p |
| | 3 | 960 | 875 | 85 | |
| PCABS-1 | 1.5 | 960 | 875 | 85 | g,p |
| | 3 | 960 | 875 | 85 | |
| PCABS-2 | 1.5 | 750 | 775 | -25 | g,p |
| | 3 | 750 | 775 | -25 | |
| PP | 1.5 | 800 | 825 | -25 | p |
| | 3 | 850 | 850 | 0 | |
| PVC | 1.5 | 960 | 930 | 30 | p |
| | 3 | 960 | 960 | 0 | |
| UP-GF | 3 | 960 | - | - | |

g – forms a gap so that the glow wire is not in contact with the specimen

d – strong deformation of the specimen

p – penetration by the glow wire

3.1.2 Vertical flame test

The results of the vertical flame test according to IEC 60695-11-4 are summarized in Figure 1-6. Details of the measurements are given in Table 1-5 and Table 1-6.

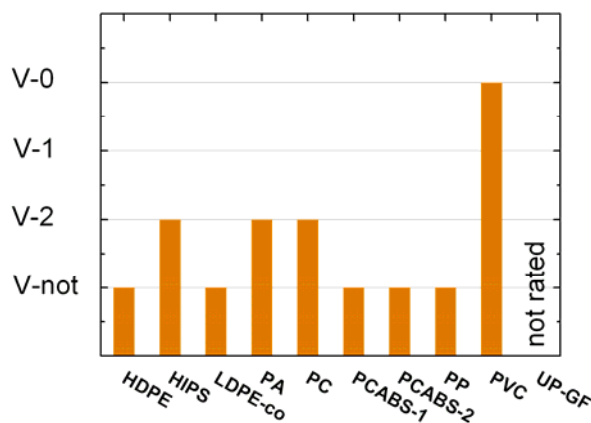


Figure 1-6: Rating of the materials in the vertical flame test. Identical ratings were obtained for both thicknesses.

For all specimens that obtained a rating, the rating was confirmed for the samples conditioned at 70 °C. In the case of the UP-GF specimen, the flame was emerging from the edge of the specimen and not from the front- and back-faces. As noted in 2.1, the UP-GF specimen could not be cut in a satisfying manner due to the glass fiber mats in the sample. The rough edge with glass fibers pointing out acts as wicks and this distorts the

result. The flame did not spread over the undamaged front surface of the specimen. The front surface of larger specimens was very hard to ignite even with a small welding flame. We suspect therefore that UP-GF would pass a V-0 ranking without the bias from the cutting. Testing recently performed by the Swedish rescue services showed that the finished product could withstand a 500 W flame without igniting. As this could not be confirmed, UP-GF will be counted as not rated (NR).

Table 1-5: Results of the vertical flame test for specimens 3 mm thick. The afterflame times $\langle t_i \rangle$ are given as average values.

| Material | $\langle t_1 \rangle$ | $\langle t_2 \rangle$ | $\langle t_3 \rangle$ | $\Sigma(t_{1i} + t_{2i})$ | dripping | category |
|-----------------|-----------------------|-----------------------|-----------------------|---------------------------|-----------------|-----------------|
| HDPE | 0 | >30 | 0 | - | yes | V-not |
| HIPS | 2 | 1 | 0 | 15 | yes | V-2 |
| LDPE-co | >30 | - | - | - | yes | V-not |
| PA | 8 | 1 | 0 | 44 | yes | V-2 |
| PC | 7 | 3 | 0 | 51 | yes | V-2 |
| PCABS | 2 | 29 | 0 | 157 | yes | V-not |
| PCABS | >30 | - | - | - | yes | V-not |
| PP | >30 | - | - | - | yes | V-not |
| PVC | 0 | 0 | 0 | 0 | no | V-0 |
| UP-GF | >30 | - | - | - | no | not rated |

Table 1-6: Results of the vertical flame test for specimens 1.5 mm thick. The afterflame times $\langle t_i \rangle$ are given as average values.

| material | $\langle t_1 \rangle$ | $\langle t_2 \rangle$ | $\langle t_3 \rangle$ | $\Sigma(t_{1i} + t_{2i})$ | dripping | category |
|-----------------|-----------------------|-----------------------|-----------------------|---------------------------|-----------------|-----------------|
| | s | s | s | s | | |
| HDPE | 8 | >30 | 0 | - | yes | V-not |
| HIPS | 2 | 1 | 0 | 13 | yes | V-2 |
| LDPE-co | >30 | - | - | - | yes | V-not |
| PA | 5 | 0 | 0 | 27 | yes | V-2 |
| PC | 6 | 6 | 0 | 58 | yes | V-2 |
| PCABS | 30 | 4 | 0 | 169 | yes | V-not |
| PCABS | 9 | 26 | 0 | 178 | yes | V-not |
| PP | >30 | - | - | - | yes | V-not |
| PVC | 0 | 0 | 0 | 0 | No | V-0 |
| UP-GF | - | - | - | - | - | not tested |

Digital photographs were taken of the samples and are compiled in Figure 1-7.

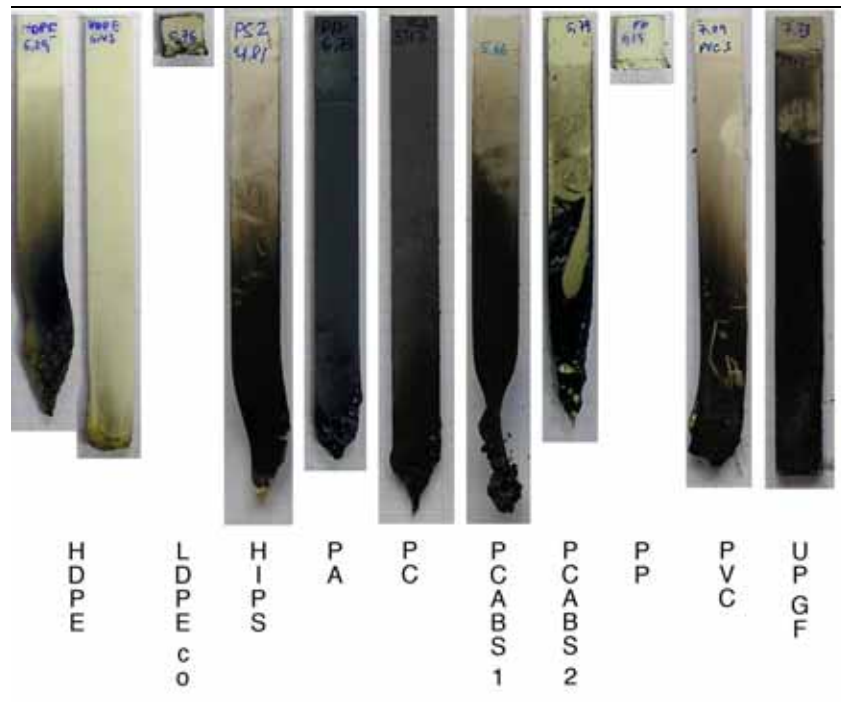


Figure 1-7: Digital photographs of the vertical flame specimens 3 mm thick. It should be noted that the HDPE specimen displayed on the left and the PCABS2 specimens were manually extinguished. Otherwise, no residue would have remained.

3.1.3 Discussion

A number of questions are worthwhile asking in order to evaluate the commonly employed bench scale tests and the materials used on the European market. First, can the fire safety criteria as outlined in paragraph 1.2 be met with the current tests and materials? Second, if the fire safety criteria cannot be met, what is the reason; what are the flaws of the test methods and the shortcomings of the materials?

Glow wire test

As seen in paragraph 3.1.1, the glow wire test results of the materials lie in the upper part of the test scale (Figure 3-1). A GWFI of 960 °C is reached by 5 of 9 materials 1.5 mm thick and 7 of 10 materials 3 mm thick. A GWFI of 850 °C, which corresponds to the threshold for materials in contact with current carrying parts [4], is reached by 9 of 10 materials 3 mm thick, versus 6 of 9 materials 1.5 mm thick. Thus, all materials qualify as enclosures for low-voltage switchgear and controlgear [4].

A comparison with the results of the vertical flame test shows that the GWFI is a poor predictor for the response of the materials to a small open flame (Figure 1-8). For materials 1.5 mm thick, a GWFI equal to or better than 850 °C appears as a threshold value to distinguish between materials that easily burn completely when in contact with a small flame and materials that at least reach a V-2 ranking (compare with Table 1-5 and Table 1-6). As a reminder, for V-2 materials, intensive melt dripping and 30 s of burning time are allowed. Their performance will be discussed in paragraph 3.1.2. For materials 3 mm thick, the GWFI must be higher than 850 °C to single out the readily burning polymers. Even with a GWFI of 960 °C, worse than V-2 performance was encountered. Using a glow wire temperature of 650 °C, as recommended for enclosures, easily ignitable materials will not be discriminated against.

Another remarkable observation is that out of the 240 glow wire tests that were performed for this study, ignition of the indicator paper underneath the specimen holder occurred only once. In the vertical flame test, ignition of the cotton indicator occurred for 8 of 10 materials. As will be seen in section 3.3, strong melt dripping was also observed for those 8 materials in the vertical cone calorimeter test. Hence, we conclude that the glow wire test is not a suitable method to judge the risk of flame spread by melt dripping.

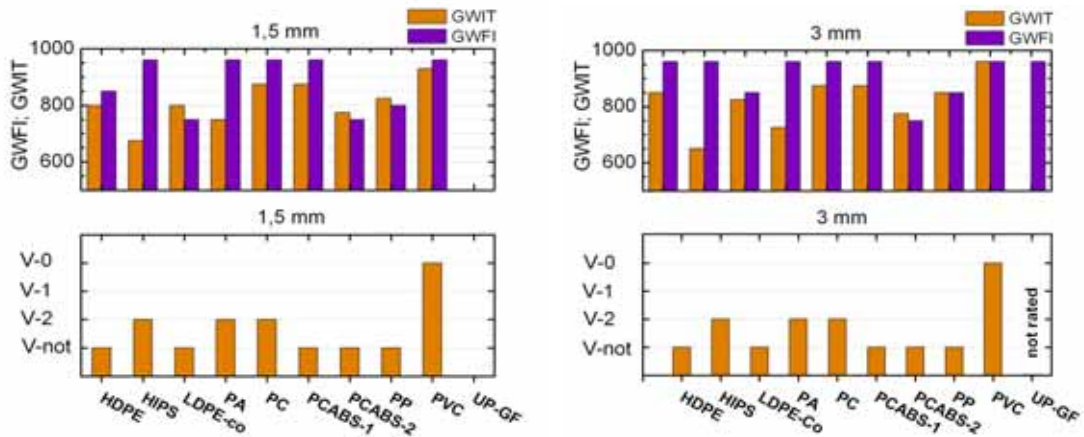


Figure 1-8: Comparison of glow wire and vertical flame test results.

Information on the ignitability of the material might be gained from the GWIT. In order to test the validity of this assumption, the GWIT of the materials was compared to the time to ignition (TTI) of the material in the cone calorimeter. The latter is a measure for material ignitability that is widely accepted by the research community. Contrary to the glow wire test, the method does not allow for any flow or removal of material from the heat source. The comparison of results from both methods is given in Figure 1-9.

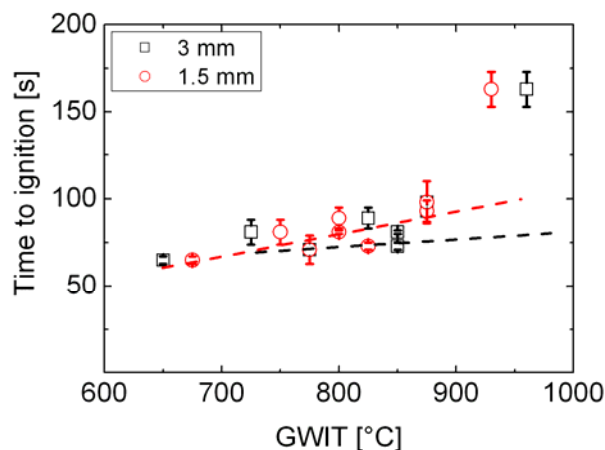


Figure 1-9: Comparison of glow wire ignition temperature and time to ignition measured in the cone calorimeter. The dotted lines represent linear regressions to the 3 mm and 1.5 mm specimens.

For both specimen thicknesses, a weak overall correlation of GWIT and TTI exists. From a safety point of view, another observation is more important. The GWIT varies considerably (675 to 875 °C) and non-consistently for materials with TTI in the rather narrow range of 65 to 98 s. A considerably higher TTI is only found for the material with a GWIT higher than 875 °C. This data suggests that the GWIT is an indicator for ignitability, but not a reliable one.

The inconsistent assessment of flammability in the glow wire test arises mainly from the rapid removal of material from the proximity of the glow wire that was observed for most of the materials in this study. PA, HIPS, PC and PC-ABS tended to melt and deform quickly and opened a considerable gap between the glowing wire and the rest of the specimen. This behavior was more pronounced for the 1.5 mm specimens. For other materials, such as HDPE, PP and LDPE-co it was observed that a char layer of the mineral filler formed around the glowing wire. This is a desirable effect. Later in the test however, this char layer and even burning material can be withdrawn from the bulk of the sample as the glow wire is removed. Burning material is transferred from the specimen and consumed rapidly in a flame flashing on the glow wire. Only UP-GF, which contains a glass fiber fabric, was under no circumstances penetrated by the glow wire. For the other samples, penetration occurs depending on material hardness and melting point at different temperatures and different stages of the experiment. All the observed effects have the consequence that the contact area and duration of application are inconsistent for different materials (Figure 1-10). Hence, the measured data becomes inconsistent.

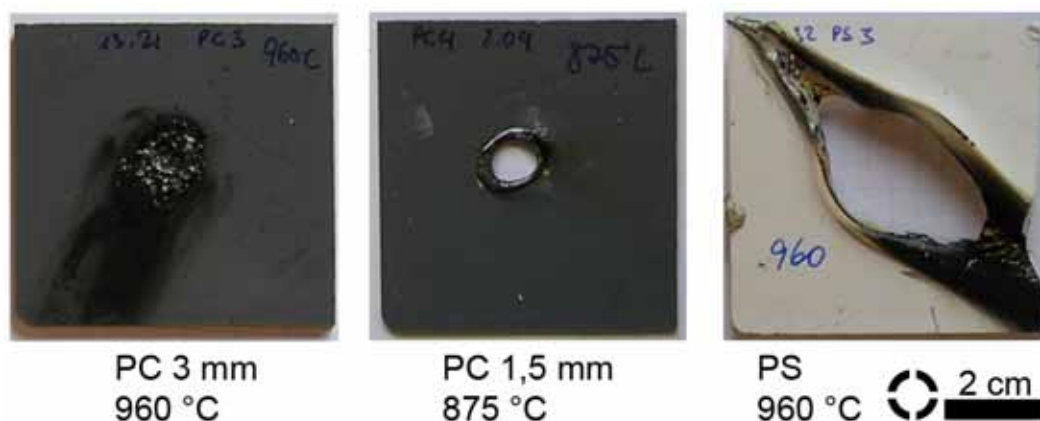


Figure 1-10: Few examples of the varying contact area in the glow wire test. The size of the glow wire tip is indicated next to the scale bar.

The lack of information on melt dripping given by the glow wire test has a simple geometrical cause. As illustrated by an infrared image of a glow wire experiment (Figure 1-11), the glow wire heats a very small area in the center of the sample, whereas the rest of the sample remains close to room temperature. Consequently, any molten material flows over the cold surface and for many materials cools sufficiently to not cause ignition of the paper indicator.

An argument that is often brought forward is that the glow wire test represents a specific scenario, the response of a material to an overheated conductor. Therefore, the argument continues, it is not supposed to judge the response of the material to an open flame and effects such as the withdrawal of material occur in reality. Yet, this cannot satisfy any fire risk assessment such as given in section 1.2. To accept that the material burns up to 60 s to pass the glow wire flammability index is proof in its own that contact with flames is an issue. Further, effects such as hole-opening by molten material are highly geometry dependent and the withdrawal of the Cr-Ni wire from the sample does not have any counter-part in reality.

An interesting change to the glow wire test protocol was proposed at the working group level of the IEC technical committee TC89 that maintains the glow wire test standard. The proposed change would disqualify materials that have a GWFI which is identical or only slightly larger than the GWIT. This change aims at eliminating materials that pass a certain GWFI, e.g. 800 °C, as they do not ignite, but as soon as ignition occurs, the sample is completely consumed. Requiring a minimum difference of for instance GWFI-

GWIT ≥ 50 °C in combination with an elevated GWFI, the most readily burning materials can be determined. Obviously, materials with a GWIT above 900 °C should be exempted from such a rule. According to the proposed scheme (see Table 1-4) HDPE 1.5 mm, LDPE-co, PCABS2 and PP would be sorted out. As can be seen from the results of the vertical flame test (Figure 1-7 and Figure 1-8) and as will be confirmed by vertical cone calorimeter measurements (section 3.3) this method successfully identifies the materials which pose the highest fire risk.

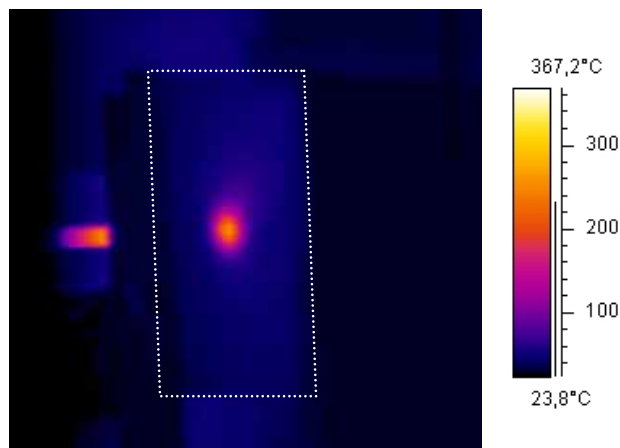


Figure 1-11: Infrared image acquired at a 45° angle of the backside of a 2mm thick Teflon sample at 28 s of contact with a glow wire heated to 800 °C. The temperature bar gives the black body temperature. The sample position is indicated by a dotted frame.

Conclusions

The glow wire test alone fails to satisfy the fire safety criteria due to:

- 1.) Resistance towards ignition by a small flame is not adequately judged.
- 2.) Flame-spread by flaming droplets is not accurately considered in the test.
- 3.) Containment of a small flame within the enclosure of the apparatus cannot be judged.

The results indicate that a glow wire flammability index of 850 °C for samples 1.5 mm thick and 875 °C for samples 3 mm thick is a threshold value for which some resistance against ignition by a small flame can be assumed. Requiring the GWFI to be at least 50 °C larger than the GWIT of a materials at identical thickness was shown to be a promising method to identify the most readily burning materials.

The glow wire ignition temperature was varying considerably and non-consistently for materials that lie within a narrow range of times to ignition in the cone calorimeter test.

The glow wire test can be used a simple low-cost method to pre-select materials for further testing. Yet, it should not be used as the sole requirement by any standard.

Vertical flame test

In the vertical flame test, five of the materials did not pass the requirements for a classification. Three materials reached a V-2 and one material a V-0 classificationⁱ. Of the materials that failed classification, three materials burned readily up to the sample holder (PCABS-2, LDPE-co, PP) and two materials (HDPE and PCABS-1) narrowly missed to qualify. The overall performance of the materials in this test is thus poor. This limits our ability to evaluate the full scale of the test method, as there are too few V-0 materials. It is

ⁱ The UP-GF material is not taken into account, as the edge effect may lead to a biased analysis.

generally accepted that the V-0 classification is a predictor for the resistance to ignitability by a small candle-like flame. The V-0 material tested here (PVC) is also part of those materials that cannot be ignited with a small flame. Never the less, it was recently questioned that a V-0 classification alone is a suitable material selection criterion to prevent electrical fires [1]. Bundy et al. have shown [3] that the V-0 classification gives an insufficient indication of the materials performance in a larger fire.

It is much more uncertain what information a V-2 classification gives about the material. In the studies of Bundy and Morgan [2,16] that attempted to correlate cone calorimeter data with data obtained by the vertical flame tests, the V-2 materials showed a considerable variation of their fire behavior. As a consequence, this section focuses on the materials in the controversial V-2 class. It is investigated how the V-2 materials studied reached their classification and how other materials failed to be classified. The multitude of behaviors observed for the materials is explained by a simplified physical description of material reaction in the vertical flame test.

Experimental details of the vertical flame test are given in Table 1-7 for: V-2 materials (PA, PC, HIPS); two materials that just failed V-2 classification (HDPE, PCABS-1); a material that clearly failed classification (LDPE-co) and clearly passed V-0 (PVC).

Table 1-7: Flame times (in s) of selected materials in the vertical flame test (thickness = 3 mm).

| material | # | HDPE | PA | PC | PCABS-1 | LDPE-co | HIPS | PVC |
|---------------------------|---|------|-----|-----|---------|---------|------|-----|
| t_1 | 1 | 0 | 8 | 7 | 3 | >60 | 1 | 0 |
| | 2 | 0 | 8 | 9 | 2 | >60 | 2 | 0 |
| | 3 | 0 | 9 | 4 | 1 | - | 4 | 0 |
| | 4 | 0 | 8 | 10 | 2 | - | 2 | 0 |
| | 5 | 0 | 8 | 4 | 2 | - | 1 | 0 |
| t_2 | 1 | 0 | 0 | 8 | 42 | >60 | 1 | 0 |
| | 2 | 0 | 1 | 3 | 13 | >60 | 1 | 0 |
| | 3 | 13 | 2 | 3 | 47 | - | 1 | 0 |
| | 4 | 12 | 0 | 0 | 34 | - | 1 | 0 |
| | 5 | >30 | 0 | 3 | 11 | - | 1 | 0 |
| $\Sigma(t_{1i} + t_{2i})$ | | - | 44 | | 157 | - | 15 | 0 |
| dripping | | Yes | Yes | Yes | Yes | Yes | Yes | No |

A series of infrared images was taken on model samples that clearly fit into the V-0, V-2 and V-not categories. The observation made of these samples will help to explain the classification reached in Table 1-7 and allow us to formulate a physical description.

V-0 material: As an ideal V-0 material, a 2 mm thick Teflon sample was heated up with the 50 W flame for ten seconds. As no flame persists, the material rapidly cools down. The PVC material showed the same behavior with a stronger deformation of the specimen. Although this wasn't the case here, it should be noted that V-0 specimens can also drip melting material as long as the cotton indicator is not ignited.

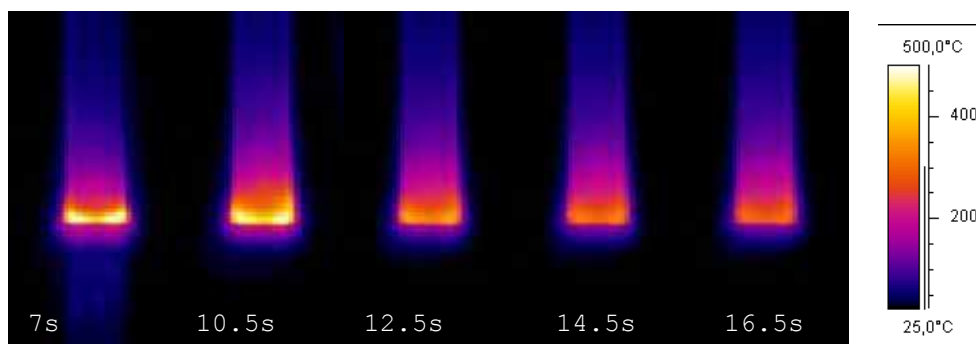


Figure 1-12: Series of black body infrared images acquired at the indicated times of a 2mm thick Teflon specimen exposed to the 50 W flame of the vertical burner. $t = 0$ s at the application of the flame.

V-2 material: Two V-2 materials were studied with the IR camera. The first was an additional polycarbonate material, the second PA.

The PC sample was heated up by the small flame and the flame started to self-propagate (Figure 1-13). Propagation of the flame upwards was slow. Melt dripping leads to the formation of a large droplet, so that the burning material falls to the cotton indicator, whereas the remaining sample cools rapidly, as no flame persists. The heating and decomposition of new material by upward flame spread was hence slower than flow of hot material from the sample.

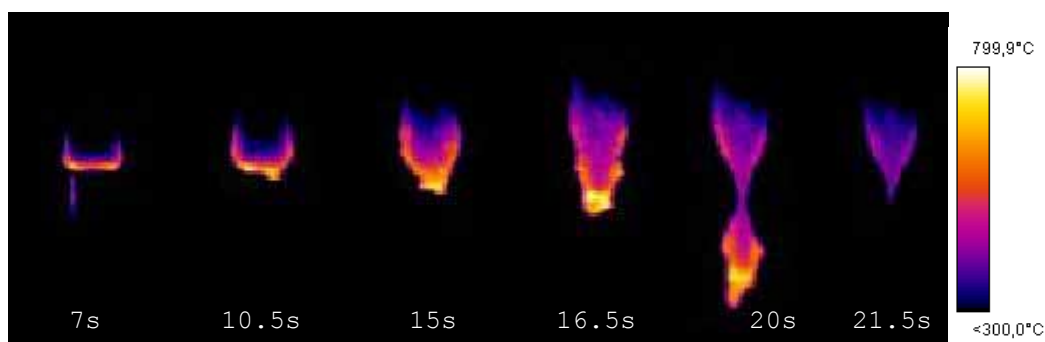


Figure 1-13: Series of infrared images acquired at the indicated times of a 2mm PC specimen exposed to the 50 W flame of the vertical burner. $t = 0$ s at the application of the flame. Observe the change in temperature scale as compared to previous figures.ⁱⁱ

After heating by the flame, the PA sample was significantly colder than the PC sample (Figures 3-10 and 3-9). Very few, small droplets formed that fell on the cotton indicator and the flame extinguished rapidly.

ⁱⁱ The thin blue line in the first picture to the left is a wire attached to the edge of the burner used to mark its position and to keep a uniform distance from the sample.

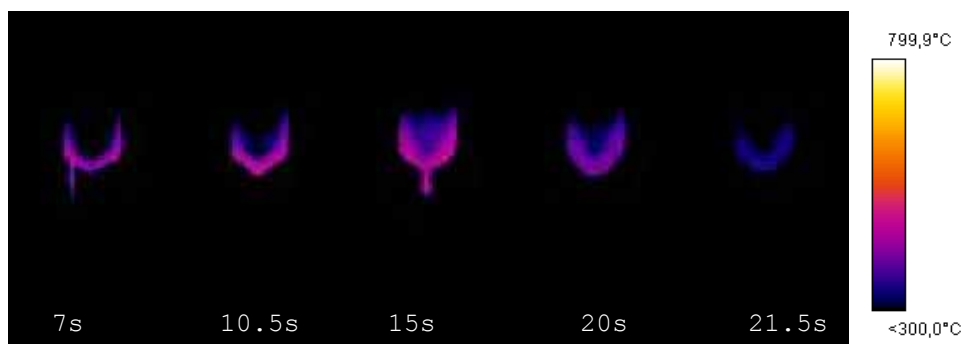


Figure 1-14: Series of infrared images acquired at the indicated times of a 2 mm PA specimen exposed to the 50 W flame of the vertical burner. $t = 0$ s at the application of the flame.

V-not: This class is illustrated by a polyolefin sample with a rapid flame spread over its surface. The material started to flow and large chunks of material fell on the cotton indicator. As flame spread was fast, the sample burned above the part of the specimen that fell down and continued to burn and drip.

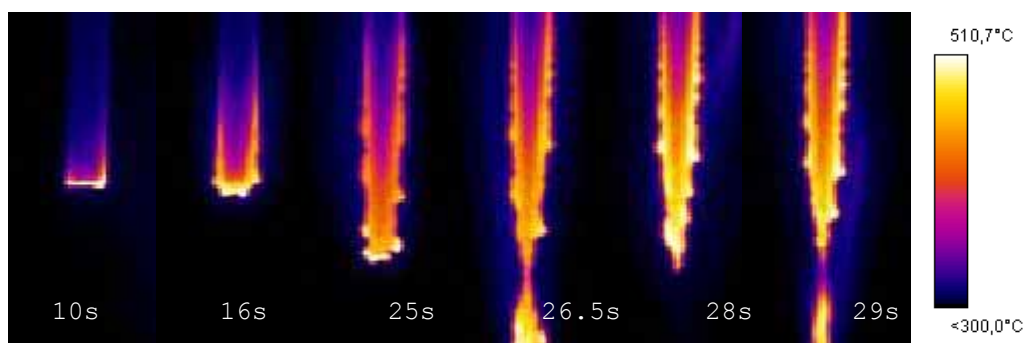


Figure 1-15: Series of infrared images acquired at the indicated times of a 2 mm polyolefin specimen exposed to the 50 W flame of the vertical burner. $t = 0$ s at the application of the flame. Observe the change in temperature scale as compared to previous figures.

The visualization given in Figure 1-12 to Figure 1-15 is representative of the behavior of the materials in Table 1-7. The PVC specimens, with after-flame times of 0s match the Teflon sample. The PC considered in this study matched the additional model PC sample in its behavior. The HIPS behaved similar to the PA. The material becomes even more fluid and the amount of material dripping to the cotton indicator is considerable. Meanwhile, the flame on the residual sample extinguished rapidly. Lastly, LDPE-co, PCABS-2, PP showed a similar, although not as dramatic behavior as the polyolefin V-not test sample. HDPE was a special case. In the first flame application, no after-flame persisted. In the second flame application, two cases were observed. Firstly, its behavior matched PA. Secondly, for a few samples, the propagation of the flame on the sample became faster. In the latter case, the sample did not self-extinguish but continued to burn and produce droplets.

Based on these observations, we propose the following simplified description of the V-classification scheme:

Heat up cycle - 10 s of flame application (repeated once).

The lower part of the sample attains a certain start temperature, which depends on its:

- Thermal capacity
- Endothermal degradation processes (decomposition, water vapor...)
- Exothermal degradation processes (fuel production by decomposition)
- Surface re-radiation

Flame is withdrawn

Reaction:

- V-0** The energy produced by exothermal decomposition is too low to heat up further areas of the sample to overcome endothermal decomposition and in some cases heat losses caused by the flow of hot melt (not burning).
→ Self-extinguishment
- V-1** As V-0. More time is given for char formation that isolates flame and unconsumed sample.
→ Self-extinguishment
- V-2** The energy produced by exothermal decomposition is too low to overcome the combined heat losses by endothermal decomposition and flow of burning melt.
→ Self-extinguishment
- V-not** The energy produced by exothermal decomposition is higher than the combined heat losses by endothermal decomposition and withdrawal of material by flow.
→ Propagation

Scheme 3-1: Simplified physical description of the material response in the vertical flame test.

There is an obvious difference between V-0, V-1 and V-2 materials (Scheme 3-1). Materials in the V-2 class may rely on an additional heat transfer mode that is flow of burning material. Otherwise the material would fulfill V-1. Therefore, a V-2 material with a strong melt flow can have a considerable imbalance between exothermal effects and endothermal effect. That means the material can burn considerably when it is hindered to flow. Therefore, the V-2 class accommodates such a wide range of materials. On one hand, materials such as PA and PC, where the imbalance between exothermal effects and endothermal effect is small, but flow cannot be avoided, although it only contributes little to self-extinguishment. On the other hand materials such as HIPS or PCABS-1, where the imbalance between the exothermal effects and endothermal effect is larger, but flow removes most of the heated material.

The HDPE specimens showed a special behavior that leads us to an important point. The material rapidly self-extinguishes after the first flame application, but burns in self-propagation after the second application. During the first flame-application, the metal-hydroxide is pristine and the energy balance on the endothermic side. During the second flame application, a part of the metal hydroxide is depleted and the energy balance tips. That is true for many materials designed for test methods with a simple and coarse classification scheme. Some of these materials are optimized to fulfill the specific criteria

and just these. Consequently the amount of flame retardant added corresponds fairly well to what is needed to pass the double application of the small flame. However, this limit was arbitrarily chosen, and in reality, the material might be subjected to much longer exposure time, especially in the case of electronic fires [1]. Therefore, one of the major disadvantages of the vertical flame test is the very limited information on the true nature of the material. This is why it is important to complement the test method with other experiments that yield more information on the material such as the cone calorimeter, as will be shown in the next chapter. For the vertical flame test, Morgan et al. have shown that the V-0 classification corresponds on average to a certain heat release potential [16]. This limit thereby emerges as non-arbitrary. Deviations from the average were observed, which were ascribed to different results of the vertical flame test obtained by different operators. Materials such as HDPE which are specifically designed just to pass a test contribute to the deviation of the data from both tests.

As will be shown in 3.2.3 for the materials studied here and as in agreement with the literature [2], the V-2 classification does not correspond well to other measures of the flame-retardancy of the material. That follows straightforward from the geometry-dependence of the heat transfer by flow. The vertical flame test further fails to provide information on the integrity of the enclosure (see fire risk assessment 1.2).

Conclusions

The majority of materials chosen for this study underperformed in the vertical flame test.

Materials with widely different fire behavior classify as V-2 in the vertical flame test. The allowance of heat transfer by melt dripping introduces an undesired geometry dependence of the test results. This classification is thus not useful as a single criterion for a fire hazard assessment and must be complemented by other measurements, such as heat release based tests.

The vertical flame test does not provide information on the integrity of the enclosure (holes opening, flames emerging from the apparatus).

3.2 Heat release based tests

The results from the measurements with the cone calorimeter and the pyrolysis combustion flow calorimeter are given in the sections below. Each section contains a brief guidance on the interpretation of the results.

3.2.1 Cone calorimeter

Heat release

The major result of the cone calorimeter test is the heat release rate curve, an example of which is given in Figure 1-16. It yields information on the heat produced by the combustion of materials under the impact of an external radiation. The interpretation of heat release curves follows the following, straight forward pattern:

-
- The later ignition occurs, the better
 - The lower the heat release rate, the better
 - The lower the integral value, the better
 - The later a significant heat release occurs, the better
-

Scheme 3-2: Short guideline to interpreting heat release rate curves.

It is important to take the whole shape and time scale of the heat release curve into account, instead of reducing the discussion to single measured values, such as the peak heat release rate (pHRR) [17]. Also, the criteria for good performance outlined in Scheme 3-2 are in general not interchangeable and should all be met for a good performance of the material.

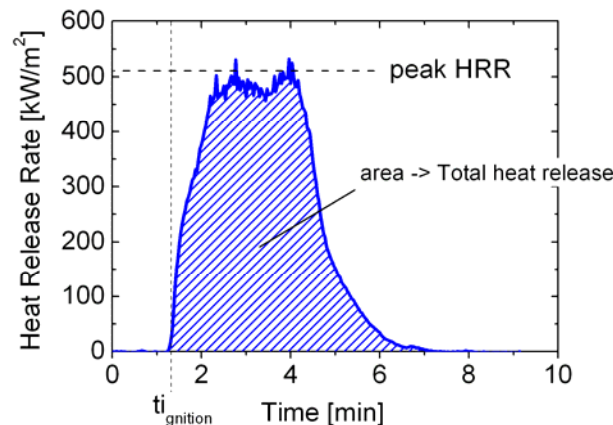


Figure 1-16: Heat release rate from the combustion of PA in the cone calorimeter with an external heat flux of 35 kW m^{-2} .

The cone calorimeter simulates a specific fire scenario, which is the developing (early) phase of a fire under well-ventilated conditions. The materials are typically exposed to heat fluxes of 10 to 100 kW m^{-2} . For instance, at 30 or 70 kW m^{-2} , the polymer surface will reach 400 °C in approximately 90 s and 30 s respectively [17]. The setup of the cone calorimeter simulates most closely the heat flux emerging from a burning item of considerable size, for instance a stack of paper or a trash can, to an adjacent item, as e.g. a wooden wall.

In this study, we are concerned with the earliest phase of the fire, with ignition and fire growth from a small heat source and the spread of fire from this small heat source. Self-extinguishment of the fire as distance is gained from the small ignition source, is the desired material property. The high heat flux applied uniformly to a $10 \times 10 \text{ cm}^2$ surface area in the cone calorimeter does not come very close to this scenario. As the cone calorimeter continues to radiate heat on the sample to force complete combustion, self-extinguishment is the exception for thermoplastic materials. However, the cone calorimeter yields much information on the behavior of the material under thermal attack. Important parameters, such as the total heat stored in the material, the rate at which the heat can be released and time to ignition can be measured. More so, these parameters are measured in a satisfyingly reproducible way with the elimination of flow phenomena.

The heat release rate curves of the samples in this study are plotted in Figure 1-17.

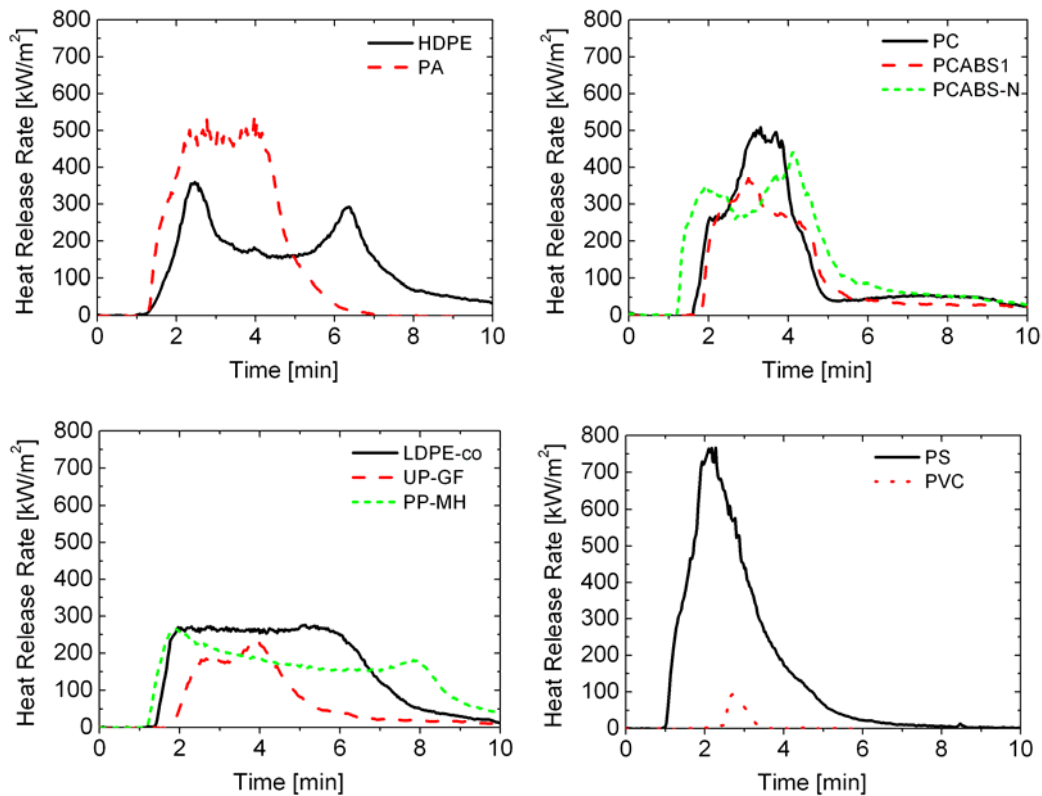


Figure 1-17: Heat release rate measured in the cone calorimeter. The external heat flux was 35 kW m^{-2} .

The principal descriptive parameters obtained from the heat release rate curves are displayed in Figure 1-18.

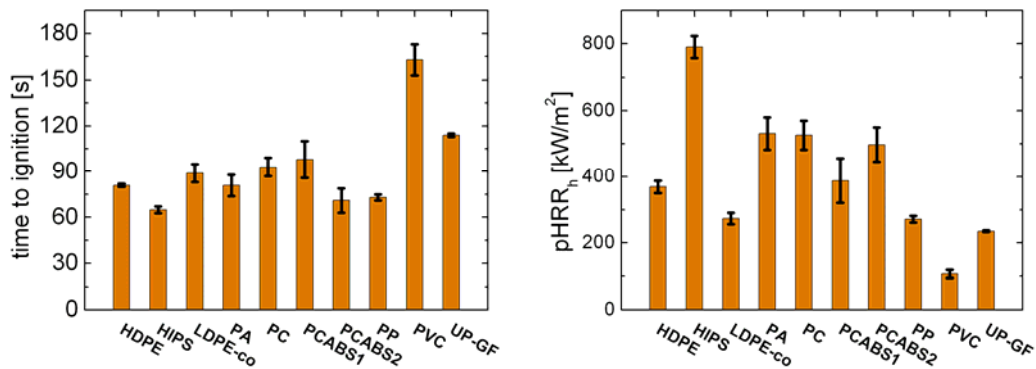


Figure 1-18: Comparison of important parameters of the cone calorimeter measurements.

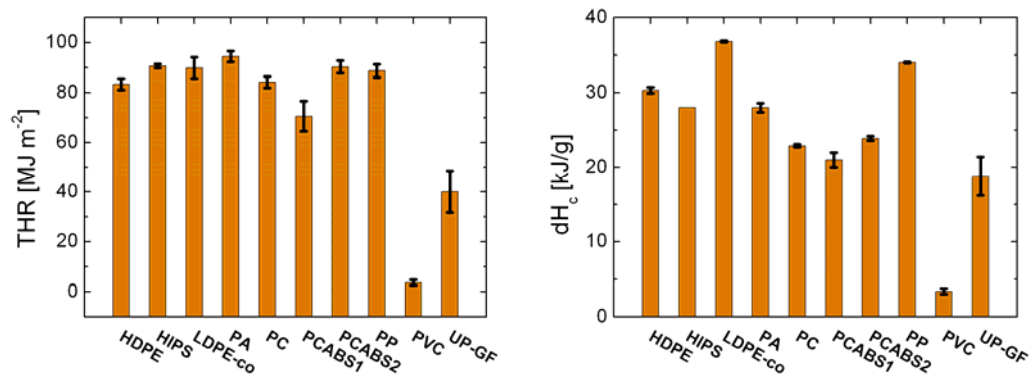


Figure 1-18: (continued) Total heat release rate (THR) and effective heat of combustion (dH_c) obtained by the cone calorimeter test.

Smoke and carbon monoxide/dioxide production

The cone calorimeter is equipped with a smoke detector and gas analyzers for carbon monoxide and carbon dioxide production. Hence smoke and carbon oxide production can be determined for the scenario of a well-ventilated, developing fire. Both smoke and gas measurements are related to the time to escape. Smoke for the obvious reason of obscurity. For instance, a cable tree of plasticized PVC exposed to a 30 kW burner is able to totally darken a 13 m long corridor (2×2.4 m² width×breadth) in 7 min [18]. The smoke production data are graphically displayed below. Clearly, the HIPS and the polycarbonate formulations (PC, PCABS1, PCABS2) showed considerably higher total amounts and rates of smoke produced than the rest of the materials

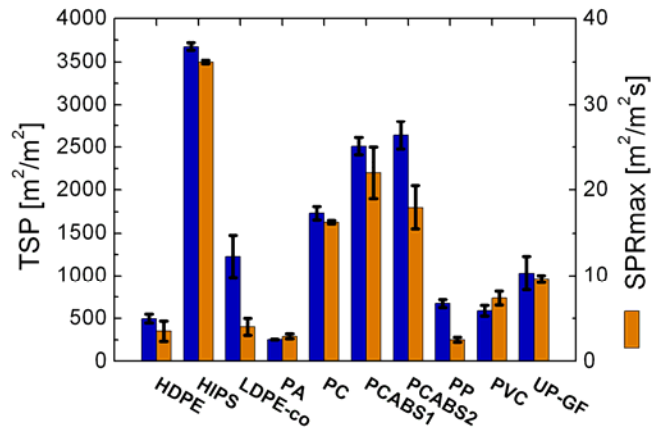


Figure 1-19: Total smoke production (TSP) and peak smoke production (SPR_{max}) measured in the cone calorimeter with an external heat flux of 35 kW m^{-2} .

Carbon monoxide is a narcotic gas and one of the major causes for fire related death. Carbon dioxide has a negative effect in making any person trying to escape breath harder and thereby more likely to inhale toxic gases and to lose consciousness. Therefore, low levels of both gases are desirable. As can be seen in Figures 3-16 and 3-17, the total amount of carbon dioxide produced by the materials which burned at high rate was of similar magnitude. The materials which burned to a lesser extent showed reduced (UP-GF) and strongly reduced (PVC) levels of carbon dioxide. Wider differences were observed for the amount and rate of carbon monoxide produced. The polycarbonate formulations had two to three times the amount of carbon monoxide produced as compared to the rest of the materials. The rate of CO production by the polycarbonate formulations was also a multiple of the rates that other materials, besides HIPS, displayed.

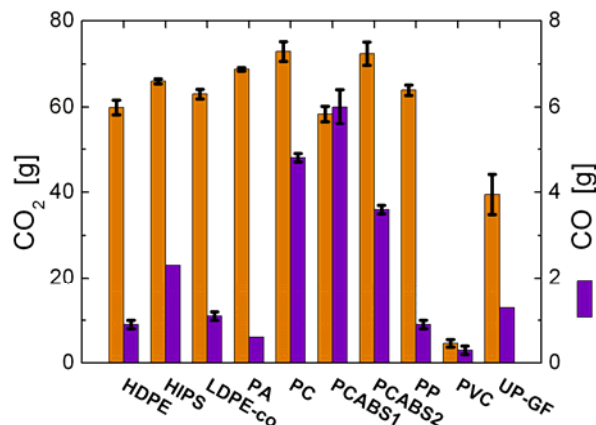


Figure 1-20: Total production of carbon dioxide and carbon monoxide measured in the cone calorimeter with an external heat flux of 35 kW m^{-2} .

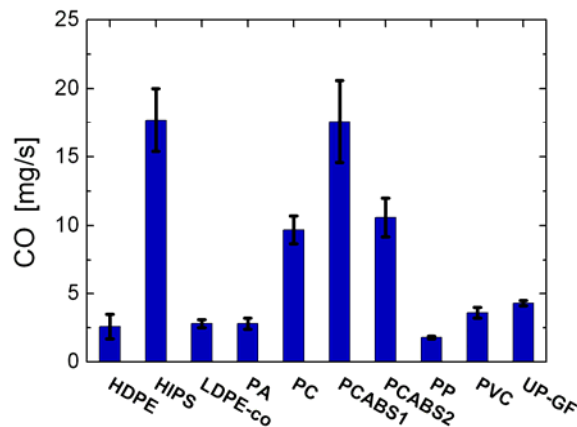


Figure 1-21: Maximum rate of CO production measured in the cone calorimeter with an external heat flux of 35 kW m^{-2} .

Finally, a summary of the cone calorimeter data can be found in Table 1-8.

Table 1-8: Summary of cone calorimeter results for specimens 3 mm thick. The external heat flux was 35 kW m^{-2} . Standard deviations were calculated from 3 to 5 measurements.

| | Time to ignition | Peak heat release rate | Total heat release | Peak smoke prod. | Total smoke produced | Average mass loss rate ₁₀₋₉₀ | Effective heat of combustion | Specific extinction area |
|---------|------------------|------------------------|--------------------|-----------------------------|-----------------------------|---|------------------------------|------------------------------|
| | s | kW m^{-2} | MJ m^{-2} | $\text{m}^2 \text{ m}^{-2}$ | $\text{m}^2 \text{ m}^{-2}$ | $\text{g m}^{-2} \text{ s}^{-1}$ | kJ g^{-1} | $\text{m}^2 \text{ kg}^{-1}$ |
| HDPE | 81 ± 1 | 369 ± 19 | 83 ± 2 | 4 ± 1 | 497 ± 50 | 7 ± 1 | 30 ± 0 | 181 ± 16 |
| HIPS | 65 ± 2 | 790 ± 33 | 91 ± 1 | 35 ± 0 | 3677 ± 41 | 16 ± 2 | 28 ± 0 | 1135 ± 2 |
| LDPE-co | 89 ± 6 | 273 ± 17 | 90 ± 4 | 4 ± 1 | 1228 ± 247 | 6 ± 1 | 37 ± 0 | 503 ± 97 |
| PA | 82 ± 7 | 531 ± 49 | 94 ± 2 | 3 ± 0 | 251 ± 6 | 15 ± 2 | 28 ± 1 | 75 ± 3 |
| PC | 93 ± 6 | 526 ± 44 | 84 ± 2 | 16 ± 0 | 1735 ± 79 | 7 ± 1 | 23 ± 0 | 473 ± 14 |
| PCABS-1 | 98 ± 12 | 388 ± 67 | 71 ± 6 | 22 ± 3 | 2511 ± 101 | 9 ± 5 | 21 ± 1 | 738 ± 40 |
| PCABS-2 | 71 ± 8 | 497 ± 52 | 90 ± 3 | 18 ± 3 | 2639 ± 161 | 12 ± 3 | 24 ± 0 | 698 ± 54 |
| PP | 75 ± 2 | 266 ± 9 | 87 ± 3 | 2 ± 0 | 648 ± 47 | 5 ± 0 | 34 ± 0 | 252 ± 10 |
| PVC | 163 ± 9 | 91 ± 12 | 4 ± 1 | 7 ± 1 | 589 ± 63 | 6 ± 0 | 3 ± 0 | 541 ± 48 |
| UP-GF | 114 ± 1 | 235 ± 3 | 40 ± 8 | 10 ± 0 | 1032 ± 196 | 6 ± 0 | 19 ± 3 | 485 ± 58 |

3.2.2 Pyrolysis combustion flow calorimeter (PCFC)

The pyrolysis combustion flow calorimeter, also called microcalorimeter, was developed with the aim to identify inherently non-combustible polymeric materials for cabin materials in the aircraft industry. The underlying concept is that the rate of heat release from a material in a fire is limited by the rate of volatile fuel production from the polymer pyrolysis, as mixing and gas phase reactions in the flame are much faster in comparison [12]. Hence, an experimental setup was developed that allows determining this rate of volatile fuel production. As it is difficult to determine the type of fuel and its energy content analytically, the volatiles produced are completely oxidized and the heat release rate is determined via the oxygen consumption method. Thus a rate of heat production (release) instead of a rate of volatile fuel production is obtained.

The central parameter from this test and in the thermodynamic theory of combustion presented by Lyon et. al. is the heat release capacity (HRC) [12]:

$$\text{HRC (J g}^{-1} \text{ K}^{-1}) = \frac{\text{max. specific heat release rate}}{\text{heating rate}} = h_{c,v}^0 (1 - \mu) \frac{E_a}{eRT_p^2}$$

The HRC is the maximum heat that is produced by a sample per unit mass when heated at a certain rate. This determines how much the sample material can contribute to a fire. As the parameter is determined for a milligram sample, any dependence on sample thickness, sample orientation, melt flow etc. should be eliminated. As can be seen from the left hand side of the above equation, the HRC is further linked to thermodynamic properties of the sample material: E_a is the global activation energy for pyrolysis; T_p , the temperature of maximum mass loss rate; e , R are the natural number and gas constant, respectively, and $h_{c,v}^0 (1 - \mu)$ is the heat of combustion of the fuel gases per unit initial mass of the sample.

The practical measuring procedure with the PCFC is the following: A milligram sample of the polymer is pyrolysed in a stream of nitrogen at heating rates between 1 and 4 °C s⁻¹. The volatiles produced by pyrolysis are mixed with oxygen and completely oxidized in a combustor. The heat release rate is computed from the signal of an oxygen analyzer. Typical results from measurement with the PCFC are shown in Figure 1-22 (left).

The HRC is then calculated by dividing the maximum heat release rate with the heating rate. By integrating the curve, the total heat release (THR) can be determined. The temperature of peak heat release rate (T_p) can also be determined from the curve.

Many of the polymers used in this studied showed heat release curves with two peaks or a peak with a shoulder (Figure 1-22, right). In cases such as PCABS, where both peaks arise from polymeric material, the sum of both peaks was used to calculate the HRC. For PVC, only the second peak was used for the evaluation. Since the first peak is due to the release of chlorine which has a flame-quenching and not a flame-feeding effect [19].

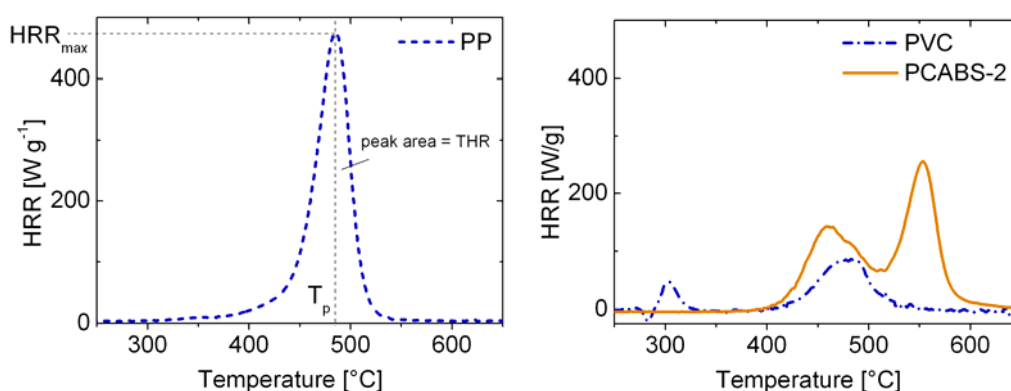


Figure 1-22: “Simple” PCFC measurement at a heating rate of 1 °C s⁻¹ of PP (left) and special cases (right) as encounter for polymer blends (e.g. PCABS-2) or polymers with several degradation steps (e.g. PVC).

The data acquired with the PCFC is summarized below and will be discussed in the following paragraph.

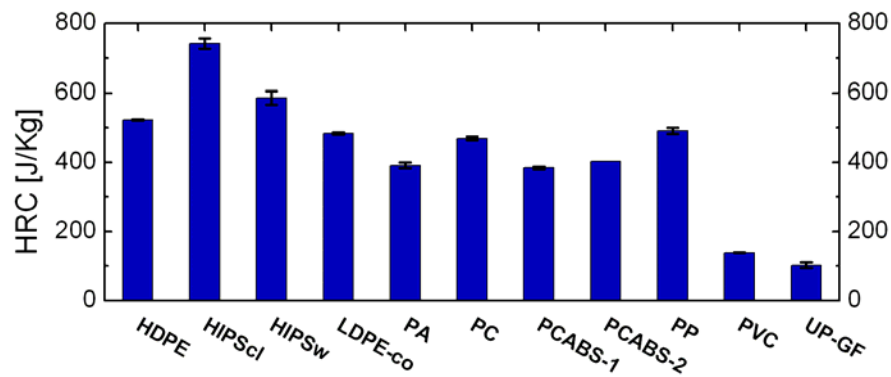


Figure 1-23: Heat release capacity measured with a heating rate of $1\text{ }^{\circ}\text{C s}^{-1}$.

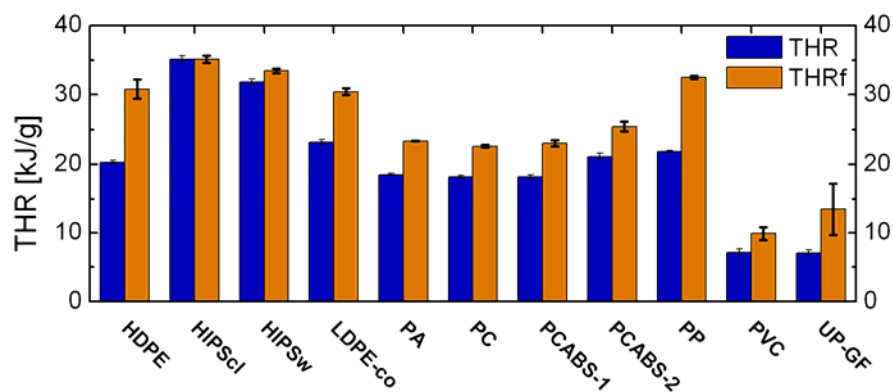


Figure 1-24: Total heat release as determined by the PCFC using a heating rate of $1\text{ }^{\circ}\text{C s}^{-1}$.

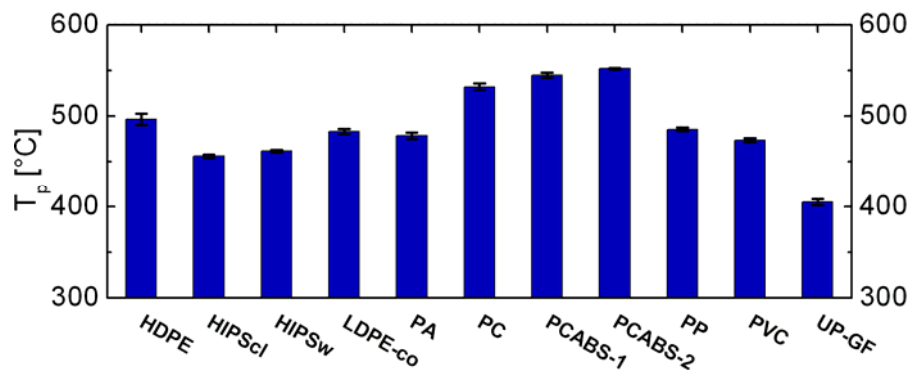


Figure 1-25: Temperature of peak heat release as determined by the PCFC using a heating rate of $1\text{ }^{\circ}\text{C s}^{-1}$. For polymer blends, the T_p of the major component is reported.

3.2.3 Discussion

First, the performance of the materials in the cone calorimeter and PCFC shall be regarded. In a next step, the discussion will focus on how the information gained from the calorimeters may be used to enhance the fire safety assessment.

The first event in the cone calorimeter experiment is ignition. Eight materials studied here lie in a rather narrow range of time to ignition (65 to 98 s) with the exception of UP-GF and PVC that have higher TTIs (114 and 163 s respectively). In terms of the heat release rates of the materials there are roughly three groups of materials with one exception

(Figure 1-17). PA, PC, PCABS1 and PCABS2 all have average heat release rates of 300 – 500 kW m⁻². The polyolefin formulations HDPE, LDPE-co and PP have average heat release rates between 200 and 300 kW m⁻², whereas UP-GF and especially PVC displayed lower heat release rates. HIPS showed the worst performance of the materials with the highest heat release rate and shortest TTI. Surprisingly, the total heat release from the materials is essentially equal for all materials but PVC and UP-GF (Figure 1-18). With the criteria given in Scheme 3-2 in mind, it is easy to single out PVC and UP-GF as the least combustible materials. HIPS emerges as the material with the highest heat release potential. The rest of the materials is less straight forward to rank. PA, PC, PCABS1 and PCABS 2 are consumed at a higher rate in the experiment, although the longer TTI for the polycarbonate rich materials PC and PCABS1 is advantageous. Otherwise the polyolefin based materials HDPE, LDPE-co and PP show a lower rate of heat release.

It is very instructive to compare the effective heat of combustion and the total heat release of the materials (Figure 1-18). The polyolefin resins have a higher heat release potential of the pure polymer than PA, PC, PCASB and HIPS and thus a higher effective heat of combustion (= heat produced/mass consumed). The total heat release for all samples is never the less the same, due to a higher filling level used in the polyolefin materials, reducing the amount of combustible polymer. The data suggests that there might be a certain amount of filler that is deemed sufficient to reach about the same flame retardancy for different polymer resins.

The heat release capacity measured by the PCFC was similar for many of the materials studied (Figure 1-23). The bulk of the materials had a HRC in a range of 380 to 520 J g⁻¹ K⁻¹. Only UP-GF and PVC had significantly lower heat release capacities, whereas HIPS had a higher HRC. It is interesting to see that the polyolefin formulations (HDPE, LDPE-co, PP) had similar values, as for the heat release rate in the cone calorimeter, and that the same is true for PA, PC, PCABS1 and 2. The trend is however opposed, as the HRC values of the polyolefin formulations are higher. The same is true for PVC and UP-GF, where UP-GF obtained a better result (lower HRC) in the PCFC as compared to a worse over all performance in the cone calorimeter.

The total heat release data measured in the PCFC (Figure 1-24) shows the same pattern of performance as the HRC data. This is also true for the THR normalized to the fraction of consumed mass (THR_f). As expected the temperature of peak heat release (T_p) had the highest values for the polycarbonate based materials. The UP-GF sample had the lowest temperature of maximum heat release.

With regards to the fire risk assessment, it would be very desirable if the calorimeter data allowed us to answer the following questions:

- QA** Can the worst materials be singled out?
- QB** Can additional elements of the fire risk be identified?
- QC** Can we define a better and refined scale after which to rank the materials?

QA - Can the worst materials be singled out?

Material performance in the cone calorimeter depends on all the criteria given in Scheme 3-2. Figure 1-26 summarizes the performance of three important parameters, time to ignition, peak of heat release rate and total heat release rate. The vertical flame test ranking is also given. It is very clear that a good overall performance in the cone calorimeter is only achieved for PVC with a V-0 ranking and UP-GF (suspected V-0). The V-2 and V-not materials cannot be distinguished. The same is true for the heat release capacity (Figure 1-27). This assessment adds to the evidence gathered by Morgan et. al. that also showed a significant variation for V-2 and worse materials [16].

An observation that cannot be stressed enough is that focusing on single material parameters, such as the peak of heat release rate, can be widely misleading. By doing so, materials that readily burn to the clamp in the vertical flame test (LDPE-co, PP, HDPE) might be preferred over materials with a better resistance to ignition by a small heat source (PA).

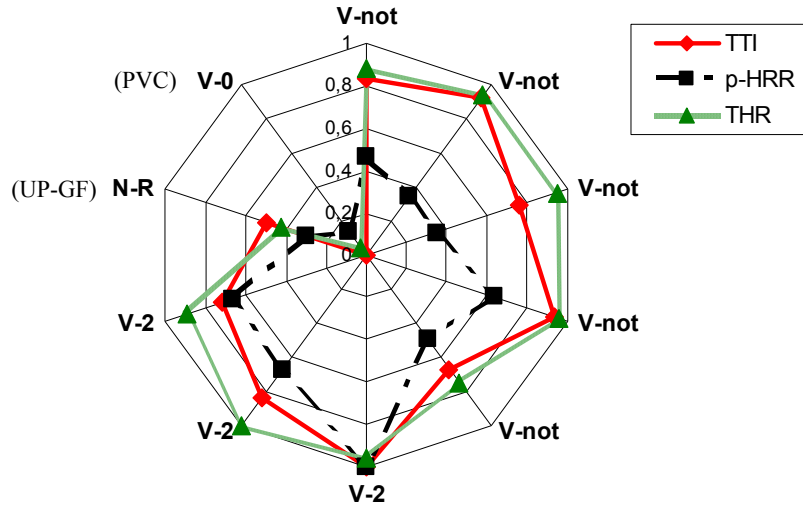


Figure 1-26: Radar plot of cone calorimeter parameters time to ignition, peak heat release rate and total heat release. The data was linearly normalized. The closer a value is to the center, the better is material performance.

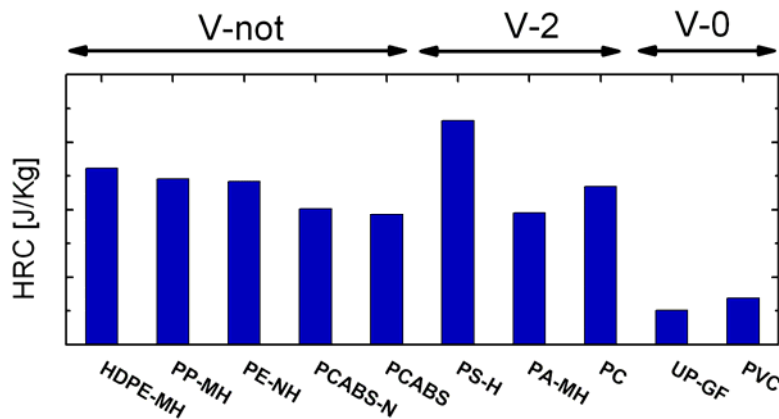


Figure 1-27: Comparison of the heat release capacity and the vertical flame ranking.

The observations from Figure 1-26 and Figure 1-27 lead us to an important advantage and disadvantage of the calorimetric measurements:

Advantage:

In both calorimeters, heat transfer by melt flow is impossible and hence the “true nature” of a material in terms of the potential to contribute to a fire will be revealed. The bias introduced in the small flame test by the removal (flow) of the hottest part of the material (3.1.3) is avoided. The data is indifferent to arbitrary choices, such as whether the flame / glow wire should be applied for 10 s, 20 s or 30 s. The best example here is the HIPS material. It reaches commonplace vertical flame and glow wire test ranking, whereas the material is highly combustible and might lead to a significant fire when hindered to flow.

Disadvantage:

As both calorimeters use a high external flux of heat which prevents self-extinguishment and forces combustion to complete fuel depletion. The PCFC further has the disadvantage

to misjudge flame quenching flame retardants [19]. For both environmental and economic reasons a very important question to answer is: How much flame retardant is enough? Or how much flame retardant is enough to reduce threat to life by 99.95 or rather 99.99 %. Here, we are not concerned with answering this question. It becomes however clear, that the high thermal insults imposed on the materials in the calorimeters point towards a worst case scenario. The reduction in external heat flux as distance is gained from a small ignition source is not reproduced. Therefore at the current state of the art, the calorimetric methods are suitable only to set a tough limit of material performance if reliability is desired. Any attempt to set an intermediate limit will end up in the grey-zone that in this study comprises materials such as the HDPE, PA, PC and PCABS-1 materials. An attempt by other scientists to overcome this difficulty will be presented in response to QC. More work in this field is needed.

QB - Can additional elements of the fire risk be identified?

It goes without saying that the cone calorimeter is an utmost useful tool to assess the fire performance of materials, were the scope of this study expanded from the very ignition scenario to treating the apparatus as the victim of fire. For this specific scenario, the ignition times as measured by the cone calorimeter are a more suitable method to obtain a ranking of ignitability than the glow wire ignition test, as the former test method is more reliable. The temperature of maximum heat release rate from the PCFC is not a suitable parameter. The PCFC's combustor operates at very high temperature and high oxygen concentration. Thus flame poisoning and flame dilution, very important factors for ignitability in any real life situation, are misjudged.

Smoke and gas production by the samples are valuable information gained by the cone calorimeter. This information is however hard to apply on the scenario in question. The cone calorimeter yields (again) data for forced combustion under well-ventilated conditions. Assume that materials were selected that do self-extinguish when threatened by a small flame or hot wire even under longer exposure than in the current tests. Smoke production then follows the formula (mass consumed until extinguishment) \times (smoke production/mass). The masses of material consumed by a small flame are very low as long as the fire does not spread from the localized source. Therefore, the question of smoke production is considered secondary to the prevention of fire spread in the first place for this specific scenario. For toxic gases this might not be true, as low concentrations of these gases might be lethal. Here, the much higher rates of carbon monoxide production by the polycarbonate and polystyrene formulations rise concern. The relationship of initial fire growth and toxic gas / smoke production needs further research. It should then be taken into account that the fire initiation in the enclosure happens under oxygen vitiated conditions.

QC - Can we define a better and refined scale after which to rank the materials?

In paragraph 3.1 it was shown that the glow wire and vertical flame tests do not yield enough information for a sound fire hazard assessment. It would therefore be desirable to use the information from the heat release measurements to fill the gap. As has been shown in this chapter, the heat release based methods only clearly separate materials with very good and very bad performance. The grey zone of rather good to rather bad materials is not useful for regulative decisions. At this point, we would like to point out a technique that is a step in the right direction to make better use of the cone calorimeter data. It could not be used in this study as the cost of testing on ten materials was excessive. For the sake of a complete discussion, it should be mentioned here however. This technique consists in calculating the heat release rate at zero incoming heat flux (HRR_0). Heat release rate measurements are made at different, typically three heat fluxes. The peak of heat release rate is plotted versus incoming heat flux. A linear fit of the data is used to extrapolate to the y-axis intersect at 0 incoming heat flux, yielding HRR_0 . The

purpose of this technique is to eliminate the external radiation from the cone calorimeter and to establish a parameter (HRR_0) that is purely a material property. The work of Bundy, Morgan and Ohlemiller [16] applies this technique for thermoplastic insulation materials. With one exception, all 9 V-0 and 2 V-1 materials tested in their study had average HRR_0 values below 400 kW m^{-2} . Between 400 and 600 kW m^{-2} , one V-0 and one V-2 material could be found. For the rest, V-2 and V-not materials had HRR_0 between 600 kW m^{-2} and 1400 kW m^{-2} and could not be separated by the technique. This is again due to heat transfer by flow for V-2 materials (3.1.3).

It is difficult to compare a new technique, the HRR_0 method, with a very simple and coarse technique, the vertical flame test. Therefore, more work should be invested into establishing a correlation between HRR_0 and a more versatile test for the ignition and flame spread from a localized heat source. It is foreseeable that one difficulty with horizontal cone calorimeter tests will be hard to overcome. The materials tested such are not subjected to gravitational stresses that are very significant for real life applications.

Conclusions

The calorimetric test methods are most suitable to identify which materials have the lowest and highest inherent flammability. As melt flow and deformation do not influence the measurements strongly, the intrinsic flammability of the material can be determined. The test methods allow estimating the rate of heat release in case that ignition results in a large flame and fire.

The calorimetric test did not prove to be useful to rank the performance of materials with mediocre flame resistance. The high external heat flux typically imposed on the sample is not well adopted to simulate self extinguishment of a material that is exposed to a small heat source. Flame inhibition is a less important effect in the calorimeter than in the bench scale test with a small flame or a over-heated wire.

The data presented in this study underlines the need for multi parameter analysis of cone calorimeter test results.

The cone calorimeter test method provides information on smoke and carbon oxides formation. This helps to identify additional elements of the fire risk, although a straight forward application to the scenario of a small heat source is difficult.

3.3 Vertical cone calorimeter - melt flow experiments

The objectives with the vertical cone calorimeter tests were the following:

- To measure the heat release from the materials when exposed to a radiant heat flow in a vertical position, in order to test the integrity of char forming polymers that might be misjudged in the horizontal cone calorimeter test.
- To test the dimensional stability and flow behavior of the materials in a configuration that resembles the outer part of an enclosure.
- To determine which materials might form a pool fire.

As in the horizontal cone calorimeter test, the sample is subjected to a uniform heat flux and ignited by a pilot spark or flame. The test set-up used was modified from what is described in the informative annex to the ISO standard [10] to gain additional information from the tests. The test set-up used is described below.

The aim was to simulate the conditions for a material that is used as the outer shell of an apparatus. The specimens were therefore not supported on their backside and allowed to flow freely at the lower edge (Figure 1-28).



Figure 1-28: Two views of the sample holder used for the vertical cone calorimeter experiments.

In a series of preliminary experiments, it was found that using a backing support for the sample did not prevent irregular flow behavior. An important disadvantage when using a backing support was a non-uniform thickness of the sample on the aluminum foil due to melt flow. This led to a stronger heating of thinner parts of the sample on the aluminum foil, where the heat radiation is reflected. This effect strongly influences the burning behavior. Therefore testing without backing, which also comes closer to the real application, was preferred.

In vertical tests, the volatile gases flow upwards in a few millimeter thick layer on the specimen surface. The gas stream is then disturbed when reaching the edge of the sample and becomes turbulent. It is very difficult to position the small spark given by the electrical igniter in such a way that it sits in gas stream in a repeatable manner. Therefore, a pilot needle flame was preferred in order to cover a wider part of the gas stream. Considering the position of the pilot flame, there are two non-optimal alternatives. First, a flame can be applied to the specimen surface directly and information on ignitability will be lost. This causes problems in case that the burning part of the specimen falls to the catch pan leading to extinguishment as observed for the V-2 material (paragraph 3.1.3). Second, a pilot flame can be placed in the stream of degradation gases and ignition will occur when a sufficient concentration of combustible gases is reached. This approach was chosen here. Its disadvantage is that it allowed some very easily flowing materials to “escape” before ignition.

A catch pan used to collect the melt was placed on a balance. This allows distinguishing how much weight in the sample holder is lost by combustion and how much by flow. Further, the mass loss on the catch pan is a good indicator of how intensively the material burns on the catch pan and thus for pool fire formation. The catch pan can either be placed very close to the specimen and heat radiation and flames from the melt will affect the sample. Or it can be placed further away in order to prevent heat-feedback. This is an arbitrary choice with strong influence on the result of the measurement. Here, a relatively long distance of 10 cm between the lower edge of the sample holder and the catch pan was chosen in an attempt to minimize the heat feed-back. This simulates the less severe scenario of equipment installed on a wall, where flaming materials is more likely to fall for some distance to other installations or the floor than to stay in the vicinity of the apparatus. Positioning the catch pan very close to the sample could also be justified. A different quantitative test result would have been obtained. The catch pan material also affects the result. Depending on the material used for the catch pan, heat transfer from the

melt to the pan will be significantly different. Here a material with low thermal conductivity was used to minimize the amount of heat transferred to the catch pan.

Results and discussion

The materials tested can be grouped after three types of qualitative behavior (Figure 1-29). Two materials, PVC and UP-GF did not show any melt flow to the catch pan at an external heat flux of 35 kW m^{-2} . HDPE, LDPE-co, PA, PCABS-2 and PP deformed to a lesser extent before ignition, but melt flow to the catch pan became very rapid once the specimen ignited. For PC, PCABS-1 and PS the deformation and flow of the specimen were excessive before ignition, to such an extent that the specimen did not ignite. PC and PC-ABS1 specimens had an interesting behavior. Heating the sample led to a lateral contraction and increase in thickness of the materials (Figure 1-29).




| Type I | Type II | Type III |
|--|--|--|
|  |  |  |
| The material did not flow | The material flowed and formed a burning pool | The material flowed before ignition |
| PVC UP-GF | HDPE LDPE-co PA PCABS-2 PP | HIPS PC PCABS-1 |

Figure 1-29: Flow behavior of the materials in the vertical cone calorimeter test. The external heat flux was 35 kW m^{-2} .

It is very interesting to note that two of three Type III materials were V-2 materials and PCABS-1 narrowly failed this classification. All three materials use a combination of a small amount of a gas phase active additive and intensive melt flow. The gas phase active component limits flame spread for the time needed for the material to escape. This behavior proves to be very suitable for bench scale tests, where only little constraints are set to flow and only one material is tested at once. In an apparatus however many

components are placed at small space. The removal of material as observed here cannot be expected. Therefore, this test results does not credit any improved flame retardancy to the materials at question.

For Type I and Type II materials we can compare ignition and heat release rates with the measurements in horizontal position. Further we can see how likely the materials are to form a pool fire.

Ignition

Four of seven materials could be ignited in a very reproducible manner, with a standard deviation of ± 1 s, those are HDPE, LDPE-co, PCABS-2 and PP. All these materials contained no highly effective flame inhibiting additives (such as halogens or phosphorous). For these materials, ignition times were very similar, more reproducible and slightly shorter in the vertical configurationⁱⁱⁱ (Figure 1-30).

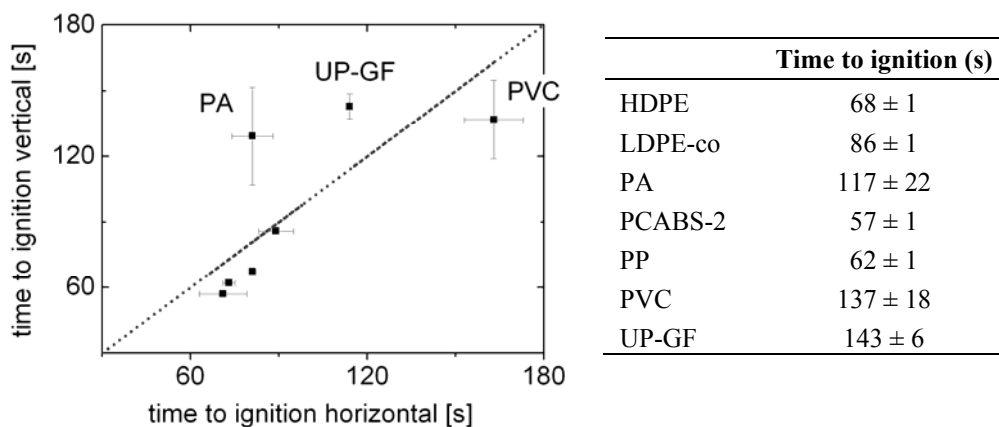


Figure 1-30: Comparison of time to ignition in the vertical and horizontal cone calorimeter configuration at an external heat flux of 35 kW m^{-2} . The results from the vertical measurements are tabulated on the right.

The materials with flame-poisoning additives (PA, PVC, UP-GF) were difficult to ignite with the pilot flame. For PVC and PA, the pilot flame had to be lit over and over again, resulting in significant standard deviations of the time to ignition^{iv} (Figure 1-30). It is very interesting to note that the ignition times for these samples were significantly different for the vertical and horizontal configuration beyond the observed standard deviation; especially in the case of PVC and UP-GF, where the measurement was not influenced by material flow. In vertical specimen the gas phase agent mixes into a thin gas layer in laminar upward flow. In the horizontal standard configuration, the gas phase agent mixes in a larger volume of air above the hot specimen surface. The temperature and ignitability of both gas mixtures differ.

Heat release

It is very challenging to make sense of heat release rate measurements in vertical configuration tests, as the surface area of the specimen is changing with deformation and flow. The contribution of material that burns in the catch pan should not be neglected. A one-to-one comparison of horizontal and vertical data is therefore impossible. The interest with the current test was to see whether the horizontal cone calorimeters

ⁱⁱⁱ That is probably due to the larger area covered by the pilot flame as compared to the spark igniter.

^{iv} For PA, four specimens were tested

measurements capture the behavior of the materials or whether large deviations can occur in vertical configuration. These deviations are very revealing and shall be discussed below.

As can be seen in Table 1-9, the most significant deviations occurred for samples LDPE-co, PA, PP, PVC and UP-GF. Each of them will be considered in brief.

Table 1-9: Vertical cone calorimeter results for specimens 3 mm thick. The external heat flux was 35 kW m^{-2} . Standard deviations were calculated from 2 to 4 measurements.

| | Time to ignition s | Peak heat release rate kW | $\frac{\text{pHRR vertical}}{\text{pHRR horizontal}}$ % | Total heat release MJ m ⁻² | $\frac{\text{THR vertical}}{\text{THR horizontal}}$ % |
|---------|------------------------------|-------------------------------------|--|---|--|
| HDPE | 68 ± 1 | 5,2 ± 0,3 | 94 | 55 ± 0 | 44 |
| LDPE-co | 86 ± 1 | 3,1 ± 0,3 | 217 | 60 ± 12 | 66 |
| PA | 117 ± 22 | 2,4 ± 1,1 | 51 | 16 ± 17 | 16 |
| PCABS-2 | 57 ± 1 | 4 ± 0,9 | 91 | 40 ± 10 | 67 |
| PP | 62 ± 1 | 3,9 ± 0,4 | 163 | 81 ± 30 | 93 |
| PVC | 137 ± 18 | 0,9 ± 0,2 | 113 | 11 ± n.a. | 304 |
| UP-GF | 143 ± 6 | 3,9 ± 1 | 186 | 39 ± 5 | 96 |

LDPE-co

The heat release rate was roughly double in the vertical set-up as compared to the standard configuration. This was due to a relatively tough flow of this material which led to a strong elongation of the specimen and produced a flame bridging catch pan and specimen holder.

PA

The polyamide sample had a significantly lower heat release in the vertical configuration. This was due to the fact that a large proportion of the material transfers as a melt to the catch pan where it burned with low intensity (Figure 1-29) The melt flow on the surface continuously removes the most overheated part of the material.

PP

The PP material had a much higher heat release rate in the vertical cone calorimeter configuration due to the same reason as for LDPE-co. It is further interesting to note that the sample was almost completely consumed besides the strong flow, as is seen by the high THR. This indicates a high potential for a pool fire.

PVC

The total heat release from the PVC sample was 3 times that from the horizontal configuration (Table 1-9, Figure 1-31). Combustion in the vertical configuration was thus much more effective. It should be remembered that this material did not flow. As can be seen in Figure 1-29, the PVC sample burned largely on top of the sample holder and not as much on the sample surface. On the sample surface, the chlorine concentration can be expected to be rather high and the burning rate of the gas is low. Upstream the chlorine is more and more diluted by mixing with air from the surroundings. It may also play a role that chlorine is a much heavier gas than hydrocarbons resulting in a separation effect. This dilution of the chlorine leads to a significantly later extinguishment in the vertical configuration. This indicates that the data collected in horizontal orientation might be inaccurate for real life applications.

UP-GF

The UP-GF sample had twice the heat release rate in the vertical configuration as compared to the horizontal configuration. This is most of all due to the fact that the sample starts to burn on the backside (Figure 1-31). Undesirable as it might be, this effect might occur in a real combustion scenario.

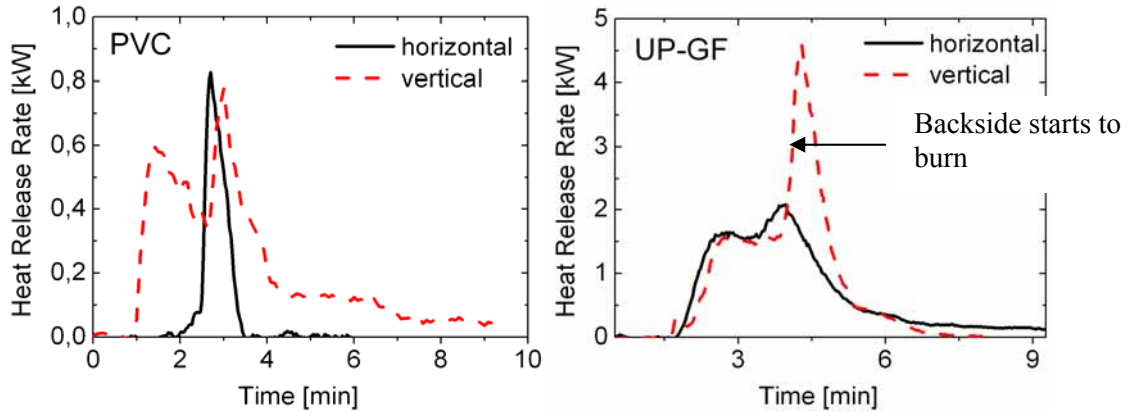


Figure 1-31: Comparison of horizontal and vertical cone calorimeter measurement for the samples that did not flow (Type I).

Pool fires

The signal from the balance holding the catch pan was used to evaluate how intensively the melt continued to burn on the catch pan. This is a reasonable indicator for the likelihood that the material might form a pool fire.

As can be seen from Figure 1-32, HDPE, PP and PCABS-2 continued to burn for considerable time on the catch pan. The mass loss on the catch pan was of the order of 25 % of the material transferred to the catch pan. We therefore conclude that these materials have a high potential to spread a fire by melt dripping.

LDPE-co had very large flames during the melt flow but extinguished comparatively fast once transferred to the catch pan. Due to the intensive flaming during the transfer, the risk for flame spread is high, whereas the high viscosity of the material makes the formation of a pool very unlikely.

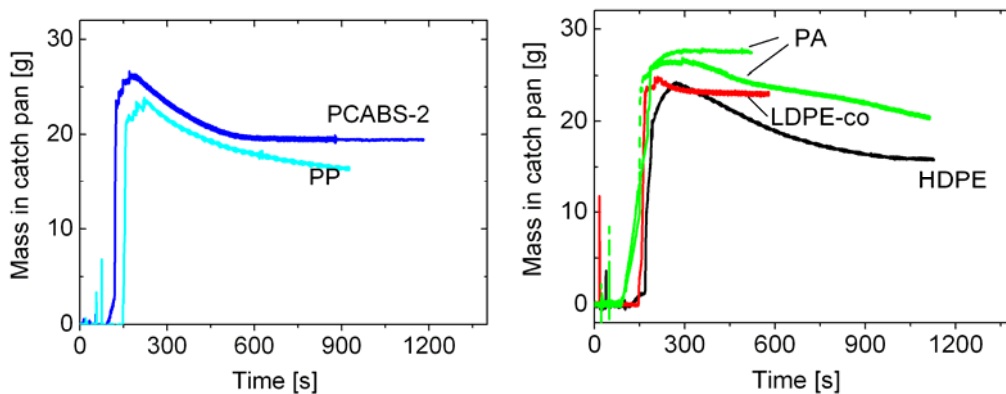


Figure 1-32: Mass gained on the catch pan during material flow (initial increase) and mass lost by burning on the catch pan (subsequent decrease) for the vertical cone calorimeter experiments at 35 kW m^{-2} external heat flow.

The PA sample showed an interesting behavior. In 3 of 4 cases, flames on the pool extinguished when no fresh melt flowed to the catch pan (Figure 1-32). In one case however, the polyamide continued to burn continuously. In the latter case, the threshold for the depletion of the gas phase agent was trespassed and the character of the material resembled pure polyamide. This was the result of an earlier ignition of the specimen which led to a stronger heat impact on the material before it was transferred to the catch pan.

Conclusion

The erratic nature of vertical cone calorimeter test presents a considerable challenge for any standardized assessment of material flammability. The test performed here, crude as they may be, reveal however some interesting material properties and shed light on phenomena that are not captured by other tests. This shall be discussed in the following, along with potential solutions to counter melt flow and considerations for a better test setup.

Information gained from vertical measurements:

A very important result of the vertical cone calorimeter measurements is the simple fact that they allow identifying materials that do not flow even under high thermal impact.

The measurement of the PVC sample, which does not flow in the vertical cone calorimeter test, showed that the flow of combustible gases and gases that act as flame retardants might be significantly different in vertical configurations and therefore also in real life applications as compared to the horizontal setup. The heat release rate in the vertical configuration was shown to be a multiple of the standard measurement. This might lead to considerable error in the prediction of flame spread from standard cone calorimeter measurements.

Another instructive observation can be made by comparing the PP and PA material performance in the vertical and horizontal cone calorimeter. Concluding from the standard test result only (see Table 1-8), both materials appear indistinguishable, with some advantages and disadvantages on both sides. The vertical cone calorimeter measurement shows however, that the PP material is much more likely to produce a significant fire and spread the fire by pool fire formation. Clearly, the PP material is overvalued in the horizontal cone calorimeter measurement with respect to the PA material.

Difficulties in testing:

A paradox with any measurement in vertical configuration is that materials with higher resistance to flow, as desired in principle, will be exposed to the heat source for longer times; meaning that the same test is tougher for a material with higher resistance to flow. This effect renders a consistent testing in vertical position almost impossible, as the materials are subjected to different doses of heat. The authors are not aware of any technical solution that overcomes the difference in heat exposure experimentally. In many real scenarios, the situation is the same. A material might melt and flow and thereby ignition might be prevented. Unfortunately, the geometries differ largely between bench scale test (very simple, flat sheets) and real products (complex geometry and many narrow spaces). So the bench scale test cannot reliably predict the flow behavior for the product or combinations of products.

Changing surface areas make vertical testing very difficult. For all the materials but UP-GF, deformation led to an initial increase in the surface area. The transfer of material to the catch pan led to an initial increase in burning area (flames on sample and catch pan) and a subsequent reduction (only flames on the catch pan). How much the materials

spreads out on the catch pan is another factor. Hence, even in the same instrumental setup the heat release data will be different for materials with different degree of deformation and flow, as the heat release is strongly affected by the area covered by a flame.

Materials that do not flow:

Figure 1-33 illustrates in which way the PVC and UP-GF sample succeeded in resisting gravity. The PVC sample acted as an intumescent material. That is to say that the exposed surface formed an expanded char layer that protects the residual sample from heat. Hence, the sample backside was not heated sufficiently to flow readily. The UP-GF material is not thermoplastic, but contains long glass fiber stripes which effectively prevent deformation (Figure 1-33). As was shown by TG, the material contains approximately as much glass as polymeric resin. Both approaches are very promising for obtaining materials with a high resistance to melt flow, which might be used as barrier materials^v.

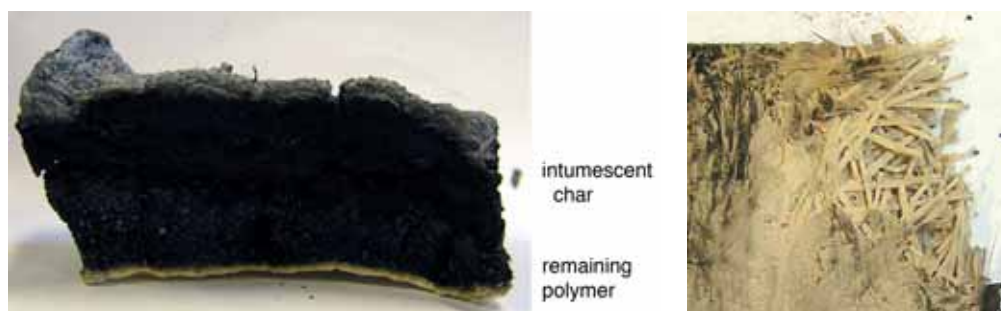


Figure 1-33: Digital photographs of the sample residues of PVC (left) and UP-GF (right) after the vertical cone calorimeter experiment. The UP-GF sample was broken in order to reveal the interior glass fiber structure.

3.4 Evaluation of the SBI apparatus as a test bench

As a preliminary study for future research projects, appliance enclosures made of the HIPS material were tested in full scale. The single burning item (SBI) apparatus (see section 2.9) was considered as suitable for the purpose of testing the ignition and burning behavior of a full-size electrical appliance box mainly due to that:

- The appliance can be mounted in a vertical position on a non-combustible board fitted in the test frame of the apparatus.
- This mounting gives good access to the appliance and a draught-free environment.
- Smoke gases from ignition experiments are collected by the hood of the smoke exhaust system.
- The heat release rate (HRR) and total heat release (THR) of the appliance can be measured in a burning behavior experiment.
- Visual obscuration, carbon dioxide (CO₂) and carbon monoxide (CO) can be measured in the smoke gases from the appliance.
- Any melt flow and dripping of material can be collected safely below the appliance.
- The experiments can be photographed and videotaped through the glass windows of the test room.

^v It should be born in mind that the glass fiber reinforcement requires a special production process which significantly limits the geometrical features of the apparatus.

A critical step for full scale testing of electrical fires is the choice of the right ignition source. In electrical fires, the heat source can persist for rather long times, as an arc sits on a faulty contact or a wire is overheated without the circuit being broken. The authors are not aware of any standardized solution to simulate this scenario. Whereas it would be desirable to use a faulty contact or an arcing device, the design of such an ignition source which works in a reproducible setup was not possible in the framework of this project.

Therefore, the next best approach to this problem was chosen, which consists in the use of a premixed flame. In this case, the combustible is mixed with a stream of air at the exit of the burner. By this means, an early extinguishment of the flame by oxygen depletion is prevented and the flame can be applied steadily for longer times.

For positions which were difficult to access with the burner, methamine pills were used. Methamine pills burn for approximately 1 min with a low intensity. The procedures used and the observations of the fire development are summarized in Table 1-10. A picture of the ignition source and an overview of the positions of application are given in Figure 1-34.



Figure 1-34: Left: Positions of flame application or placement of methamine pills for the full scale test. The burner was introduced through the flexible cable inlet to reach positions 1, 5, 6, 8 and 9 from the inside of the enclosure. Right: Burner outlet with the small premixed flame.

The results given in Table 1-10 can be summarized in the following manner. Although the material easily caught fire initially, the application of a small flame sources at 9 different positions did not lead to the initiation of a large flaming fire. Self-extinguishment occurred due to two effects. First, oxygen depletion in the enclosure quenched the flame. Second, melt flow caused the withdrawal of material from the vicinity of the flame. The material easily formed holes such that no material was present close to the heat source (Figure 1-35, centre).

Melt flow was strong in all cases and led to dripping of flaming material within the apparatus (Figure 1-36, left) and to burning droplets on the catch pan below the apparatus following the outward flame application (Figure 1-35, right).



Figure 1-35: Damage done to the enclosure after application of the small premixed flame to position 1, 5 and 7.

Table 1-10: Observations from the full scale ignition tests. The indicated positions are shown in Figure 1-34.

| Position | Flame source | Application | Observations |
|----------|--------------------|-------------|---|
| 1 | Burner | 30 s | The sample ignited readily and the flame spread upwards. 1 min after removal of the flame, the sample extinguished due to lack of oxygen. |
| 2 | Methamine pill | - | A hole forms in the enclosure such that there was no contact to the flame from the methamine pill. |
| 3 | Methamine pill | - | A hole formed in the outer wall of the enclosure such that there was no contact to the flame from the methamine pill. |
| 4 | Methamin pill | - | A hole formed in the outer wall of the enclosure. Flaming ceased after 2 min. |
| 5 | Burner | 30 s + 30 s | A hole was formed in the outer wall. The sample readily self-extinguished. The hole widened in the second application. The sample self-extinguished. |
| 6 | Burner | 60 s | The sample ignited readily and the flame spread upwards. The box was completely filled with black smoke and the flame was quenched. |
| 7 | Burner | 30 s | The sample burned for 2 min after the application of the burner. Then the burning part of the material fell to the catch pan and continued to burn for 3 min. |
| 8* | Burner | 60 s | The specimen burned for 5:25 min:s and then self-extinguished. |
| 9* | Burner | 60 s | The sample extinguished shortly after removal of the flame. |
| 10 | 3 kW welding torch | 60 s | The apparatus burned intensively. Molten material fell on the catch pan where it continued to burn intensively. |

* For these test, holes were opened in the enclosure to enhance ventilation.

With regards to the fire safety criteria, the enclosure cannot be expected to act as a barrier that contains a fire initiated in the apparatus. Flames very easily formed holes in the enclosure and burning material flowed to the surroundings. It was also seen that the material was ignited easily and burned for a few minutes. That allows for enough time to spread the flame to other items found in the full apparatus, such as cables.

The self-extinguishment of the apparatus depended strongly on the amount of oxygen available in the enclosure. It was a positive design feature of the enclosure that it had a tight seal which prevented any draft. This feature is however easily circumvented by the ease of formation of holes. The enclosure did not produce a large flaming fire when exposed to a small external heat source. However, the dripping of material that continued to burn for 3 min gives a considerable risk for a fire spread to nearby items. The ease of deformation of the material might also lead to a lack of protection against current carrying parts.

In order to see whether a larger fire of the enclosure can be measured in a suitable manner with the SBI setup, a welding torch was used to ignite the apparatus. The result of the heat release rate measurement is shown in Figure 1-36. The heat release produced by the enclosure was readily captured by the oxygen depletion measurement by the apparatus.

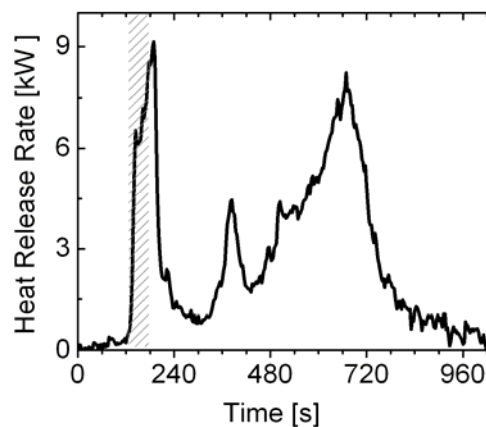


Figure 1-36: Heat release rate curve from the full-scale test in the SBI apparatus. The hatched area indicates the application of the welding torch which had an effect of 3 kW.

Conclusions

Besides the high heat release potential of the HIPS material, an ignition of the apparatus with a small flame source might be difficult in practice. A number of different scenarios should be evaluated for full scale tests.

Design features of the appliance, such as air tightness, had a strong effect on self-extinguishment.

A strong deformation of the materials gave a considerable risk for fire spread to the outside of the appliance. A lack of shielding of current carrying parts might be the consequence. Melt flow of burning material gave a considerable risk for flame spread within the apparatus and to the surroundings.

The appliance could be setup in a realistic and convenient manner in the SBI apparatus. Smoke and gases produced could be handled whilst the fire development could be observed. The HRR from the appliance can be measured should ignition result in a large flaming fire.

4 Conclusions

The current requirements on fire safety testing such as defined in IEC 60947-1 [4] do not satisfy the fire safety criteria as defined in this study. Most of all, relying solely on a glow wire test at 650° C to test enclosure materials or 960 °C for materials in contact with current carrying parts, does not provide an acceptable level of safety. The results from this study show that the glow wire test should not be used as the single criterion for fire testing, as long as there is no other fire barrier provided. It fails to judge both ignitability by a small flame and dripping of flaming material adequately. Deformation and strong melt flow of the specimen are in many cases favorable in this test method.

The heat transfer by melt flow strongly influences the vertical flame test and renders it difficult to judge intrinsic material quality. The test result is therefore geometry dependent and comparison with other testing methods is difficult. Especially the V-2 classification embraces materials of very unlike behavior and quality that may be of considerably flammable nature. Conclusion on the V-0 class could not be drawn here, as too few of the materials selected from the market reached this classification. The V-0 class is known to adequately describe ignitability by a small flame source, such as a stearin candle. Further limitations on melt flow and deformation even for the V-0 materials would be desirable to make the test less geometry dependent. For a wider fire safety assessment, more information on the mechanical integrity of the apparatus is required. Free access to live parts through holes in the enclosure and strong deformation that brings other parts of the appliance in contact with the live parts should be prevented.^{vi}

Calorimetric tests, such as the cone calorimeter and PCFC deliver very valuable information on the burning behavior of the material. Responsible material producers can with the help of these tests identify materials that do pass the bench scale test mainly by melt flow and deformation. For the time being the calorimetric methods can give clear answers when much better materials are to be distinguished from much worse materials. 7 of the 10 materials tested here showed an intermediate behavior that made it difficult to rank the materials. Some material showed a higher average heat release rate in the cone calorimeter test than others, but still their resistance against ignition by a small flame was better. Evaluation of overall performance is thus very important for cone calorimetric data. The discussion of the results should not be reduced to single parameters, such as the peak heat release rate. Both calorimeters do not provide information on self-extinguishment of samples of intermediate or poor quality in the vertical flame or glow wire test. First of all this is desirable, as the calorimetric methods are not as strongly influenced by melt flow and deformation. The underlying reason is that both calorimeters expose the samples to a significantly higher amount of external thermal energy. Due to this effect, endothermal processes and flame inhibition, which matter in the small scale flame tests, are not as effective. Further, temperature and mixing of gases – combustible volatiles, gas phase flame retardant agents and oxygen - are different in each test and hence the efficiency of the combustion will differ largely.

An experimental setup for vertical cone calorimeter tests was evaluated. Two materials could be identified that did not deform strongly when exposed to an external heat flux of 35 kW m⁻² ^(vii). 8 of 10 materials showed very intense deformation and melt-flow either before ignition (3 of 10 materials) or right after ignition (5 of 10 materials). The vertical

^{vi} To date, the 5VA classification in the UL 94 test does regard hole formation for a sample exposed to a significantly higher flame power 500W.

^{vii} One of those materials was not thermoplastic.

cone calorimeter measurements are difficult to conduct and the outcome depends on the design of the test set-up. Comparisons of different materials cannot be made in a straight forward manner. Still, valuable information could be added to what is obtained from the standard setup. Materials that have a high potential to form pool fires can be identified. For the PVC sample, a three time higher total heat release in vertical configuration indicated that data from horizontal measurements might be affected by a considerable error if used to predict vertical flame spread.

An evaluation showed that the single burning item apparatus may be used for full scale testing of switchgear in future research projects. The choice of a realistic ignition source and the necessity to evaluate various ignition scenarios are the principal challenges.

How to improve fire safety?

In the short term:

Small improvements could be made that would improve the situation. An approach as in IEC 60335 [20] which uses the glow wire tests as a first selection criterion for further testing with a flame is reasonable. Materials should however not be accepted only on the basis of a glow wire test. Requiring a minimum difference between ignition and flammability temperature will improve the situation. Materials that pass a glow wire test at for instance 800°C by lack of ignition, but are completely consumed by the flame initiated at 850 °C, should be disqualified. Stricter rules concerning melt flow are necessary. A V-0 requirement would avoid the high uncertainty that is associated with the glow wire tests or V-2 classification.

The transfer of information from fire testing laboratories to the designer that construct appliances should be improved. Designers should obtain some observation on the way the material passed classification, rather than just a label, such as V-2. In the IEC standard, the testing laboratory is required to document observation, for instance whether a test specimen passes the test by virtue of most of the flaming material being withdrawn with the glow-wire [21]. However, to date, this information does not reach the designer and is thereby effectively devoid of meaning. As material safety data sheets are nowadays communicated in electronic format, the additional work to pass on such vital information has become considerably smaller.

In the longer term:

A first option would be to set performance criteria for barrier materials and to describe some constructional requirements to what might be called a barrier. The latter could be flexible rules as to the position of current carrying parts and the relative position of barrier materials and materials of low flame resistance. A suggestion is that barrier materials could be selected by a combination of Cone calorimeter performance with a minimum time to ignition, maximum average heat release rate and maximum total heat release; and a test that considers the penetration of the material by a flame, similar to the 5VA criterion^{viii} of IEC 60695-11-20 [22]. A sufficient quality of the barrier provided, materials on the inside could be flammable to a certain degree. Material choice could concentrate on electrical and mechanical properties. Simultaneously, the definition of barriers could include considerations on the protection against electrical parts that might be freely accessible after overheating of easily melting materials. This approach relies much on the competence of the designers. An increased freedom in choice of fire

^{viii} To fulfill a 5VA criterion, a 125x13x3 mm³ specimen has to self-extinguish and cease glowing within a total time of 60 s after exposure to a 500 W flame. The flame is applied for 5 s and withdrawn for 5 s in 5 cycles. In identical manner, a plate made of the material is exposed to the flame from underneath the sample and penetration by the flame is not allowed for materials classified 5VA. In both cases, no dripping of flaming material is allowed.

performance levels of materials requires verification of the design rules by full scale tests.

A second option is to use significantly better material selection tests. The test should insure that the material withstands ignition by a small flame. The test should clearly state how melt flow and deformation affect its result. High classifications should only be reached by materials that do not pass the test by virtue of melt flow. The materials barrier properties', i.e. that no openings are formed, should be determined in the test. Finally, at least one component of the test should simulate long term exposure to excessive heat as such conditions are frequently met in electrical fires. The test result should express the materials' response to thermal insults of different magnitude. In such way a refined scale of the material's performance might be gained instead of the very coarse classification in many of the current tests. Including in the test scheme the thermal insult at which the material fails and yields a self-propagating fire, will provide vital and more reliable information. For instance, today a material might pass the 50 W vertical flame test, even if it would burn up completely when exposed to the flame for twelve seconds in stead of ten seconds^{ix}. This kind of information should be transparent to designers and end users.

A first response to the above list of requirements might be to think that the available materials cannot fulfill all the requirements. What is most important to know though, is to what extent each material fulfills the criteria and what the consequence of failure is. If this would be comprehensible for the designer, he might choose a reasonable combination of materials of different quality and consider the mass used of each and the distances between such materials. This appears to be more reasonable than just disregarding such information, as done today, or defining unreasonably high minimum criteria for all materials. A key component of this approach is to define tests and test reports that improve the communication between fire testing experts and appliance designers.

^{ix} Consider the HDPE material and its test result (see Table 1-7). This material was right on the threshold to obtain a V-0 qualification, but burned self-sustainingly with growing intensity in one test. Adding just a little more flame-retardant or batch-to-batch variation could lead to a V-0 classification of this material. The designer has no chance to see how narrowly the material passed classification.

5 Recommendations for future work

Following the conclusions drawn, we propose the following topics for future work.

Definition of performance criteria for barrier materials

A future study might consider requirements for materials that can act as a barrier between materials in contact with current carrying parts and other parts of the appliance or the surroundings. The required performance levels should make it easy to select the proper barrier for appliances of different electrical power and different amounts of combustible materials found in the appliance.

Improvement of bench-scale test methods

Substantial improvement of the current bench scale test methods is needed. Any new system should establish performance criteria in a very comprehensive manner. Considering ignition with a test flame and possibly an overheated conductor, the test should yield:

- the time to failure at different levels of thermal impact
- the consequence of failure – fire propagation at what approximate rate?
- the influence of melt flow and deformation on the result measured
- information on mechanical integrity
- the deterioration of material performance after long-time exposure to heat

The aim should be to define a new scale of performance criteria that truly gives the designer insight into what may happen in the case of a dysfunction. At the same time, such performance criteria would allow the designer to make better choices on where to employ the right type of material. Only attaining this level of information transfer will allow reaching a high level of fire safety whilst choosing the right and not excessive amounts of flame retardants. It is also needed for any attempt to simultaneously optimize different aspects of fire safety, such as flammability, smoke production and toxicity.

Design and fire safety

Future work that considers the influence of appliance design and flammability would be very valuable. The experience from the current study is that there is very limited intellectual exchange between experts from both fields. An interdisciplinary study should lead to very promising results. The development of a prototype with a high level of fire safety and minimized use of flame retardants could be an excellent starting point.

Full scale tests

The evaluation performed in this study shows the practical difficulties of full scale tests quite clearly. Many scenarios have to be tested and the result is still a coarse approximation to the real life scenario. Results from the available bench-scale tests show very limited correlation. The same difficulties are to be expected were a correlation between these tests and full-scale tests attempted. Due to the considerable cost associated with sensible full scale testing, we therefore recommend performing full-scale tests to evaluate the performance of improved bench-scale tests or new design criteria.

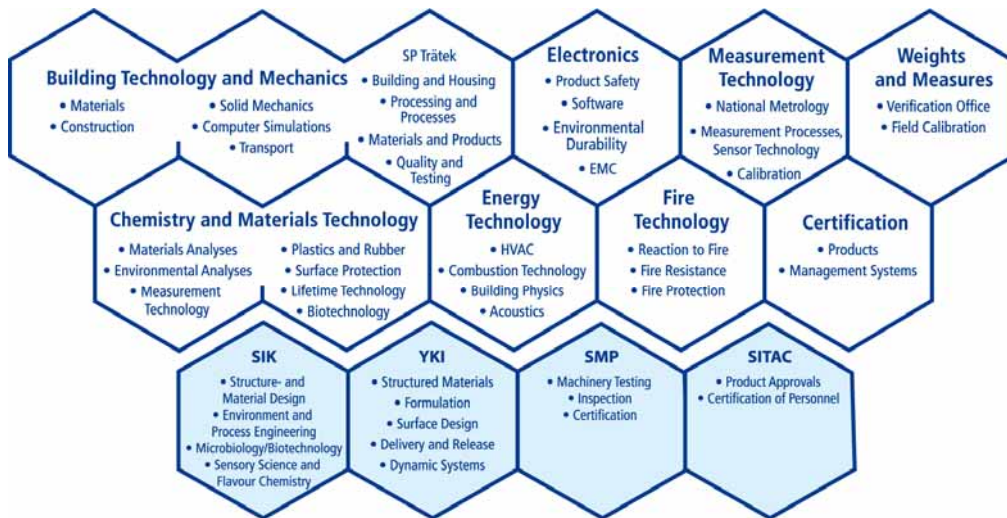
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