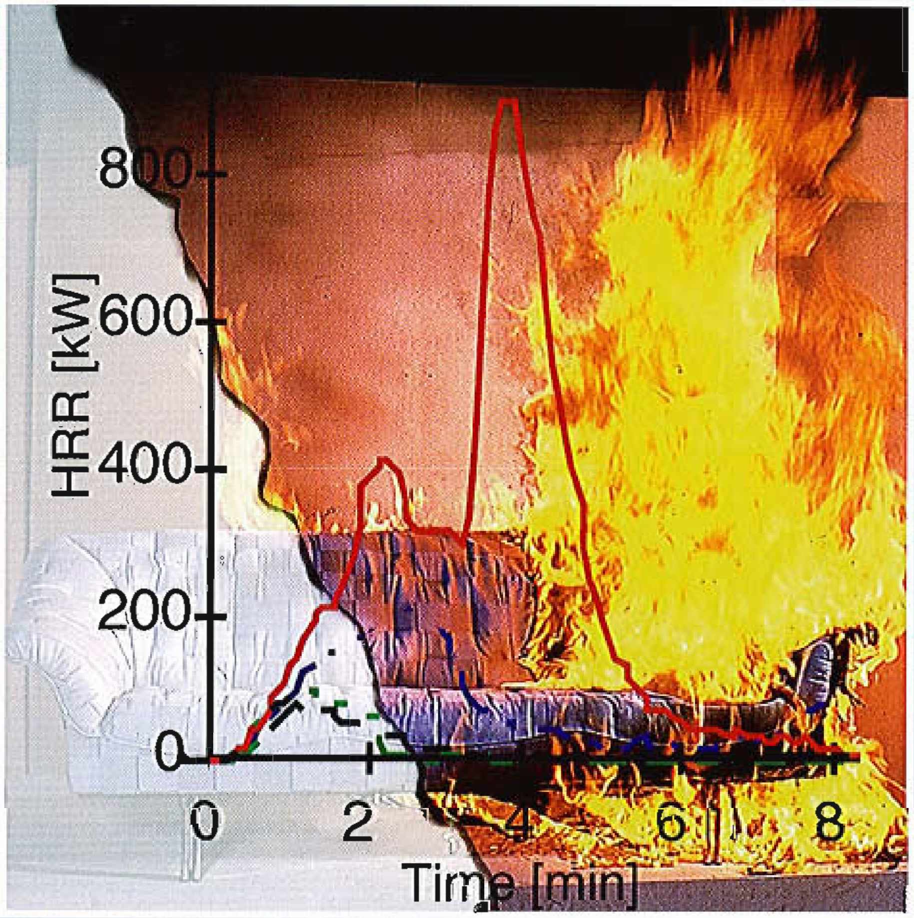
Kenneth Höglander
Björn Sundström

Design Fires for Preflashover Fires

Characteristic Heat Release Rates of Building Contents



SP Swedish National Testing and Research Institute
Fire Technology
SP REPORT 1997:36

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Abstract

When performing a risk analysis the selection of a correct design fire is a key element. This report seeks to improve the process of defining design fires by providing input of the characteristic burning behaviour of various products, for example furniture and linings. The input is based on direct test data, generic properties of products or statistical information of the burning behaviour of groups of products. The approach is to determine characteristic heat release rates (HRR) for groups of products in isolation and then put them together in a design fire that is adapted to the actual case under study. Upholstered furniture, surface linings, floor coverings, cables and some other product groups are specially studied in this work.

The research was sponsored by BRANDFORSK and SP.

Key words: design fires, upholstered furniture, surface linings, floor coverings, cables, fire engineering, fire technology

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Sammanfattning

När man gör en riskanalys så är valet av dimensionerande brand av stor betydelse för resultatet. Samtidigt kan det vara mycket svårt att finna en lämplig approximation av den brandsituation som kan tänkas ske i verkligheten. Nuvarande ISO standarder och NKB rekommendationer är ytterst grova i sina uppskattningar och ger mycket konservativa uppskattningar. ISO anger t.ex. att stoppmöbler nära brännbara ytskikt alltid ger en ultrasnabb brandtillväxt. Detta arbete syftar till att underlätta valet av dimensionerande bränder genom att ange karakteristiska brandförlopp för olika produkter.

Utgångspunkt är olika produktgruppers brandbeteende. Beroende på typ av produkt har vi utifrån försöksdata, modeller för produkters brandförlopp, generella materialegenskaper eller statistisk information anvisat karaktäristiska kurvor för avgiven värmeeffekt för möbler, ytskikt, golvbeläggningar, kablar och draperier/gardiner. Sedan visas hur sådana typbränder kan ställas samman till stöd för val av dimensionerande bränder. Ventilationsförhållanden och andra faktorer såsom släcksystem får sedan avgöra brandens maximala storlek för en slutlig anpassning till ett specifikt verklig fall.

För möbler (stoppmöbler och bäddar) och ytskiktsprodukter (skivmaterial mm) har karaktäristiska kurvor för avgiven värmeeffekt kunnat anges baserat på en mycket stor databas. Statistik på brandförloppets variation för olika möbler anges. Den visar att publika möbler generellt uppvisar långsammare brandförlopp än möbler som saluförs till enskild konsument. Det har också varit möjligt att beskriva karaktäristiska kurvor för avgiven värmeeffekt för ytskikt baserat på deras ytskiktsklass. I förlängningen blir det då möjligt att beskriva konsekvensen för brandskyddet vid val av olika yskiktsklasser, något som hittills har varit mycket svårt att göra inom ramen för byggnormen. Speciellt kan man studera hur val av olika ytskiktsklasser påverkar utrymningstider i jämförelse med stoppmöbler. Metoden tillämpas som exempel, bl.a. på ett verkligt experiment med möblerat rum.

Arbete har bedrivits med anslag från BRANDFORSK, statens, försäkringsbranschens och näringslivets gemensamma organ för att initiera, bekosta och följa upp olika slag av brandforskning. En styrgrupp har varit kopplad till projektet under ordförandeskap av prof Kai Ödéen.

1 Introduction

A new concept has emerged in fire safety engineering during recent years. It is the replacement of prescriptive fire codes with performance oriented codes. Prescriptive codes state, for example, the width of an emergency exit, the maximum distance to emergency exits, the type of surface linings in different kinds of buildings and so on. Using the prescriptive method the engineer must follow a prescribed set of rules when designing a building. The idea with performance based fire safety regulations is that a building can be constructed just the way the designer wants as long as the risk is below a certain limit, the design objective. The design objective could be that the risk for one person being killed due to a fire in a building is below, say 1%.

A person will die, or is assumed to die, when untenable conditions are reached in a fire. Untenable conditions are for example when a hot layer temperature exceeds some limit value or when the distance of the smoke layer above floor is below a certain value (say 1.5 m). For the positive outcome, no person killed, the time to untenable conditions must be higher than the necessary escape time. The necessary time for escape consists of detection time, response and behaviour time prior to evacuation and movement time. The design fire is a key factor when calculating the time to untenable conditions and this report is only treating the process of defining a design fire for preflashover conditions.

Theoretically there are an infinite number of fire scenarios for every building or every part of a building. The number of fire scenarios in a hotel room is a function of the surface linings, the floor coverings, the type of furniture, how the furniture items are positioned relative each other, were the ignition source is, the dimensions and other characteristics of the fire room, the openings etc. To make a correct risk assessment of this hotel room we have to know the probabilities for each of these configurations. Complicating it further is the response to fire of people. Hence, there are many possible outcomes and no statistics available for solving the problem. Instead a rationalised approach must be taken. We will focus the attention on actual fuel packages.

ISO/ TC 92 Fire Safety, SC 4 Fire Safety Engineering, is working on a series of documents covering the topic of fire performance concepts (ISO/CD 13387-13394 [1,2,3,4,5,6,7,8]). However, the documents are written in very general terms leaving to the consultants to interpret the documents. In the document ISO/ CD 13388 Fire Safety Engineering- Design Fire Scenarios and Design Fires, it is more the methodology of constructing a design fire that is emphasised than giving actual examples of how to do it. It is recommended that statistics for the building and occupancy under consideration is used to identify the most likely type of fire scenario. This is done using information of most common item ignited, ignition source and location of fire. The design fire is chosen from the most likely scenario having the highest fire hazard, the worst credible case is used. However, fire statistics is far from complete, engineering judgement must therefore be used.

The design fire is something that should be chosen very carefully, but there are only occasionally tangible proposals . The most frequently suggested design fire is the t^2- fire where the heat release rate is described by $\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g} \right)^2$, $\dot{Q}_0$ is normally chosen to 1 MW. The recommendations of t_{ref} are 600, 300, 150 and 75 seconds for *slow*, *medium*, *fast* and *ultra fast* fires respectively.

In Annex A in ref. 2 proposals for t^2- fires are given for various design fire scenarios, see Table 1.

Table 1. Design fires as given in ISO/CD 13388

Design fire scenario	**Category**
Upholstered furniture and stacked furniture near combustible linings	*Ultra fast*
Light- weight furnishings	*Ultra fast*
Packing material in rubbish pile	*Ultra fast*
Non- fire retarded plastic foam storage	*Ultra fast*
Cardboard or plastic boxes in vertical storage arrangement	*Ultra fast*
Office furniture- horizontally distributed	*Medium*
Displays and padded work- station partitioning	*Fast*
Bedding	*Fast*
Floor coverings	*Slow*
Shop counters	*Medium*

This report contains a further analysis on how to find a design fire for a certain scenario. We will especially study the cases with upholstered furniture, surface linings, floor coverings and cable trays. Only heat release rate will be considered, mainly because a lot of measured data is available and more importantly, heat release is assumed to be the single most important parameter influencing the fire [9]. As a first step we will develop an estimate of a characteristic heat release rate for the product group in isolation, i.e. we do not at first assume that the burning item, for example a piece of furniture, will ignite other combustibles. This approach is necessary as 1) there is very little data of complete room fires and 2) the number of possibilities to combine products is infinite and therefore it is necessary to treat this problem by considering product group by product group. Thus the resulting recommendations given in this report are based on data and expert judgement. Uncertainties in the estimates are therefore not based on general statistical data but on the actual variation in the burning behaviour of different products.

2 Upholstered Furniture

Upholstered furniture items are very special products in terms of their fire hazard. A small flame in an upholstered chair can develop into a disastrous fire in only a few minutes. There are very few, if any, items in a home that have this potential for fire development. Surveys of European statistics show that a major cause of fire fatalities are associated with burning of upholstered furniture[10]. In private dwellings they were found to cause 49% of all fatal casualties and in public buildings 15%. Ignition by smokers' materials is a common event (42% of reported cases) that can start the fire. After a period of smouldering or "hidden burning" visible flaming appears. Once the furniture is burning, the growth rate of the fire may be so large that people are not given sufficient time to escape. They become victims in a fire that develops too fast for them to escape.

One of the most stringent fire requirements on upholstered furniture in the world is found in the UK. Still, highest death rates in the UK, 35% in 1995[11], are attributed to fires that are started by smokers' materials, i.e. cigarettes, matches. Although not explicitly spelled out, it is a reasonable assumption that the ignited item is some upholstered item, a bed or a piece of furniture. Thus there is massive evidence that a design fire must include the influence of upholstered furniture if such items are present in the building in question. What are then the assumptions for a characteristic heat release rate, HRR_k , when upholstered furniture is the first item to ignite?

2.1 Characteristic heat release rates for upholstered furniture

ISO, International Standardisation Organisation, is in the process of creating a procedure for design fire scenarios and design fires, ISO/CD 13388[2]. This document is still under development before becoming a full international standard. However, it is considered to largely reflect the state of the art and therefore we will use it as a basis for some discussions.

Paragraph 7.6 of ISO/CD 13388 "Pre-flashover Design Fires" gives us the tools for estimating a design fire where upholstered furniture is the first item ignited. The recommended equation for the growth rate is the t^2 - fire as described in section 1:

$$\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g} \right)^2$$

Q_0 is 1 MW. The document gives us the following guidance on selecting the characteristic time t_g, see Table 2

Table 2. Categories of t^2 - fires

Growth Rate Description	Characteristic Time t_g (s)
Slow	600
Medium	300
Fast	150
Ultra fast	75

Annex A of ISO/CD 13388 recommends that upholstered furniture near combustible linings and that bedding (no specification of linings) should be considered as *Ultra fast* and *Fast* respectively. We can compare these categories with real data on upholstered furniture fires.

One of the largest databases on furniture fires available is from the CBUF[12] research programme. In CBUF upholstered furniture items were selected as to reasonable well represent the market in Europe as well as a wide range of burning behaviour, see figure 1.

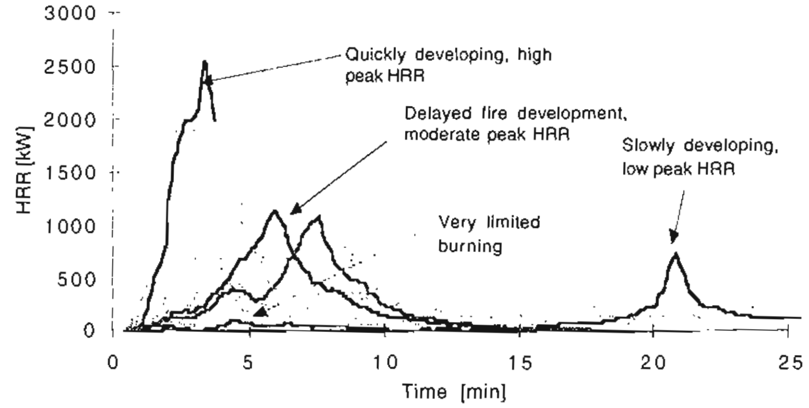

Figure 1. The burning behaviour from a selection of European furniture items.

The CBUF furniture were tested in the Furniture Calorimeter[13] or in the ISO 9705[14] room having non-combustible linings. The data refer to single objects burning under well ventilated conditions.

Four groups of burning behaviour of upholstered furniture were identified:

I Quickly developing, high peak HRR. Items in this group show a burning rate which causes flashover in most dwellings without any involvement of other combustibles.

II Delayed fire development, moderate peak HRR. Items in this group have a burning rate sufficient to cause flashover in small rooms without any involvement of other combustibles.

III Slowly developing, low peak HRR. These products will not cause flashover by themselves. The fire will in most cases stay in the room of origin unless other items in the burn room are ignited. Of course this is highly unlikely unless the fire in the item is small and localised to the furniture itself.

IV Very limited burning. Theses are products that do not burn outside of the close vicinity of the ignition source. As soon as the ignition source ceases they will also stop burning.

The shape of the curves in Figure 1 suggests that the squared-time growth of design fires will not work unless the fire is rapidly growing and actually igniting other items like the linings.

NKB[15]gives a selection of design fires depending on the type of building, see Table 3

Table 3. The NKB design fires.

Category of use	α (W/s^2)
A (dwellings)	12
B (hotel)	50
C (shops, public spaces)	190
D (schools, offices)	50
E (industry of large fire hazard)	not applicable

The design fire is expressed as $\dot{Q} = \gamma_q \alpha t^2$ where $\dot{Q}$ is the HRR, α is given above, t is time and γ_q is a partial coefficient. There are no recommendations on how to use the partial coefficient. This expression gives the same result as the earlier mentioned formula $\dot{Q} = \dot{Q}_0\,(t/t_g)^2$.

Let us now compare the ISO and NKB design fires for upholstered furniture with HRR$_k$ as measured in the CBUF project, see Figure 2.

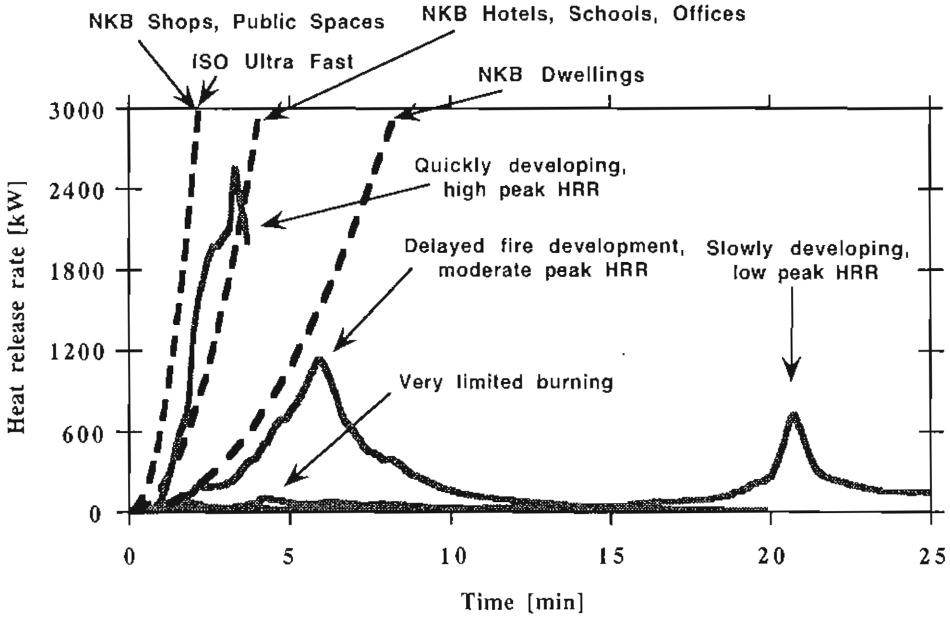

Figure 2. Heat release rate as a function of time for a representative selection of European upholstered furniture as compared to the design fires recommended by ISO and by NKB.

The ISO standard[2] attempts to estimate fires involving upholstered furniture using one design fire characteristic only. The concept of worst case has then been used. An envelope was selected that would include all possible fires in upholstery. This leads to a very conservative estimate. The *ultra fast* design fire was selected assuming a fire size of 1000 kW in one minute and 15 seconds after ignition, see Figure 2. However, in reality this approach must be modified if product burning characteristics is considered.

Many items burn very slowly, in excess of 20 minutes before the fire reaches any size large enough to pose a threat by itself or to ignite other items that will start a rapid fire growth.

The NKB dwelling design fire corresponds roughly to the ISO *medium* fire and is therefore allowing longer escape time. However, Figure 2 indicates that the fire growth in dwellings may be faster than this, but no indication is given how frequently a faster growth may occur. The answer must be found in statistics on furniture types and their use in dwellings. This issue is discussed in the section "Estimating HRRk by use of statistical data" below.

The data from Figure 2 points to the possibility to select a more appropriate design fire than so far has been recommended. There are various approaches that can be used for better precision.

2.2 Selection of the appropriate characteristic heat release rate for upholstered furniture

There are principally three ways, in decreasing order of precision of the prediction, to select a characteristic heat release rate, HRR_k, for a furniture item;
(1) to use test data on the actual items,
(2) to use generic data once the principal design is known and
(3) to use statistical data related to the type of occupancy.
Each of these possibilities is discussed in the following.

2.2.1 Estimating HRR_k by use of test data of the actual items

The use of test data is obviously the best to define the HRR_k as it will in fact in most cases reflect the real situation with high accuracy. The HRR curve (and smoke and toxic gas species) is best measured in the Furniture Calorimeter[13], see Figure 3.

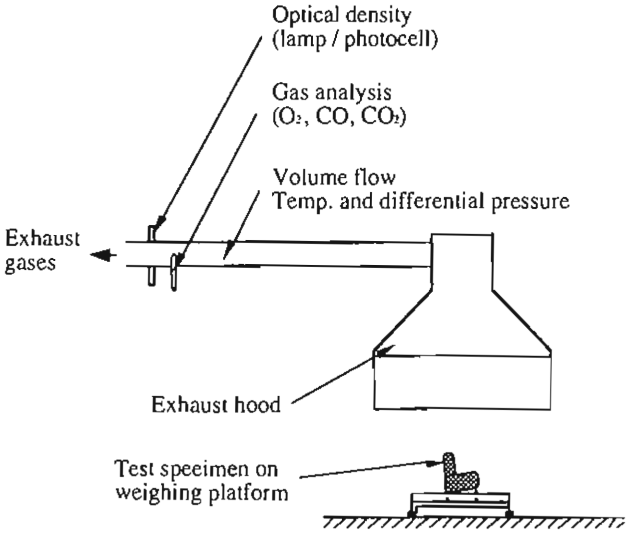

Figure 3. The Furniture Calorimeter.

The test specimen is a full size item of upholstered furniture as it appears in reality. It is ignited with a gas burner and burns freely without any restriction of air supply. In a room environment there is the possibility of increased HRR from the item due to radiation from the hot smoke layer giving extra support to the combustion. Experiments[12, 16] in a small room 3.6 m x 2.4 m x 2.4 m showed that the room influence was small. At a HRR from the item of up to about 60%, in this case 600 kW, of the HRR required for flashover there was no influence measured. Between 60% and 100% of HRR required for flashover an increase of 20% only of the HRR was noted. Thus increase of HRR from the furniture item due to room environment is neglected as 1) untenable conditions in the room of fire origin is reached before any measurable effect is expected and 2) the overall effect is small and maybe even smaller in large rooms.

For illustration, HRR data of testing identical specimens of a chair in different European laboratories is given in Figure 4.

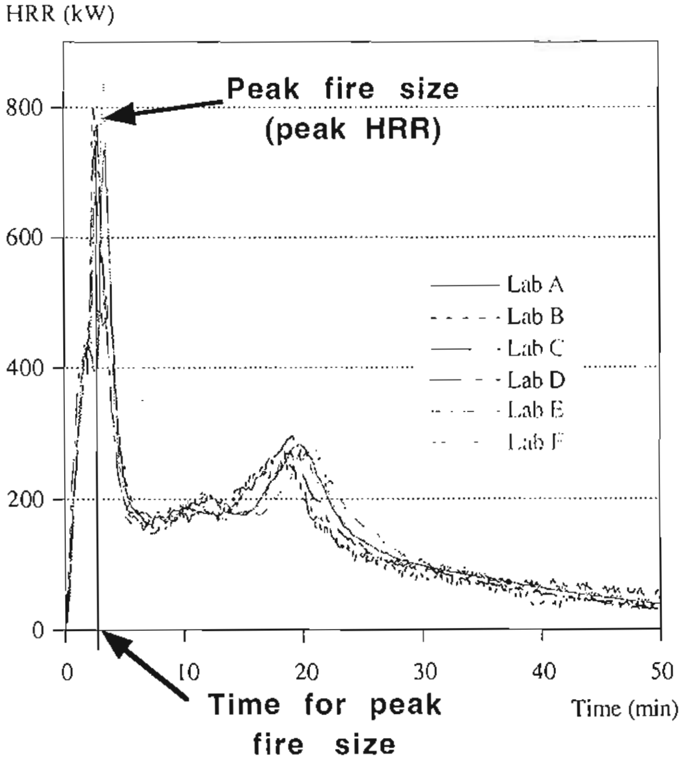

Figure 4. Heat release rate, HRR, from the same type of chair when tested in the Furniture Calorimeter by 6 different European fire laboratories. Data from the Furniture Calorimeter interlaboratory calibrations.

The high reproducibility of these results can be noted. Thus using Furniture Calorimeter data is a highly accurate approach to define the HRR_k.

The Furniture Calorimeter would be sufficient to produce indata for creating a design fire. However, it is expensive to always test full size furniture. Thus a bench scale test would be advantageous. This is the Cone Calorimeter[17].

2.2.1.1 The Cone Calorimeter for upholstered furniture

The Cone Calorimeter, ISO 5660[17], is a bench scale test method that measures all the fire parameters as the furniture calorimeter does but on samples that are only 10 by 10 cm. If one could translate HRR, smoke and toxic gases into what a full size burning furniture would give off then the link to the fire scenario is established. The procedure is given in Figure 5.

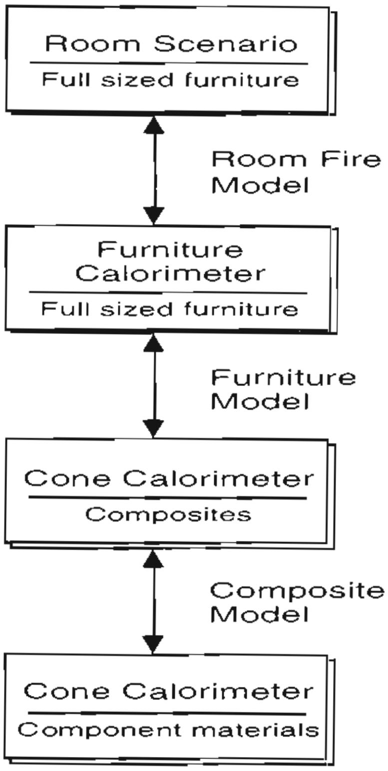

Figure 5. Validation of small and large scale calorimeters for a fire scenario. The calorimeters measure heat release rate, HRR, and rates of production of smoke and toxic gases. The Cone Calorimeter data are translated into the burning behaviour of a piece of upholstered furniture by a model; small to large scale. The Furniture Calorimeter data from a full sized furniture is translated into the fire scenario, the room conditions, by a fire model.

Computer codes like CFAST can use HRR data from the Furniture Calorimeter to model the environmental consequences of the fire in a room. However, the modelling between small and large scale is not yet fully established.

Babrauskas[18] has developed a correlation between Cone Calorimeter and Furniture Calorimeter data. The HRR curve for the Furniture Calorimeter is approximated as a triangle. Further correlation work has been done by Parker[19].

Kokkala[20] has developed a method of calculating an index that reflects the HRR of a full sized fire. This was done for surface linings in the EUREFIC research programme, but with some modifications this approach also applies to furniture.

It is essential that the models can handle the effect of furniture design. Furniture constructed of similar materials may burn quite differently due to differences in design only. Perhaps the most comprehensive study on predicting the HRR curve for a full size furniture based on Cone Calorimeter data was done in the CBUF project. The model is called "the convolution model".

The convolution model first presented in CBUF was developed by Kokkala, Baroudi and Myllymäki at VTT. It predicts the full heat release curve from a full scale furniture item based on data from the Cone Calorimeter.

The heat release rate $\dot{Q}(t)$ from a full scale burning furniture item is calculated as the convolution integral of the burning area increase rate $\dot{A}$ and the heat release rate $\dot{q}''(\vec{r};t)$ from the burning area according to:

$$\dot{Q}(t) = \int_0^t \dot{q}''(\vec{r};t-\tau)\dot{A}(\tau)d\tau$$

The heat release rate from the burning area is taken to be the same as in the Cone Calorimeter tests with an irradiance of 35 kW m^{-2} and specimen thickness of 50 mm. The exposure flux of 35 kW m^{-2} in the Cone Calorimeter is justified by measurements of heat fluxes from large scale fires.

The effective burning area *A(t)* and its derivative $\dot{A}(t)$ are functions which relates the heat release rate measured in the Furniture Calorimeter to the heat release rate per unit area measured in the Cone Calorimeter. They can be found in ref. 12.

This model was tested very successfully on a relatively large number of products in the CBUF project. Examples of comparison between predicted and measured HRR curves are given in Figure 6.

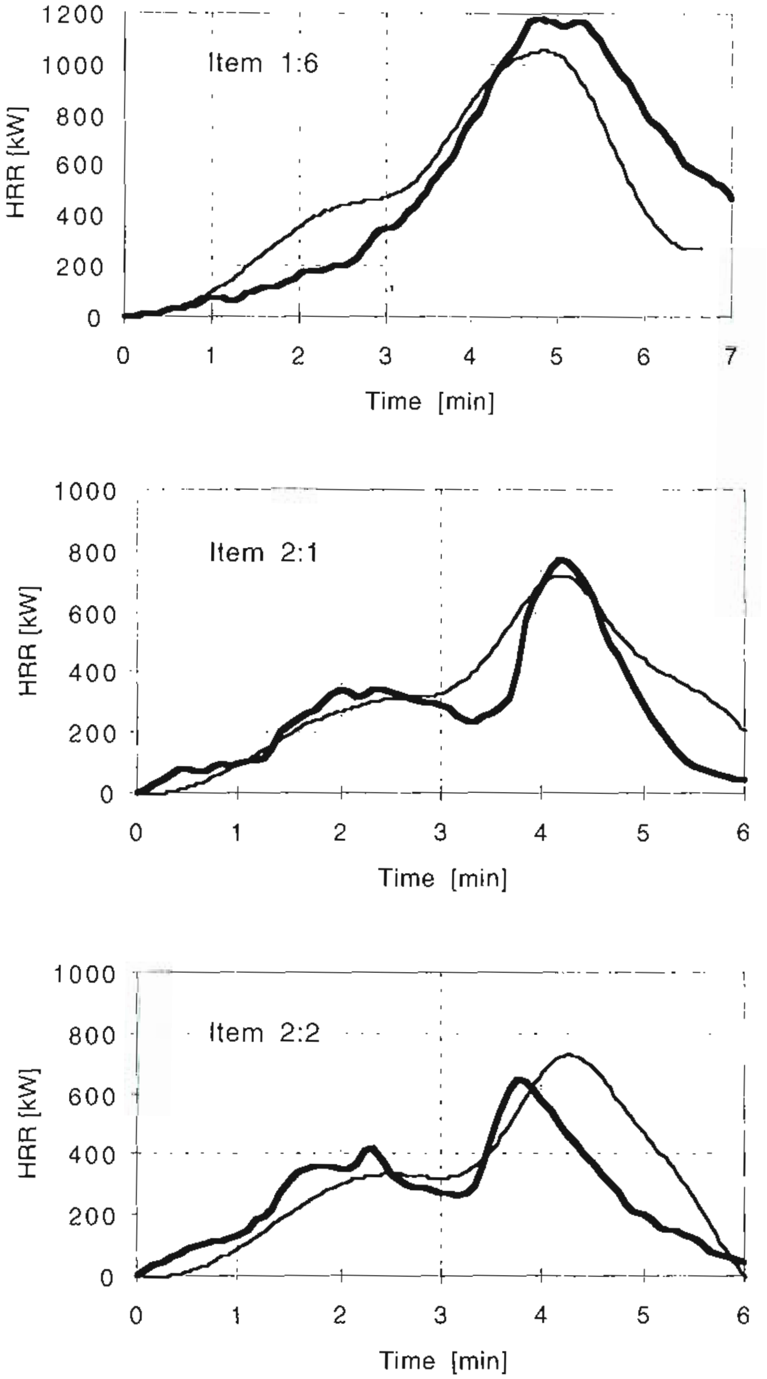

Figure 6. Measured (bold line) and calculated HRR for armchairs using the convolution model (Kokkala et al from the CBUF project).

Thus we see how test data either in full scale or bench scale can be used to generate a HRR_k with very good accuracy. However, in many cases test data is not available and only a general information about the design and materials used in the furniture is known. This case calls for estimates of a general burning behaviour based on product specification only. We call this use of generic data.

2.2.2 Estimating HRR_k by use of generic data

Different types of materials and how they are combined have a profound influence of the burning behaviour. Therefore by knowing the design and composition of an upholstered item a more or less qualified guess on the expected burning behaviour can be made. The CBUF book chapter 11 gives a comprehensive review on what was found on a typical selection of European furniture. In general the following relations apply, see Table 4.

Table 4. Effect on fire development as a function of design and material selection of upholstered furniture.

Material	**Effect on fire development**
Charring fabrics	Improvement
Melting fabrics	Impairment
Fabric weight	Varies
CMHR* foam	Large improvement
Neoprene	Very large improvement
Interliners	Very large improvement
Design features	**Effect on fire development**
Presence of armrests	Impairment
High or low back	Varies
Gaps between major cushion areas	Improvement
Internal cavities	Impairment
Button tufting	No influence
Frames	Varies
Increase of size	Impairment

* Combustion modified high resilient foam.

The data is too scant to be translated into HRR_k without a certain amount of speculation. However, it is evident that a combination of positive factors in design and material selection can result in very safe products, see Table 5.

Table 5. Products tested in the CBUF project showing limited burning during large scale testing.

Item number /type	Peak HRR (kW)	Padding	Interliner	Fabric
1:26 / divan bed	10	Various fibrous material	-	75% polyester 25% viscose
1:25 / mattress	16	Impregnated foam	-	FR vinyl reinforced sheet
5:7 / chair	22	To meet Cal. TB 133*	Glass fibre	100% cotton FR treated
1:24 / mattress	29	CMHR foam	-	100% polyester
3:18 / mattress	40	HR urethane foam	-	100% cotton FR treated
2:13 / chair	49	Full depth impregnated urethane foam	-	100% wool FR treated

Item number /type	Peak HRR (kW)	Padding	Interliner	Fabric
1:18 / office chair	39	To meet Cal. TB 133*		100% wool tweed
2:16 / chair	58	CMHR foam	Glass fibre	100% cotton
2:15 / chair	71	HR urethane foam	Proprietary FR product	100% wool
4:4 / 2 seat sofa	82	CMHR foam	-	100% wool
4:5 / chair	98	CMHR foam	-	FR vinyl coated cover
3:16 / chair	167	HR urethane foam	-	100% FR polyester
2:5 / chair	201	HR urethane foam		100% wool
3:13 / chair	226	HR urethane foam	-	100% FR polyester
3:4 / chair	251	HR urethane foam	-	100% cotton FR treated
3:6 / chair	262	HR urethane foam	-	100% cotton FR treated
3:17 / mattress	263	HR urethane foam	-	100% cotton FR treated
3:8 / chair	310	HR urethane foam	-	100% cotton FR treated
3:9 / chair	313	HR urethane foam	-	100% cotton FR treated
1:23 / mattress	330	Polyether foam	-	100% polyester
3:3 / chair	361	HR urethane foam	-	100% cotton FR treated

Key: *This chair is designed to meet the Californian standard T.B. 133

Estimating a characteristic heat release rate on generic data will of course vary in success. For the very good products the estimates are expected to be quite good as those products are designed not to burn and therefore have a stable behaviour. However, there are cases when the only information available of the occupancy is that furniture is present. Can a HRR_k be envisaged under such circumstances?

2.2.3 Estimating HRR_k by use of statistical data

It may be possible to link a certain occupancy or use of a building to a certain type of furniture. This requires detailed statistical data on the furniture population and knowledge how this particular group of products generally burn. Such data is largely lacking and this is an area where further research is needed.

However, the CBUF data base contains growth data and makes a distinction between domestic and public furniture. Although the statistics is not comprehensive it is useful for the purpose of this comparison, see Table 6.

Table 6. Time to peak HRR for domestic and public furniture in Europe. Average values from a selection representing the market place as well as a wide range of burning behaviour. The corresponding NKB data is also given.

Furniture category	Average measured peak HRR ± standard deviation (kW)	Average measured time to peak HRR ± standard deviation (s)	The time corresponding to the average measured peak HRR as calculated from the NKB recommendations (s)
Domestic	1278 ± 719	339 ± 278	326
Contract (Public)	727 ± 465	490 ± 439	121

The results are clear. The domestic type furniture burns much more and faster than the public furniture. This is probably due to a general tendency in Europe to require higher safety standards of public furniture than of domestic furniture.

The NKB recommendations for domestic fires are almost exactly similar to the HRR_k of domestic furniture. Considering the standard deviation of these data of the burning rates the NKB design recommendation would therefore lead to an underestimate of the fire hazard for many cases. The situation becomes worse when adding the fact that the furniture also will ignite other items like the linings. For hotels, schools and offices the situation is better. The design fire is a conservative estimate compared to the HRR_k of real furniture. Thus NKB design seems to express a wish to well protect public spaces but considers the domestic area of lower priority.

We can use the statistics from CBUF to define HRR_k for domestic and public upholstery. We can select the average peak HRR as maximum and the average time to reach there as input to a bell shaped curve. However, the HRR_k will not represent the worst case as it is based on an average burning behaviour. We can estimate the uncertainty of HRR_k, but instead we select, quite arbitrarily, a safety factor of two, i.e. the average peak HRR is multiplied by two and the corresponding average time to peak is divided by two. The result is the following two characteristic HRR curves:

$\dot{Q} = 2500 \exp(-0{,}4(t-3)^2)$ for domestic upholstered furniture and

$\dot{Q} = 1500 \exp(-0{,}2(t-4)^2)$ for contract (public) upholstered furniture

$\dot{Q}$ is the HRR in kW and t is expressed in minutes. At time t=0 the HRR is 50 kW following the recommendations in (12).

The resulting curves are shown in Figure 7.

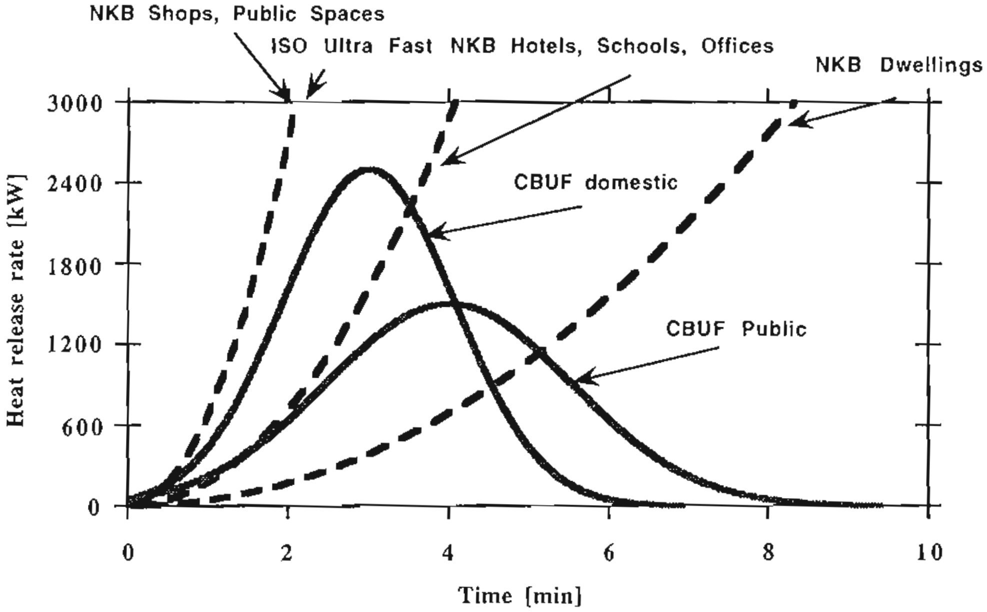

Figure 7. Characteristic heat release rate curves for public and domestic type upholstered furniture.

In comparison with the recommendations from ISO and NKB we see that:

- The proposed domestic furniture fires are close to the *Ultra Fast* ISO fire although somewhat less severe.

- The proposed public furniture fires are close to the public type NKB fires.

- The proposed furniture fires are intended to be on the safe side.

An important limitation is that we have ***only considered upholstered furniture items in isolation.*** Therefore the furniture HRR_k all decay after sometime. Involvement of other combustibles, for example linings, may lead to a faster and ever growing fire until ventilation control is reached. The actual design fire for a case of linings and furniture interacting is estimated in section 9.1 of this report. Therefore, the next step is to develop a concept for characteristic heat release rate for surface linings.

3 Surface linings

Surface linings include wall and ceiling coverings. The burning behaviour of these materials may dominate the fire growth in a room. The ignition source is rarely the surface lining itself but a wastebasket or furniture item for instance. However, the type of surface lining affect the spread of flame and hence the heat release rate in the room of fire origin[21]. A surface lining with a low contribution to the heat release rate could be neglected from the total heat release, since it is the furniture that will dominate the fire in that case. However, in most cases the surface lining should be included in the risk analysis. To do that, input data on fire growth is required. Most data available comes from fire tests in large scale.

3.1 Testing surface linings

It is difficult to state how a certain surface lining will respond to a fire, because the response will depend on the geometry of the room, ventilation conditions, position of the ignition source etc. One way of attacking this problem is to use the empirical fact that a fire propagates more rapidly in a small room than in a large [22,23,24]. A relatively small room is the ISO 9705 test room (2.4 x 3.6 x 2.4 m). Because of its frequent use in research projects [25,26] this room dimension has been used in more tests than probably any other test. In many circumstances, when the room is much larger, more well ventilated etc., a surface lining would behave in a less severe way, but until computer models are able to predict flame spread, using data from this method is one way to tackle the problem.

In the ISO 9705 test the surface lining is mounted so that the three inner walls and the ceiling are covered. Smoke gases are vented and air is let in through the door opening (0.8 x 2.0 m). The ignition source is a gas burner which is placed in one of the inner corners. The burner heat output is 100 kW for the first ten minutes and then 300 kW for another ten minutes. Heat release rate and smoke production rate are measured continuously, see Figure 8.

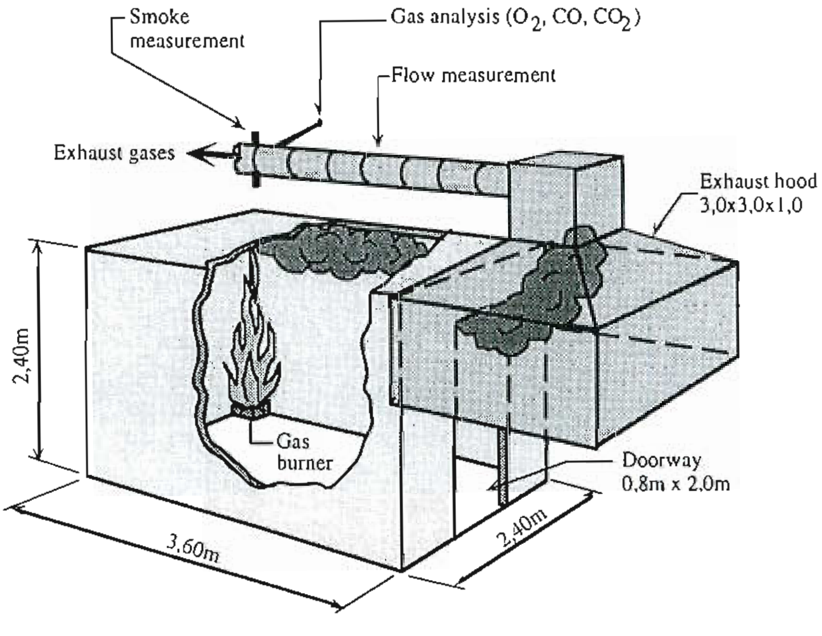

Figure 8. Schematic drawing of the ISO 9705 room test equipment.

3.2 Classification system in Sweden

In Sweden[27] three different surface lining classes are used, class I, II and III. The normal test method is SS 02 48 23 (NT FIRE 004), a small scale test where the inside of a small box is covered with the surface lining at three walls and ceiling in much the same way as in ISO 9705. A burner flame is applied to the inner wall. During the test the temperature and the smoke are measured on the outgoing fire effluents. Class I permits the lowest values of temperature and smoke and class III the highest. If the surface lining has some characteristics that make it unsuitable for testing in SS 02 48 23, thermoplastics may for instance melt and form a pool at the floor of the equipment, a full scale test by ISO 9705 could be performed. The burning rate criteria for class I are that the HRR during the 20 minutes test should not exceed 300 kW excluding burner, and the average HRR should not exceed 50 kW for the duration of the test. The criteria for class III is maximum 900 kW excluding burner during the first 2 minutes of the test. Note that class II is not used when it comes to full scale testing.

As indicated by research [28], class II surface linings may, when tested in large scale like ISO 9705, behave both like class I and class III products. Products classified as class II can therefore not be said to have some specific large scale fire behaviour, and must consequently be treated as class III products.

3.3 Surface linings fire performance

Large scale testing of surface linings has been conducted at research and testing facilities world wide. In this section results from these tests will be used to investigate the relation between the ignition source severity and the heat release rate for common surface linings.

3.3.1 Surface linings in small room dimensions

In the EUREFIC [29] research programme, 11 different surface linings were tested in the ISO 9705 room. According to the Swedish classification system four of these materials were class I, one was class II, two were class III and four were unclassified. Four of them went to flashover within the first 10 minutes of the test, three of them went to flashover between 10 and 20 minutes and four materials did not go to flashover at all.

The four materials that went to flashover during the first 10 minutes were (1) ordinary plywood, (2) plastic faced steel sheets on polyurethane foam, (3) combustible faced mineral wool and (4) FR extruded polystyrene foam. The heat release rate of these products are shown in Figure 9. It can be seen that these four materials follow a t^2 -like behaviour for the HRR, corresponding to *fast* (materials (1) and (2)) and *Ultra fast* (materials (3) and (4)). Material (1) is a class III material and material (2) is a class III material if only heat release rate is considered. Materials (3) and (4) are both unclassified. It seems like class III materials behave like *fast* when the ignition source is 100 kW.

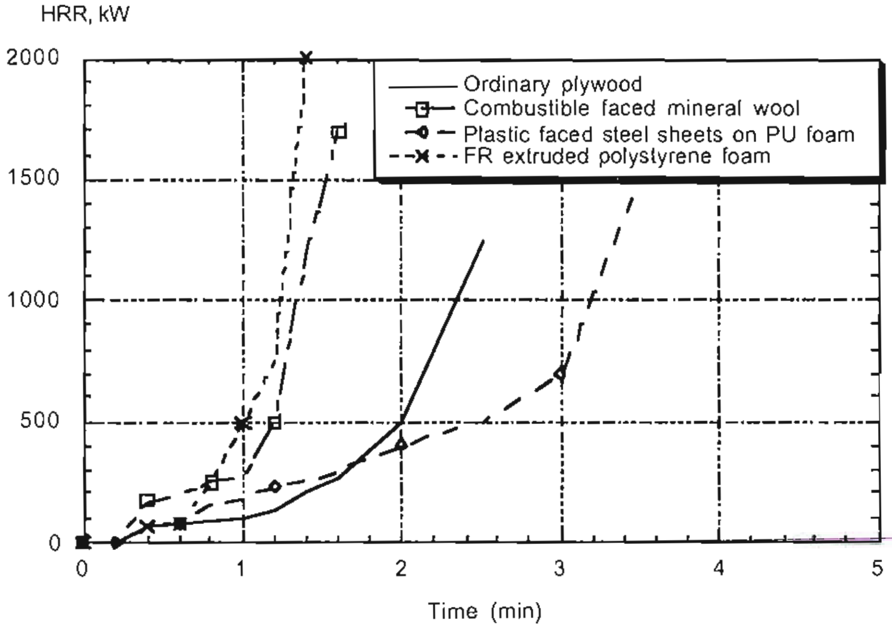

Figure 9. Heat release rate of products corresponding to fast and ultra fast t^2-fires.

The materials (5) textile wall covering on gypsum plaster board, (6) FR particle board type B1 and (7) PVC-wall carpet on gypsum paper plaster board, all went to flashover when the burner heat output was raised to 300 kW, see Figure 10. The increase in heat release rate was faster than *ultra fast* but it is difficult to know if this rapid increase had occurred if the burner output had been raised to 300 kW at time zero and not at 10 minutes as in the ISO 9705 test. Note that the heat release rate for material (5), which is a class III material, in the beginning of the test, first increases like a *fast* material before it settles to a steady state. Material (6) is a class II material and material (7) is unclassified because of too high smoke production, if only heat release is considered it would be a class I material.

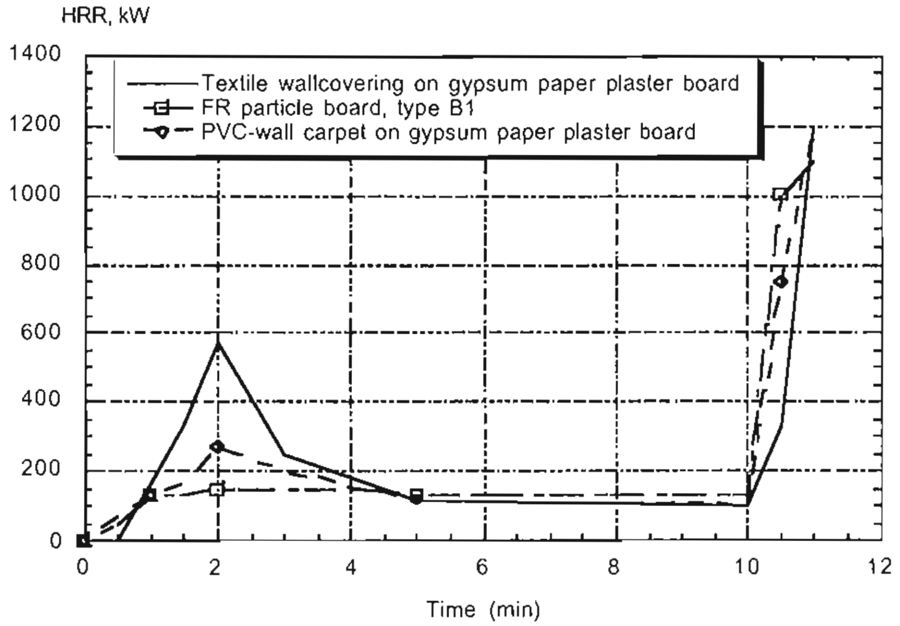

Figure 10. Flashover is reached when the ignition source is raised to 300 kW.

None of the materials (8) painted gypsum paper plaster board, (9) melamine faced high density non-comb board, (10) plastic-faced steel-sheet on mineral wool or (11) FR particle board went to flashover, see Figure 11. These four materials are all class I surface linings.

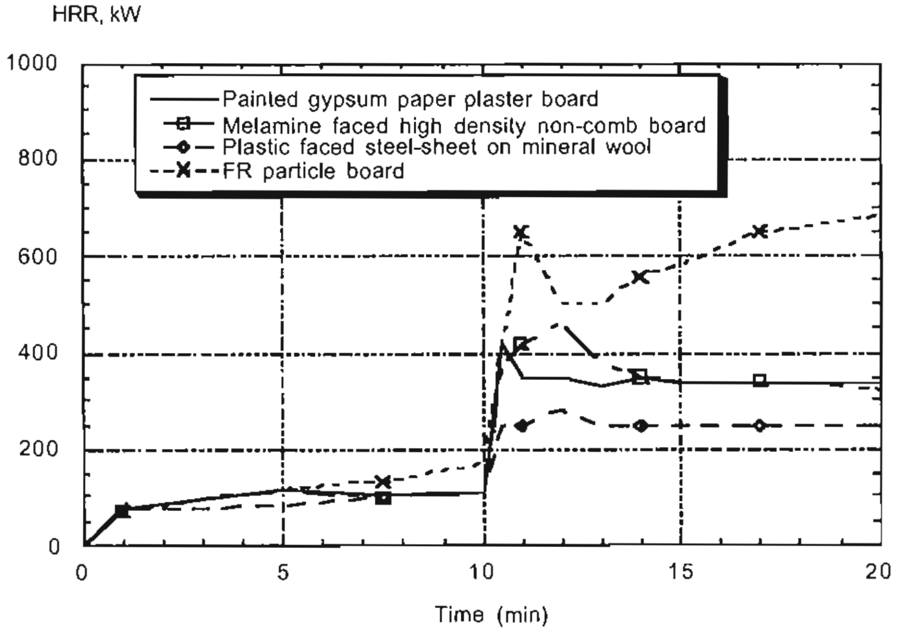

Figure 11. Class I products do not reach flashover when the ignition source is raised to 300 kW.

Janssens and Tran[25] tested six wood products in a room having the same dimension as the ISO 9705 room but with combustible linings only at the rear and right walls having the burner in the inner corner. As burner heat output they used 40 kW for the first five minutes and 160 kW for another five minutes. A product called "southern pine plywood (SP plywood)" comparable with the ordinary plywood (i.e. a class III product in the Swedish system) in the EUREFIC project ignited when the burner heat output was 40 kW. The fire growth was not comparable to a *fast* t^2-fire, but more like a *medium* one. When the heat release rate of the burner was raised to 160 kW all six wood products except fire retardant treated SP plywood (FRT plywood) reached flashover in an *ultra fast* manner.

Janssens and Tran also conducted tests with the six wood products but with the combustible lining only at the rear wall applying the burner at the lower centre line of the product. In this scenario all products except FRT plywood reached flashover like an *ultra fast* fire, when the burner output was raised to 160 kW. None of the products sustained a flame spread when the burner heat output was 40 kW. This shows how important the position of the ignition source is, a burner in the corner is most severe.

Kokkala [30] made a sensitivity analysis of the room/ corner test. He mentions how the burner size and heat output affects the room/ corner test[31,32]. At a low heat output (40 kW) a large burner (0.5 x 0.5 m) increased the time to flashover compared with smaller burners (the normal ISO 9705 burner which is 0.17 x 0.17 m and a 0.3 x 0.3 m burner). However, 40 kW was enough to cause flashover for a room lined with particleboard, which is a typical class III product. For the largest burner the time to reach flashover was approximately 5 minutes, corresponding to a *medium* t^2- fire, and for the two smaller ones about 3.5 minutes corresponding to something between a *fast* and a *medium* t^2- fire. The reason for the pronounced difference at the 40 kW level was explained by the fact that a large burner flame exposes a smaller surface area to a given critical flux level, which in the early stages of the test gives a slower flame spread. When the burner output was raised to 160 and 300 kW the size of the burner had only a minor effect. The time to reach flashover in these cases corresponded to an *ultra fast* t^2- fire, the 300 kW level reached flashover just slightly faster than the 160 kW level.

The distance from the burner to the wall is also important which was showed by Williamson et al [33]. The heat flux from the burner flame against the wall was measured when the burner-wall distance was varied between 0 and 10 cm. Williamson et al used gypsum wallboard, i.e. an almost non combustible product as surface lining in a room with the same dimension as the one used in ISO 9705, to investigate how the burner flame was influenced by the distance. The burner was placed at the floor in one of the rear corners. Because of the way the flame leaned towards the wall when the burner-wall distance decreased, the area which received a high heat flux was considerably higher when the distance was 0 cm than 10 cm.

It is evident from the above that numerous parameters affect the outcome of a fire in a room. For a given surface lining, the ignition source size and heat output, its distance from the wall, position of the ignition source in corner/ open wall are all relevant. However, even if it is known that a potential ignition source will not be very close to a wall, it is better in most design situations to use test data when the burner/ ignition source is placed in the corner as in ISO 9705, i.e. adopting a worst case scenario.

3.3.2 Surface linings in large room dimensions

The discussion above covers the ISO 9705 scenario but what happens in a larger room? As already pointed out, a small room is a more severe case than a large room, but how important is the difference?

A part of the answer is revealed in ref. 23 and 24, which describes experiments in a room having dimensions of 9.00 x 6.75 x 4.90 m (w x d x h) and a door opening of 2.00 x 2.00 m. The ceiling and walls were lined with the same lining material. Five of the EUREFIC- materials were tested. The burner, positioned in one of the corners, had a heat release rate output identical to the ISO 9705 during the first 20 minutes of the test, but it was then increased to 900 kW for another 10 minutes. Textile wall covering on gypsum board (a class III product) contributed hardly at all to the fire when the burner heat output was 100 kW. Increasing the burner output to 300 kW caused a response similar to an *ultra fast* t^2- fire for the first minute, but instead of causing flashover, the heat release settled to a steady state of about 500 kW. At 20 minutes, when the burner heat output was raised to 900 kW, an increased flame spread resulted in a heat release of approximately 3 MW lasting for roughly 1 minute. But also this time the heat release settled, now to a steady state of about 1 MW. Hence, a product that caused flashover when the ignition source was 300 kW in the ISO room (see Figure 10) did not cause flashover when the ignition source was 900 kW in the large room. However, another class III product, ordinary birch plywood, caused flashover already at a burner heat output of 300 kW, increasing approximately like a *fast* t^2- fire.

Ordinary birch plywood (a class III product) sustained some flame spread corresponding to a *slow* fire when the burner heat release rate was 100 kW.

An unclassified product according to ISO 9705, combustible facing on mineral wool, did not reach flashover but peaked at about 5 MW, increasing like an *ultra fast* t^2- fire. This peak would probably have caused a flashover if there had been any other combustibles in the room. As a worst credible envelop to a class III product (and as we will see later, class II products will also be assigned to this category) the *ultra fast* t^2- fire of the unclassified product could be used when the ignition source reaches 900 kW.

No class I product was tested in the large room. It is reasonable to assume that when a class I surface lining starts to contribute to the heat release rate it is the ignition source that dominates the fire.

3.3.3 Different surface linings on walls and ceiling

From experiments in a small room [34] (ISO 9705 dimensions), when only the walls were covered with combustible linings and the ceiling was non combustible, the fire growth was slower than for the case when the combustible product also covered the ceiling. For small ignition sources (up to 100 kW) the fire growth of wooden products was more like a *medium* t^2-fire than a *fast*. However, when the ignition source was raised to 160 kW the growth was *ultra fast* which was also the case when both walls and ceiling were lined with class III materials [31]. This has some major consequences when it comes to prescriptive rules adopted in Sweden today. The best class of building, Br1, should have class I surface linings at ceilings and class II at walls. In section 3.2 it was mentioned that class II products must be assigned to class III products since we do not know if they will behave like class I or class III products when tested in large scale.

Thus, when the ignition source is greater than 160 kW, which it certainly will be in many real cases, a building of class Br1 might act like a building of class Br3, the lowest class, where class III surface linings are accepted on both walls and ceiling.

Let us now examine how to select HRR_k as a function of type of lining.

3.4 Characteristic heat release rates for surface linings

In section 3.1 we argued that ISO 9705 could be used as a basis for HRR_k of surface linings. This was because of the severity of the ISO 9705 geometry, its small space with a relatively large ignition source.

It would be preferable if the engineer making a risk assessment could choose a HRR_k for a surface lining just from the information of classification. This is exactly what can be done from the information in section 3.3.

First of all we should make a crude distinction between small and large rooms. Even tough it is conservative, we assume that rooms with dimensions up to the same size as the large room used in EUREFIC (9.00 x 6.75 x 4.90), behaves in the same severe sense as an ISO 9705 room. Rooms larger than the large room behaves as the large room. Hence, a conservative methodology is applied.

3.4.1 Class I surface linings

3.4.1.1 In small rooms

Class I products contribute only to a small extent to the fire. When tested according to the Room/Corner Test, ISO 9705, the maximum HRR may not exceed 300 kW according to "Boverkets allmänna råd[27]". In practise these products normally show a burning rate history of a Gaussian curve having a maximum allowable peak of 300 kW. This happens at maximum heat output from the ignition source (300 kW) When the ignition source is below 100 kW, the contribution from the surface lining can be neglected. The characteristic heat release rate, HRR_k, would then have the form $\dot{Q}=300\exp(-k(t-t1)^2)$ [kW]. Assuming that the peak reaches 300 kW as fast as wood (worst credible case) means that $t1 \approx 100$s (see Figure 9 where plywood reaches 300 kW at approximately 100 s). We then assume that the fire starts at 50 kW at time 0, as used in the CBUF work, then k = 0.6(1.8e-4 x 3600).

In this way HRR_k for class I surface linings is achieved up to ignition sources of 300 kW. For larger ignition sources like 500 kW or 1 MW the response of the linings are not known and further research is needed here.

3.4.1.2 In large rooms

We do not know much of this scenario but it is reasonable to assume that a class I surface lining will not contribute to the fire, at least when the ignition source is below ≈ 1 MW. For higher ignition sources it is probably the ignition source itself that will dominate. Further research is needed to give an answer.

3.4.2 Class II and III surface linings

Class II products may, when they are tested in large scale, behave both like class I- and class III- product[28]. Class II products should therefore be treated like class III to be on the safe side (consistent with the conservative approach).

3.4.2.1 In small rooms

Class III products ignite when the ignition source is 40 kW and burns like a *medium* to *fast* design fire. When the ignition source is raised to 100 kW the fire growth is comparable to a *fast* fire and at 160 kW a class III material burns like an *ultra fast* design fire, see 3.3.1.

3.4.2.2 In large rooms

None of the five products in the large room tests [23,24], responded to a burner heat output of 100 kW. At 300 kW the response was like a *fast* t^2- fire and at 900 kW like an *ultra fast* t^2- fire, see 3.3.2.

3.4.3 Characteristic heat release rates for class I-III products in small and large rooms

To sum up we get the characteristic heat release rates, HRR_k , below for a room lined with similar classes of surface linings on walls and ceiling:

Small rooms ($A < 60\ m^2$, $h < 5$ m)

Classification	**Ignition source HRR ,$\dot{Q}$ (kW)**	**Type of HRR_k**
Class I	$\dot{Q} < 100$ kW	0
	$100\ kW < \dot{Q} < 300$ kW	Gaussian[1]
	$\dot{Q} > 300$ kW	Not known
Class II & III	$\dot{Q} < 40$ kW	*Slow* [2]
	$40\ kW < \dot{Q} < 100$ kW	*Medium*
	$100\ kW < \dot{Q} < 160$ kW	*Fast*
	$\dot{Q} > 160$ kW	*Ultra fast*

Large rooms ($A > 60\ m^2$, $h > 5$ m)

Classification	**Ignition source HRR, Q (kW)**	**Type of HRR_k**
Class I	$\dot{Q} < 900$ kW	0
	$\dot{Q} > 900$ kW	not known
Class II & III	$\dot{Q} < 300$ kW	*Slow*
	$300\ kW < \dot{Q} < 900$ kW	*Fast*
	$\dot{Q} > 900$ kW	*Ultra fast*

---

[1] The Gaussian curve should be chosen as $\dot{Q}=300*\exp(-0,6(t-1,7)^2$, where $\dot{Q}=50$ kW at t=0.

[2] Estimation assuming that a class II and III product will ignite even for small ignition sources.

4 Floor coverings

Flame spread on floor coverings can sometimes be neglected if there are also combustible surface linings within a room and we consider only the fire phase up to flashover. However, care should be taken for floorings on staircases and products of very low fire rating.

4.1 Full scale flooring tests

Tests[35] conducted in a room 2.4 x 3.6 x 2.4 m (w x d x h), having non combustible wall and ceiling linings with different types of floor coverings, showed that floor coverings may contribute considerably to the heat release in a room, see Figure 12.

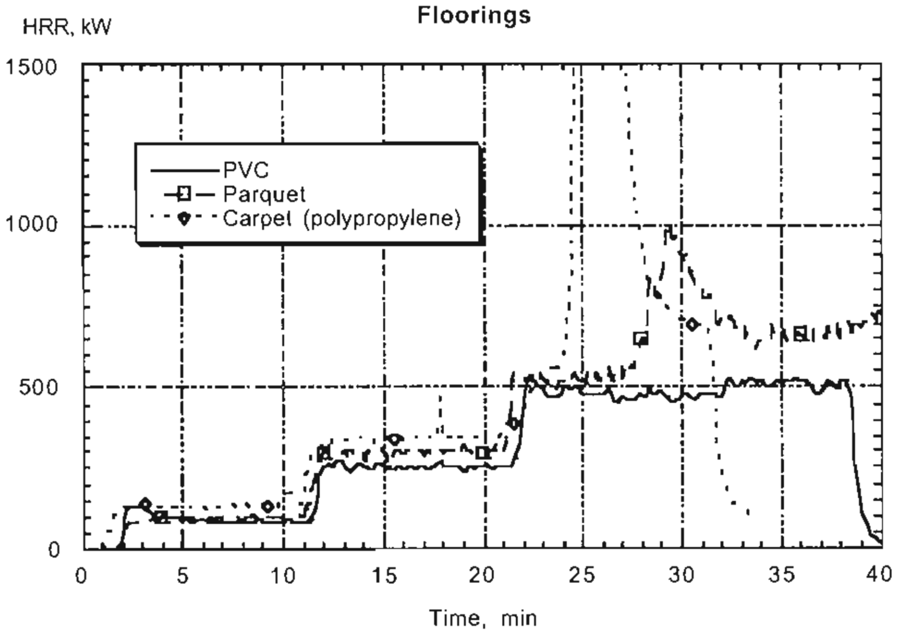

Figure 12. Data from large scale tests on floor coverings.

In one of the test series three identical carpets of polypropylene were tested, varying the ventilation openings and burner position. The burner, placed at the floor produced a heat output of 100 kW for the first 10 minutes, 300 kW for the next 10 minutes and 480 kW for another 10 minutes. None of the carpets contributed to the fire when the burner output was 100 kW, but, when raised to 300 kW, one of them ignited and spread flame in an *ultra fast* manner, the other two caused flashover when the burner was raised to 480 kW. The flame spread was *ultra fast* in both these cases too. In all three tests the flame spread started immediately after the burner output was raised.

In another test series, 17 floor coverings were tested in a room/ corridor configuration, the room had the same dimension as above. Identical floor coverings were applied in the room and corridor. However, only about one third of the floor closest to the door was covered with floor covering. On top of the floor covering in the room, a small pilot burner, intended to ignite the pyrolysis gases, was placed. The main burner was positioned in the corner 2 - 2.5 m away from the floor covering. The door between the room and corridor was completely open. The burner heat output was slightly different in this test series, at 20 minutes, the burner output was raised to 580 kW and maintained for 40 minutes if necessary (if flashover was not reached). The 17 materials were divided in: 6 carpets (3 made of polyamide, 2 of polypropylene and 1 of wool) , 5 PVC-, 3 parquet-, 2 linoleum- and 1 rubber- coverings. Apart from heat release rate, flame spread in the corridor was also measured. Six products sustained flame spread 7 meter from the opening of the room, equivalent to the length of the corridor. All of the 17 coverings except two of the PVC products sustained flame spread out in the beginning of the corridor.

Some conclusions from the heat release measurements in these 17 tests are that: PVC coverings spread flame very slow, definitely slower than a *slow* design fire; two of six carpets produced heat like *ultra fast* fires (one was made of polypropylene and the other of polyamide) shortly after the burner was raised to 580 kW, one carpet started to behave like *ultra fast* before 580 kW (made of polypropylene); one parquet covering behaved like *ultra fast* but 15 minutes after the burner output was raised to 580 kW, hence wooden flooring could be regarded as slower than *slow*.

In another experiment [36] a room of dimension 3.6 x 2.4 x 2.4 m (w x d x h) was connected to a 10 m long corridor, width 1 m, height 2.1 m. Three different floor coverings (carpets of wool, nylon and polypropylene) were applied to the floor both in the room and corridor. As ignition source a sofa was used inside the room. The heat release rate in the room/ corridor and flame spread in the corridor were measured.

It is somewhat difficult to extract the contribution from the floor coverings in these experiments since the heat release from the sofa probably fluctuated. If the blank test with just the sofa (no floor covering) is subtracted from the total heat release rate in these experiments, it can be seen that all three coverings spread flame like an *ultra fast* fire, when they were attacked by the heat from the sofa (which was considerable, approximately 1.8 MW already after 50 s). Hence, even materials like wool which behaved relatively well in ref. 35, will spread flame in an *ultra fast* way if affected by a severe ignition source. When the heat from the sofa started to decay the contribution from the covering settled to a steady state for some minute before decaying to zero. From the flame spread measurements in the corridor and the total heat release it was clear that the nylon carpet was the best, only sustaining flame spread for 2 m (in both tests) into the corridor. Polypropylene sustained flames all the 10 m length of the corridor (in both tests) while the wool carpet sustained flames for 2, 4.5 and 6 meters (three different tests).

Apparently, some carpets may spread flame like an *ultra fast* fire while others like PVC- and wood-floor coverings spread flame like *slow* when the ignition source is high enough.

4.2 Characteristic heat release rates of floor coverings

In this chapter we have not tried to connect a certain class of floor covering to a specific HRR_k but rather to give some examples of floor coverings fire behaviour. Referring to typical design fires in chapter 1, taken from ISO/ CD 13388, it looks like many floor coverings behave like a *slow* design fire. It should be stressed though, that some floor coverings, may behave like *ultra fast* when the ignition source becomes 300 - 500 kW.

5 Cable trays

Cable trays are commonly found in cable shafts between floors in buildings, hidden above the ceiling in corridors etc.

Fire growth of cable trays depend on the diameter of the cable, spacing/ no spacing between the cables, horizontal/ vertical orientation, distance to wall or ceiling etc. Testing cable trays in large scale should therefore, as close as possible, represent real fire scenarios regarding amount of cables, spacing between cables, ignition source and so forth.

Since cable trays exist in both vertical and horizontal position inside a building, it is natural that test methods use the position causing the most severe fire growth. A vertical position is assumed to cause the most rapid flame spread and is therefore used in most large scale test methods. The disadvantage, of course, is that it is difficult to state how a cable, acting in a certain way in a vertical scenario, will act in a horizontal scenario and consequently, it is hard to arrive at a characteristic heat release rate for the horizontal scenario.

5.1 Large scale testing of cable trays

Full scale testing of cable trays in the Nordic countries is normally conducted according to IEC 332-3 [37] , see Figure 13. A test rig of dimension 2 x 1 x 4 m (d x w x h), with a cable ladder of length 3.5 m mounted vertically at the inside wall. The burner applied at the lower end of the cable tray has a heat output of 20 or 40 kW depending on cable class. A cable pass the test if the damaged length at completion of test is below 2.5 m.

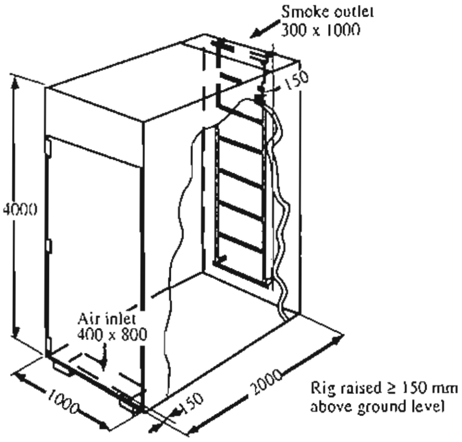

Figure 13. The test rig of IEC 332-3.

One of the test methods used in the US is UL 1666 [38] , the test rig and procedure are comparable to IEC 332-3, but the burner heat output is 154 kW. It is considered as representing a more realistic scenario than IEC 332-3.

In two reports written by P. Van Hees and P. Thureson [39,40]different cables were tested in UL 1666 and IEC 332-3. Measurements of heat release rate were conducted. Using their result indicates that the heat release rate could be expressed as $\dot{Q} = k*t$, i.e. the heat release rate increases linearly. An example of the cables tested in UL 1666 is shown in Figure 14. Identifying the linear constants in their measurements gives the results given in table 7.

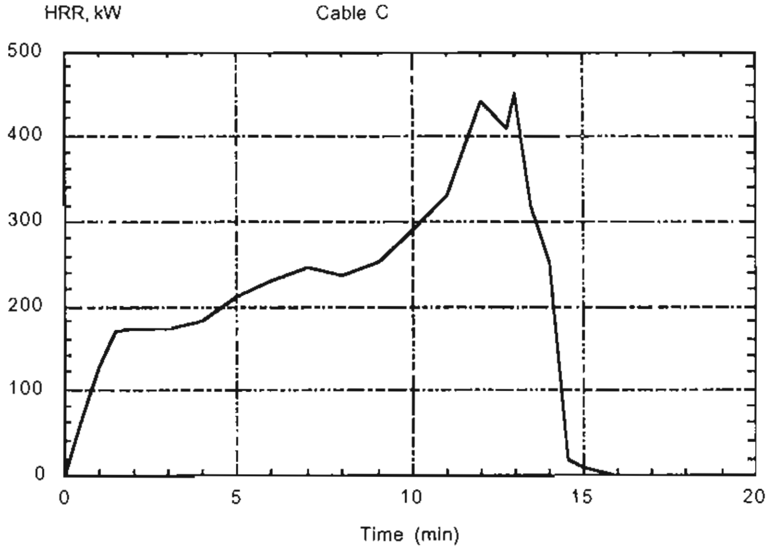

Figure 14. Cable C, tested in UL 1666. The ignition source is 154 kW, hence the contribution from the cable tray increases approximately linear with a constant of about 0.35 kW/s.

From Table 7 one could make the crude assumption that cables passing IEC 332-3 have a maximum k of about 0.4 (0.35) when tested in UL 1666. Regarding UL 1666 as a more realistic scenario than IEC 332-3 implies that a HRR_k for cables passing IEC 332-3 could be written like $\dot{Q}_{pass} = 0.4*t$, where t is measured in seconds. Cables not passing the IEC- test have a distribution in k between 0.1 to 2.5. A k-value of about 2 could therefore be used to express failed cables, i.e. $\dot{Q}_{fail} = 2 * t$. Note that these values should be used when the cable tray is vertical.

Table 7. Heat release rate (HRR) of cables expressed by HRR = k*t, where k is the linear constant. The bold underlined values indicate that the cable passed the test.

Cable	k (kW/s) UL 1666	k (kW/s) IEC 332-3
A	2.5	0.3
B	<0.1	**<u>≤0.1</u>**
C	0.35	**<u>≤0.1</u>**
D	**<u>≤0.1</u>**	<0.1
E	1.0	0.4
F	1.4	1.4
G	-	0.9
H	0.3	**<u>≤0.1</u>**
I	**<u>≤0.1</u>**	**<u>≤0.1</u>**
J	**<u>≤0.1</u>**	<0.1
K	2.1	0.2

6 Heat release rate of curtains

Large curtains have been shown to give off large amounts of heat [41], see Figure 15. The heat is released during a short time period and affecting a large wall area. Smaller curtains would normally not ignite nearby surface linings. Upholstered furniture close to burning curtains on the other hand is assumed to pose a hazard because burning curtain pieces may form a fire on the floor igniting nearby objects. The HRR curves shown in Figure 15 are from curtains of size 3 x 3 m so they are not supposed to be found in small apartments but in assembly halls and other large areas. The HRR_k of these curtains are mostly very fast, even faster than *ultra fast*. The results in ref. 41 show that glass and FR polyester curtains have the lowest heat release while cotton and acrylic have the highest. Only flame retardant polyester did not contribute to the fire.

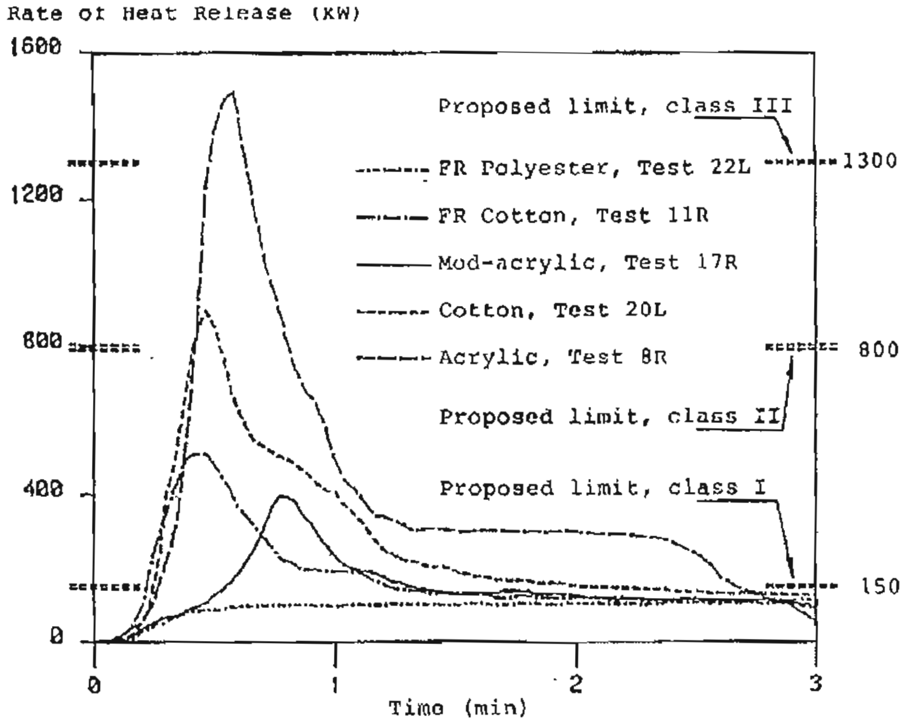

Figure 15. Different 3 x 3 m pleated curtains ignited with a 100 kW burner. The curtains were hanging approximately 0.1 m from a wall. The class I, II and III indicated in the figure were the proposed classes during the project [41].

So far we have discussed upholstered furniture, surface linings, floor coverings, cable trays and curtains. There are many more items that should be covered. Särdqvist [42] and Babrauskas [43] give examples of heat release rate measurement of, among other things, TV-sets, wardrobes, Christmas trees etc. However, for most products only sample data is available and sometimes only one experiment is behind a certain HRR curve. Therefore, when creating a design fire using characteristic HRR data the representativity of results should be considered.

7 Comments on using a t^2-fire

The characteristic fire growth can be described in many ways. This report gives examples of product burning behaviour that may be described by a bell shaped curve, a linear curve or a t^2 relationship. In this report we have described for example burning linings with different t^2- fires, (*slow, medium, fast* and *ultra fast*). We have adopted this description because it seems to describe real fires reasonable well. However, a better fit can be achieved if we use two parameters to fit the characteristic fire growth. In Figure 16 plywood tested in ISO 9705 (see chapter 3) and a *fast* t^2-fire and an exponential curve fit is shown. It is seen that the exponential curve agrees best to the real curve but as an approximation the *fast* t^2-fire works quite well.

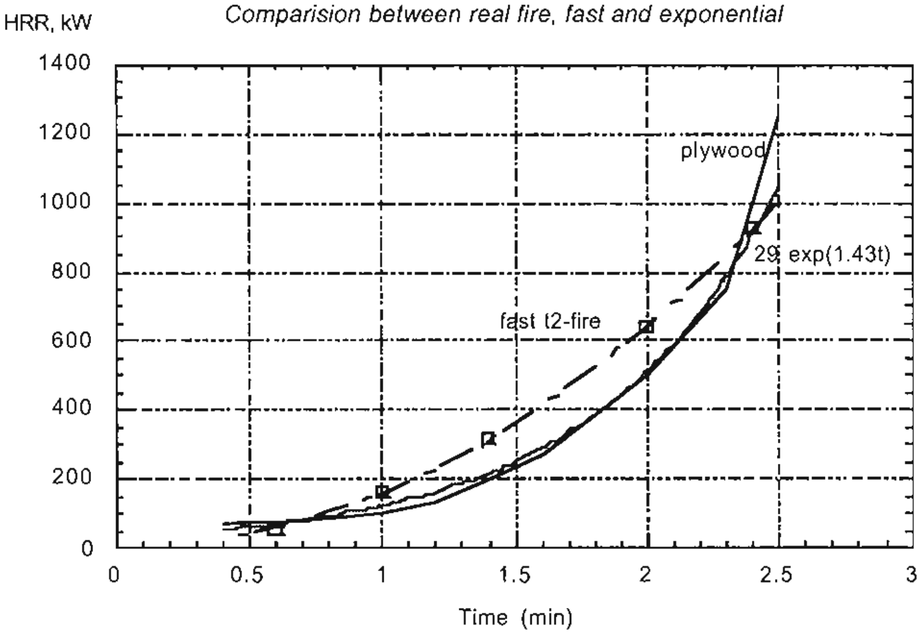

Figure 16. Plywood when tested in ISO 9705 agrees quite well with a fast *t^2-fire. However, an exponential curve fit gives a better description.*

Figure 17 shows the HRR curve from a burning acrylic curtain (see also Figure 15 in chapter 6), an exponential and a t^2 curve fit of the curtain are also shown. As a comparison an *ultra fast* t^2- fire is shown exemplifying that sometimes the four t^2-fires are not enough to describe real fires.

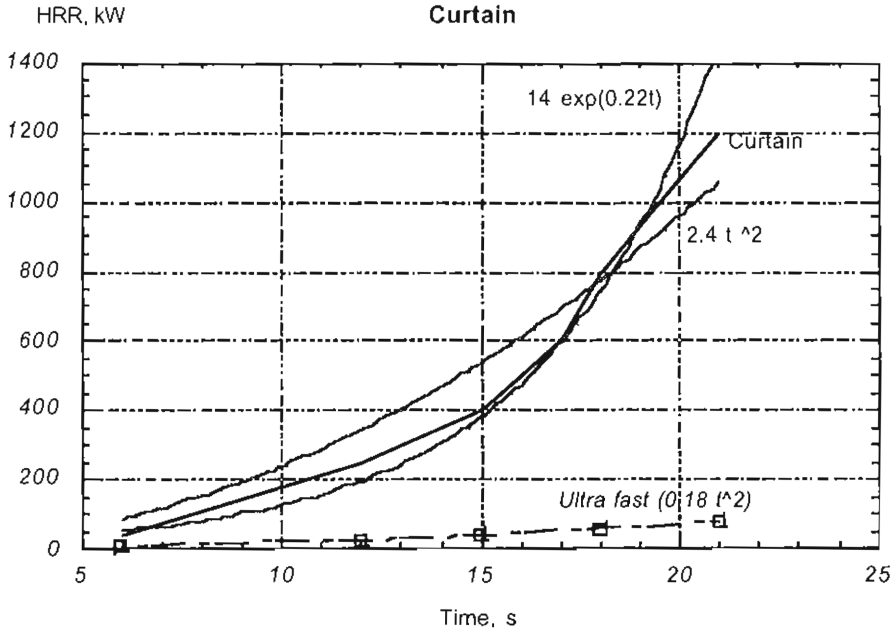

Figure 17. A burning acrylic curtain can not be described by an ultra fast t^2-fire (0.18 t^2), 2.4 t^2 gives a better fit but an exponential curve fit gives the best result.

One criteria for a t^2-design fire to give a good description of real fires is that the real fire has an increasing fire growth rate. The fire growth rate is equivalent to the time derivative of the heat release as a function of time which for a t^2-fire is proportional to t. When this is not the case like for a class I surface lining (see chapter 3) it is better to use some other HRR_k as a component in estimating the design fire like a Gaussian profile or perhaps a constant fire.

7.1 Mathematical representation

The t^2- and the exponential fire are different ways of curve fitting. However, we can also view them from a point of different physical assumptions. The t^2-fire assumes that the velocity of the flame front is constant over a surface, independent of the heat release rate. The heat release rate is proportional to the burning area, and the burning area is proportional to the square of the burnt distance. This gives a design fire of the form $\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g} \right)^2$

The exponential design fire arise from the assumption that the fire growth rate, that is the time derivative of the heat release rate, is proportional to the heat release rate:

$$\frac{\partial \dot{Q}}{\partial t} = k\dot{Q} \Rightarrow \dot{Q}(t) = \dot{Q}_0 e^{kt},\ \dot{Q}_0 = \dot{Q} \text{ at } t = 0$$

$\dot{Q}_0$ is the initial HRR at t = 0

8 Ignition of a second item

It may be important to know when objects close to the first burning item ignites. In the examples of furniture and surface lining we have assumed that the furniture is standing close to the surface lining and thus affecting it by direct flame impingement. In addition there are many cases when the flames will reach the ceiling before any other object is directly involved. However, what are the conditions for fire spread when the linings cannot be assumed to be involved?

From work conducted by Ahonen[44], the heat flux from a burning object on a horizontal target could be described as:

$$\dot{q}'' = 0.46 \frac{\dot{m}}{R^2}$$

where $\dot{q}''$ is the heat flux in kW/m^2, $\dot{m}$ is the mass burning rate in g/s and R is the distance in meter.

If the heat of combustion is assumed to be 20 KJ/ g this equation becomes:

$$\dot{q}'' = 0.023 \frac{\dot{Q}}{R^2}$$

From CBUF it was found that the ignition time at 35 kW/m^2 for different horizontal furniture compounds was about 15 seconds. Horizontal surface linings which where tested in EUREFIC showed a large scatter in ignition times and only a weak correlation between classification and ignition time was observed. At 50 kW/m^2 an ignition time of about 30 seconds is very common even though the scatter in data varied from 4 to 200 seconds. Thus we have a condition for very fast ignition at these levels of irradiance. It should be observed that the conditions we have selected here are **not** the critical values for ignition. For upholstered furniture the critical value after long time of heating is about 10 kW/m^2. However, we are considering rapid fire growth and therefore we select the high values creating a fast ignition.

To get an idea when flame spread to nearby objects may occur Table 8 shows the distance from a burning object which will cause the heat flux to be 35 and 50 kW/m^2 when different heat release rates are considered.

Table 8. Furniture materials and surface linings ignite in about 15 and 30 seconds respectively when affected by a heat flux of 35 kW/m^2 and 50 kW/m^2 respectively. This table shows at what distance from a burning object these heat fluxes are attained.

Heat release of burning object	Distance in meters from burning object to reach 35 kW/m^2	Distance in meters from burning object to reach 50 kW/m^2
100 kW	0.3	0.2
500 kW	0.6	0.5
1000 kW	0.8	0.7

If for example the distance between an upholstered furniture and a burning object giving off 500 kW of heat is 0.6 m the furniture could be assumed to start burning after 15 seconds.

It may be concluded that flame impingement is the most rapid way of fire spread and that a fire will jump over distances at the order of a meter only when they become large.

9 Creating a design fire

Estimating a design fire for a real situation is a very complicated task that cannot be done on a general basis. The following examples are estimates of simple situations where different items of fuel appear. The design fire is made simply by adding the characteristic heat release rate curves, HRR_k, from the items neglecting the fact that burning objects interact and accelerate their burning rate.

The design fire must also be created in conjunction with a model like CFAST or some other model that takes ventilation control into consideration. The design fire could otherwise grow to infinity.

9.1 A furniture item in a hotel lobby

As an example consider a furniture item standing in a hotel lobby. The lobby is having the dimension 7 x 7 x 3 m (w x d x h). Standing close to one of the corners is a furniture item, the ventilation to the room is through an open door (2.1 x 1.2 m). We are going to estimate design fires for this case for two different scenarios:

Scenario 1

Furniture item: Contract (public) type
Flooring: PVC floor covering.
Linings: Swedish class I.

Scenario 2

Furniture item: Domestic type
Flooring: Polyamide floor covering.
Linings: Swedish class III.

9.1.1 Scenario 1

a) Furniture

The HRR_k for the furniture item is taken from chapter 2, contract furniture, which is:

$$\dot{Q} = 1500\exp((-0.2(t-4)^2) \text{ kW}$$

b) Lining

The HRR_k for a lining in a room having an area less than 60 m^2 is taken from chapter 3, which is:

$$\dot{Q} = 300\exp((-0.6(t-1,7)^2) \text{ kW}$$

when the ignition source is between 100-300 kW.

c) Flooring

The PVC floor-covering in this case is supposed to release only small amounts of heat and is therefore ignored.

d) Design fire

To make a design fire for scenario I involves a problem. The expression for Q is valid when the ignition source is between 100 - 300 kW, but what happens above that level? Assume that the ignition source, the furniture item, could be subdivided in smaller ignition sources of a maximum size of 300 kW each affecting the surrounding linings. Thus when the ignition source reaches 100 kW a Gaussian class I surface lining fire growth starts; when the ignition source reaches 400 kW, that is 300 kW + 100 kW another Gaussian fire growth starts and so on for 700 kW, 1000 kW and 1300 kW. By using the HRR_k for a contract furniture item, $\dot{Q} = 1500 \exp(-0.2(t-4)^2)$ we can calculate the times when 100, 400, 700, 1000 and 1300 kW are reached to 0,4 min, 1,5 min, 2,1 min, 2,6 min and 3,2 min respectively. We have then only taken the HRR from the furniture into consideration when making the calculation. The characteristic heat release rate for the surface lining then becomes $\dot{Q} = 300\ [\exp(-0.6(t-(1.7+0.4))^2) + \exp(-0.6(t-(1.7+1.5))^2) + \exp(-0.6(t-(1.7+2.1))^2) + \exp(-0.6(t-(1.7+2.6))^2) + \exp(-0.6(t-(1.7+3.2))^2)]$ [kW]. The resulting curve is shown in Figure 18.

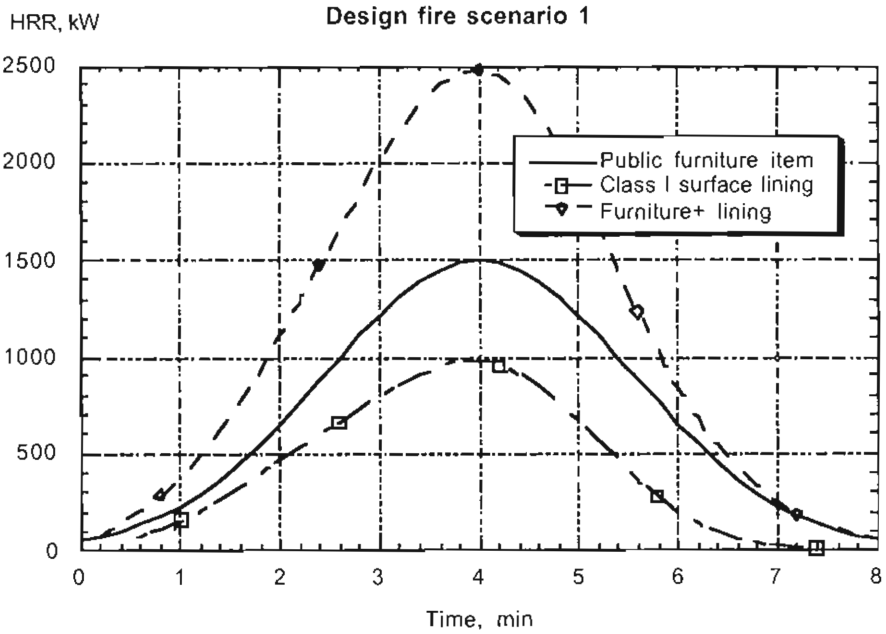

Figure 18. Design fire for a public furniture item in a hotel lobby with class I surface linings.

There is an uncertainty in this design fire close to the peak HRR as we have only reliable data on the response of the lining for ignition sources up to 300 kW while the furniture item is peaking at 1500 kW. However, a similar technique of adding the HRR in steps during the course of the fire has been found to be very successful in predicting the HRR in the Room/Corner Test using data from the Cone Calorimeter, the model developed by Wickström and Göransson[45]. In any case the approach should be quite useful for prediction of available escape time during the growth period of this fire.

We note from this example that the furniture item is dominating the fire growth. Thus selecting a better product will result in a dramatically improved design fire. Also note that in a larger room ignition of the linings may appear very late when the HRR from the furniture increases 900 kW (chapter 3.4.3). Thus the linings of class I are not contributing significantly to the fire growth in this case.

9.1.2 Scenario 2

a) Furniture item

In scenario 2 the HRR_k for the domestic furniture item is taken from chapter 2:

$$\dot{Q} = 2500 \exp((-0,44(t-3)^2) \text{ kW}$$

b) Linings

From chapter 3.4.3 a small room lined with class III surface linings shows an ultra fast fire growth when the heat release rate of the ignition source reaches about 160 kW. This means that the surface lining in the hotel lobby in this scenario will start to contribute like an *ultra fast* fire when 160 kW from the furniture item is reached (the surface lining would start to contribute before the 160 kW level but because of the fast increase in the heat release rate from the domestic furniture item the error will be small).

c) Flooring

When the HRR from the fire becomes approximately 500 kW the carpet will start to contribute like an *ultra fast* fire, see chapter 4.

d) Design fire

After about 55 s after the ignition of the furniture item the total heat release rate of the furniture item and surface lining becomes 500 kW igniting the floor covering which has an *ultra fast* fire growth. The design fire for scenario 2 is shown in Figure 19. The *ultra fast* behaviour of the surface lining and floor covering is seen to dominate the design fire. The actual fire would according to CFAST be ventilation controlled at about 7 MW.

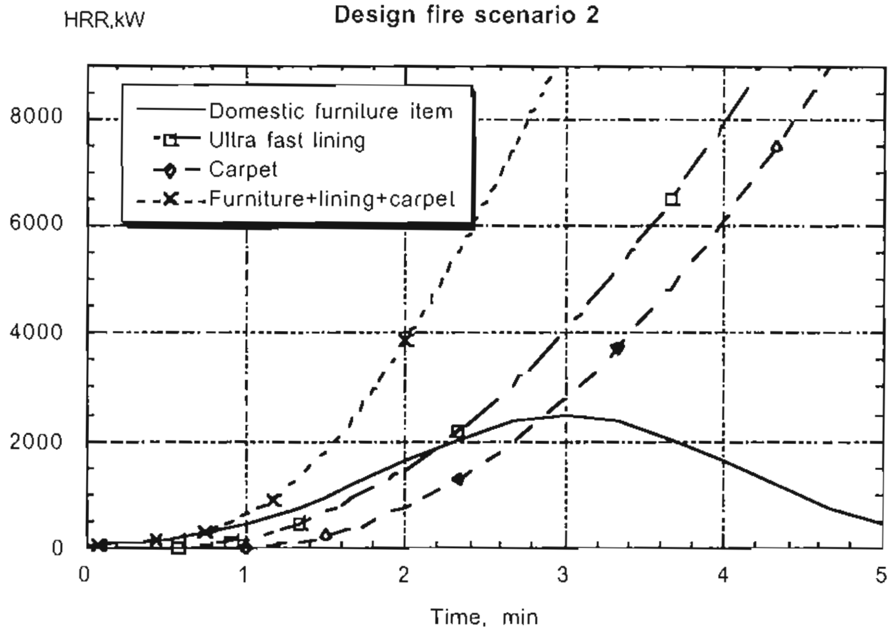

Figure 19. The design fire for a domestic furniture item in a hotel lobby having class III linings and a floor covering that burns like ultra fast.

We see from this example that the linings (and the flooring) may dominate the fire growth. Thus selecting class I linings and a better flooring will improve the situation. We also note that a combination of class I ceiling and class II walls will not improve the situation. As class II products in large scale fires are seen to behave either as class I or class III they cannot be assumed to be of the highest performance. This assumption leads to two questions. 1) To what extent is the requirement of class II in the building code increasing safety and 2) Do we need a class II lining performance requirement in Sweden??.

9.2 Comparison with experimental data

To compare our proposal of design fire with a real fire we will study an experiment. In this experiment a room 4.3 x 4.9 x 2.4 m, w x d x h having a 1.2 x 2.0 m door opening was lined with different surface linings. The wall lining was composed of paper wall covering on gypsum paper plaster board, the ceiling lining right above the furniture was made of particle board (2.4 x 2.4 m) and the rest of the ceiling was made of gypsum paper plaster board. The whole ceiling was then painted with water-soluble paint. The furniture item was a sofa which could be defined as domestic according to the terminology in this report. In the room there were also three tables made of wood, an upholstered wooden chair and finally a book shelf with some binders and magazines. There was also an artificial plant behind the sofa. The room plan is shown in Figure 20.

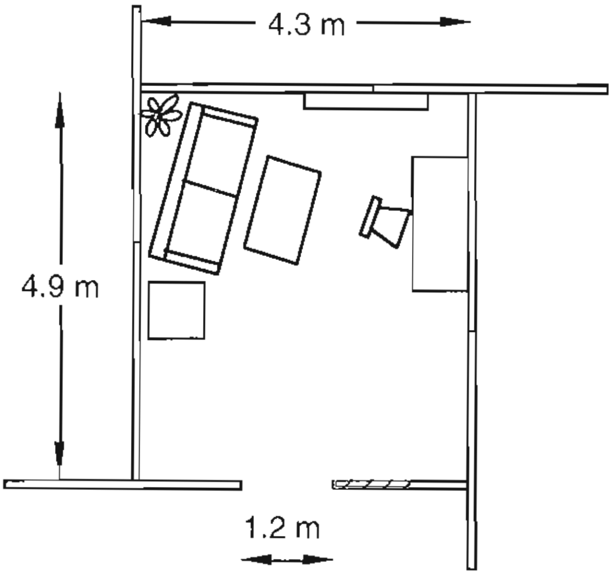

Figure 20. Room plan for fire experiment.

The experiment started by putting a burning candle in one of the corners of the sofa. There was eventually ignition and at about 1:30 minutes the heat release reached 50 kW. According to our earlier discussion we denote that as time zero. Three minutes later the heat release reached approximately 4 MW. From the video recording one can see that the contribution to the fire is only from the sofa and the ceiling up to about 4 minutes of the test.

A characteristic design fire for this scenario is close to scenario 2. The difference is that no floor covering is present and that only part of the ceiling is class III. We run into problems specifying the surface lining as this test set up was not reflecting a real case in the sense of linings covering only parts of the ceiling with a class III product and everything else being of class I. Obviously class III at wall and ceiling is too tough but class I would be the opposite.

To be on the safe side we therefore assume class III surface linings. Thus the lining will start to contribute to the fire like *ultra fast* when the furniture fire reaches 160 kW. The domestic furniture has a characteristic heat release of

$\dot{Q} = 2500 \exp((-0{,}4(t-3))^2)$ kW. For comparison we also choose linings that would contribute as *fast* and as *medium*. The design fires made up from the domestic furniture and the different lining alternatives are shown in Figure 21.

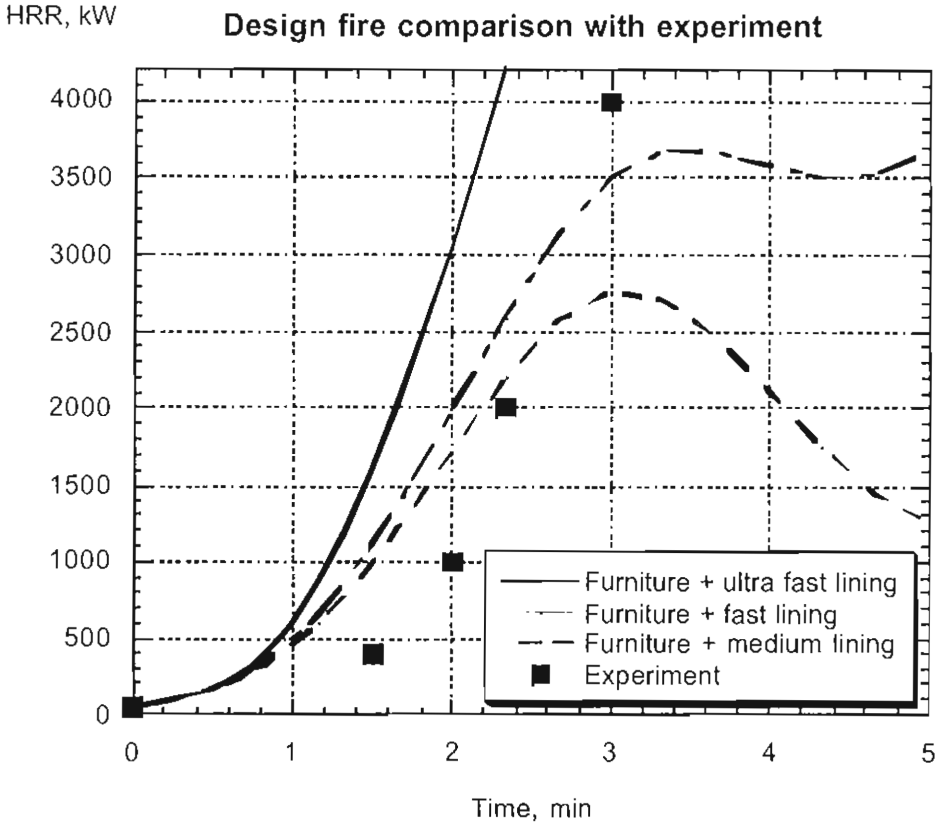

Figure 21. Design fire of an experiment with a domestic sofa in a room having class III ceiling and class I walls.

As is seen from the design fire assuming class III linings for all surfaces in Figure 21, 4 MW is reached at about 2:20 (min:s) which should be compared to 3 minutes in the real test. The time difference to reach 4 MW would be smaller if a more realistic surface lining was used. We see that by choosing fast contribution for the linings the timing is greatly improved but that the selection of a medium lining fire is not very successful. To this we should add the contribution to the fire from the book shelf and tables. From the visual observations their contribution were limited but appeared at the latest stages of the fire. However, for this scenario a very good prediction was reached by using the simple tools described in this report.

10 Conclusions

When conducting a risk analysis, the selection of design fire is of profound importance for the result. The forthcoming ISO standard and the Nordic NKB recommendations are rather crude and provide for very conservative estimates. This work aims to support the process of estimating a design fire based on products burning behaviour in a fire situation.

Starting point is the burning rate of different groups of products. From test data and generic burning behaviour general characteristic heat release rates versus time have been selected for upholstered furniture, surface linings, floorings, cables and curtains. The t^2- fire seems to be a good approximation for some linings. However, for upholstered furniture bell shaped curves provides for a better fit and for cable trays a linear approximation was taken. These type fires have then been merged to design fires in examples of an upholstered furniture item and linings burning together. Comparison with a fully furnished room fire experiment showed good correlation.

The results are very promising as characteristic heat release rates of good accuracy seems to be possible to define for upholstered furniture, surface linings, cable trays and large curtains. For upholstered furniture and linings the characteristic HRR curves are based on a very large data base. A measure of the variation of the characteristic HRR curves for furniture is also given. It appears as public furniture generally show a much slower fire build up than domestic furniture. It was also possible to describe characteristic HRR curves for linings based on the Swedish classification system. This means that it may be possible to describe the consequence for the fire protection by selection of different performance classes of the linings, which so far has been very difficult to do. The occurrence of flashover or not may be predicted. Of special importance is the possibility to study the influence of the furniture compared to the linings. Questions are raised on the importance of the Swedish lining class II for safety.

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