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RAPPORT

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Trätek

INSTITUTET FÖR TRÄTEKNISK FORSKNING

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CONTENT

PREFACE

This report presents a joint work carried out by Trätek Swedish Institute for Wood Technology Research, Stockholm, SINTEF NBL Norwegian Fire Research Laboratory, Trondheim (*) and NTH University of Trondheim Norwegian Institute of Technology, Division of building and construction engineering (**). The Swedish work has dealt with correlation studies and the Norwegian work with predicted parameters as presented in Chapter 6.

The report forms part of the work carried out within the Nordic fire research programme "EUREFIC -EUropean REaction-to-FIre Classification". The programme is managed in cooperation between the national fire laboratories in Denmark, Finland, Norway and Sweden.

Data from an earlier extensive Scandinavian study have also been included in the analysis as well as some data from interlaboratory testing within ISO.

The Norwegian work presented in this report has been carried out within EUREFIC project 4 "Models for predicting the fire growth in the Room/Corner Test based on results from the Cone Calorimeter", while the Swedish work has been sponsored by BRANDFORSK, the Swedish Board for Fire Research, which is kindly acknowledged.

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ABSTRACT

The smoke production in the full scale room fire test ISO 9705 and in the cone calorimeter has been analysed for three sets of building products including a total of 28 products.

The smoke production may be critical for the fire classification of surface products since some products produce large amounts of smoke in the room fire test even if they do not reach flashover within 20 minutes.

Several smoke parameters in the cone calorimeter and the room fire test have been analysed. Good correlations have been obtained only when the products are divided into two groups: products with more than 10 minutes to flashover in the room fire test and products with less than 10 minutes. These two time categories correspond to the two heat output levels in the room fire test, 100 kW for the first 10 minutes and then 300 kW up to 20 minutes. For products with **more** than 10 minutes to flashover, the average rate of smoke production and the total smoke production seem to be useful parameters for predictions of smoke release in the room fire test. Both parameters have good correlations between data from the cone calorimeter and the room fire test.

For products with **less** than 10 minutes to flashover, no parameter seems to give useful predictions. For **all** products evaluated together, the correlations are not so good, but the same regression lines as for products with more than 10 minutes might be used as a first rough estimate. In this case the total smoke production in the cone calorimeter could be used to estimate the smoke production in the room fire test for different building products, independant of their estimated time to flashover.

SAMMANFATTNING - SWEDISH SUMMARY

Rökutvecklingen från ytmaterial på väggar och i tak vid rumsbrandprovning och vid småskalig brandprovning i den s k konkalorimetern har jämförts. Totalt har data för 28 olika ytmaterial studerats.

Rökutvecklingen måste inkluderas i den brandtekniska bedömningen av ytmaterial. Detta är särskilt viktigt eftersom flera ytmaterial avger stora rökmängder vid rumsbrandprovning även om de inte når övertändning inom 20 minuter (vilket är den maximala provtiden enligt provmetoden). Dessa starkt rökalstrande material måste kunna identifieras på ett enkelt sätt.

Ett flertal rökparametrar, som uppmätts eller beräknats i de båda metoderna, har jämförts, bl a rökutvecklingshastighet, maximal rökutveckling, total rökutveckling och rökutveckling per värmeutveckling. Dessutom har några rökindex från konkalorimetern jämförts med rökutvecklingshastighet vid rumsbrandprovning.

Bra korrelationer har uppnåtts endast om ytmaterialen indelas i två grupper: de som övertänder **före** 10 minuter och de som övertänder **efter** 10 minuter. Dessa tider motsvarar de två effekter hos antändningskällan som används vid rumsbrandprovning, 100 kW de första 10 minuterna och därefter 300 kW i ytterligare 10 minuter.

Bäst korrelation har erhållits för ytmaterial som övertänder efter 10 minuter, vilket är lovande eftersom rökutvecklingen för dessa material kan vara avgörande för deras brandklassificering. Rökutvecklingshastigheten och den totala rökutvecklingen ger bäst korrelation, 0,91 i båda fallen, och med endast ett material av totalt 13 som avviker. Detta är ett smältande material, vars brandbeteende är svårt att förutsäga, men som är på 'säkra' sidan, dvs dess rökutveckling är mindre vid rumsbrandprovning än vad som förväntas enligt data från konkalorimetern. Sådana material måste provas i rumsskala för att om möjligt uppnå en bättre klassificering.

För ytmaterial som övertänder före 10 minuter har inga goda korrelationer uppnåtts.

Om **alla** ytmaterialen inkluderas i analysen blir korrelationen relativt låg, men regressionslinjerna är ungefär desamma som för ytmaterial som övertänder **efter** 10 minuter. Dessa regressionslinjer bör därför kunna användas för samtliga ytmaterial som en första uppskattning. Den rökparameter som då bör väljas är totala rökproduktionen. Ett enkelt samband ges, som kan användas för alla ytmaterial. För ytmaterial som övertänder efter 10 minuter kan sambandet användas med större säkerhet.

1. INTRODUCTION

Smoke is produced in almost all fires and presents a major hazard to life. Smoke particles reduce the visibility due to light absorption and scattering and leads to disorientation. The possibility to find exit signs, doors and windows may disappear. Those aspects are becoming more important in all European countries since they are included in the Draft Interpretative Document /5/ for the Essential Requirement on 'Safety in case of fire' of the Construction Products Directive /7/.

The production of smoke and its optical properties are often measured simultaneously with other fire properties as heat release and flame spread. The measurements are usually dynamic in full scale, i.e. they are performed in a flow through system. In small scale, they may be either dynamic as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. The ability of small scale tests, both dynamic and static, to predict full scale behaviour is of major interest. However, predictions of smoke production have been much less studied than predictions of heat release, and with limited success so far/2, 3, 6, 9, 16, 18, 19, 28/.

This report will present basic smoke data for 28 products and make an attempt to correlate data from small and full scale testing in order to develop predictive models.

2. EXPERIMENTAL

2.1 Tested products

Three sets of building products have been tested: a new set of 11 EUREFIC products, see Table 1, another new set of 4 products from the Nordic round robin within ISO TC 92/ SC1/ WG 7 for the room fire test, see Table 2, and an old set of 13 products earlier frequently used for fire studies in Scandinavia, see Table 3. Thus, a total of 28 lining products are included in this study.

Table 1. EUREFIC products.

No.	Product	Thickness mm	Density kg/m^3	Surface weight g/m^2
1.	Painted gypsum paper plasterboard	12	800	100 ***
2.	Ordinary birch plywood	12	600	
3.	Textile wallcovering on gypsum paper plasterboard	12+1 *	800	505 ****
4.	Melamine-faced high density non-combustible board	12+1.5 *	1055 **	
5.	Plastic-faced steel sheet on mineral wool	23+0.15+ +0.7 *	640 **	
6.	FR particle board, type B1	16	630	
7.	Combustible-faced mineral wool	30+1 *	87 **	37
8.	FR particle board	12	750	
9.	Plastic-faced steel sheet on polyurethane foam	80+0.1+ +1 *	160 **	
10.	PVC-wallcarpet on gypsum paper plasterboard	12+0.9 *	800	1250 ****
11.	FR extruded polystyrene foam	25	37	

* Thickness of surface layer(s).
** Total.
*** Paint weight.
**** Base paper + surface covering.

Table 2. Nordic round robin products.

No.	Product	Thickness mm	Density kg/m^3
12.	Birch plywood	12	600
13.	FR plywood	9	620
14.	Melamine-faced particle board	12+0.1 *	680
15.	FR polystyrene	25	30

* Thickness of surface layer.

Table 3. Scandinavian products.

No.	Product	Thickness mm	Density kg/m^3
16.	Particle board	10	670
17.	Insulating wood fiber board	13	250
18.	Medium density wood fiber board	12	655
19.	Wood panel, spruce	11	450
20.	Melamine-faced particle board	12+1 *	870
21.	Plastic wallcovering on gypsum board	13+0.7*	725
22.	Textile wallcovering on gypsum board	13+0.5 *	725
23.	Textile wallcovering on rockwool	42+0.5 *	150
24.	Paper wallcovering on particle board	10+0.5 *	670
25.	Rigid polyurethane foam	30	32
26.	Expanded polystyrene	49	18
27.	Paper wallcovering on gypsum board	13+0.5*	725
28.	Gypsum board	13	725

* Thickness of surface layer.

2.2 Test methods

The full scale room fire tests have been performed according to NT Fire 025/ISO 9705 at different Nordic laboratories: for the 11 EUREFIC and the 4 Nordic round robin products at the national fire laboratories in Finland, Norway and Sweden /15, 22/ and for the 13 Scandinavian products at the Swedish National Testing Institute /20/. All tests have been performed with both the walls and the ceiling covered with the product tested. In all cases, the smoke obscuration has been measured in the exhaust duct with white light and a photocell which has a response simulating the human eye.

The cone calorimeter tests have been performed according to ASTM E 1354 since the equivalent ISO 5660 does not include smoke measurements. All products have been tested by using the recommended stainless steel retainer frame /23, 24, 25/. For the predicted parameters in chapter 6, cone data from testing without retainer frame have been used /26/. Only data at an irradiance of 50 kW/m^2 have been chosen, since all products ignite at 50 kW/m^2, but not at 25 and 35 kW/m^2. For most products, the smoke obscuration in the cone calorimeter has been measured with two light systems used simultaneously, a helium-neon laser and a white light system. The two systems give equal results as earlier reported /28/.

3. AVAILABLE SMOKE PARAMETERS AND DATA

The same smoke parameters and units have been used both for the full scale and the cone calorimeter data. In addition to that, some smoke indices calculated from the cone calorimeter data have also been used.

The **rate of smoke production**, RSP, has been calculated according to NT Fire 025 since most full scale data are given in that way /20, 22/.

$$RSP = 10(1/L)\log(I_0/I)\,V_f \qquad (1)$$

where RSP is rate of smoke production (m^2/s)

L is pathlength of beam through smoke (m)

I is intensity of transmitted light

I_0 is intensity of incident light

V_f is volume flow rate (m^3/s)

Both **average and maximum rates of smoke production** have been used.

The **total smoke production** is defined as

$$TSP = \int_0^t RSP(t)dt \qquad (2)$$

where TSP is total smoke production (m^2)

t is time (s)

The **total smoke production per total heat release**, TSP/THR, has been used in order to separate products which release more smoke than heat in both scales. It has been calculated as an average by taking the ratio between total smoke production and total heat production.

A **smoke index** can be defined from cone calorimeter data in the same way as indices for ignitability and heat release /12, 13/. Here the following definition has been applied

$$I_s = \int_0^{t_{ig}} RSP(t)dt / t_{ig}^{\,n} + \int_{t_{ig}}^{t_{ig}+300} RSP(t)dt/300^{\,n} \qquad (3)$$

where I_s is smoke index (m^2/s^n)

t_{ig} is time to ignition (s)

n is an exponent which has been varied between 0.4 and 1.0.

Smoke indices are available only from the cone calorimeter. They have been correlated with the average rate of smoke production in the room fire test.

For the cone calorimeter, the smoke production is usually expressed as **specific extinction area**, which is a mass-based unit.

$$SEA = k\ V_f\ /\ MLR \tag{4}$$

where SEA is specific extinction area (m^2 /kg)

k is light extinction coefficient (m^{-1})

MLR is mass loss rate of fuel (kg/s)

For the room fire test, the mass loss rate is not known, but the specific extinction area can be calculated by using the effective heat of combustion, which is determined in the cone calorimeter and can be supposed to be fairly constant and independent of scale. The following expression has been used:

$$SEA\ (room) = EHC\ \ 0.1\ \ \ln 10\ \ TSP/THR \tag{5}$$

where EHC is effective heat of combustion in the cone calorimeter at 50 kW/m^2 (MJ/kg)

Combined units of smoke and heat release have also been used since the smoke production is largely dependent on the general burning behaviour of the product. A **smoke parameter**, which is the product of the peak rate of heat release and the specific extinction area, and a **smoke factor**, which is the product of the peak rate of heat release and the total smoke production, have earlier been suggested /2,9/. Here the following definitions have been used.

$$\text{Smoke parameter} = RHR\ \ SEA \tag{6}$$

$$\text{Smoke factor} = RHR\ \ TSP \tag{7}$$

In all cases the different smoke parameters have been calculated from start of test to flashover in the room fire test or to 20 minutes for products not reaching flashover. In the cone calorimeter different periods of time have been used, e.g. total test time as specified in the standard or the time from start of test to 5 minutes (300 s) after ignition. Both include the time before ignition, which seems to be essential. The time periods used for cone data are indicated in tables and diagrams.

The main available data from the room fire test are presented in Table 4 and from the cone calorimeter in Tables 5a and 5b.

Table 4. **Room fire test data** up to time to flashover or to 20 minutes for products not reaching flashover.

	Products	Time to flashover min:s	Average RSP m^2/s	Max RSP m^2/s	TSP m^2
1.	Painted gypsum paper plasterboard	> 20	1.8	4.1	2110
2.	Ordinary birch plywood	2:30	9.2	49.2	1380
3.	Textile wallcovering on gypsum paper plasterboard	11:00	1.9	11.5	1240
4.	Melamine-faced high-density non-combustible board	> 20	8.5	46.4	10160
5.	Plastic-faced steel sheet on mineral wool	> 20	6.3	20.9	7570
6.	FR particle board, type B1	10:30	6.3	86.4	4000
7.	Combustible-faced mineral wool	1:20	2.6	12.1	210
8.	FR particle board	> 20	14.3	41.2	16680
9.	Plastic-faced steel sheet on polyurethane foam	3:15	9.7	33.7	1890
10.	PVC-wallcarpet on gypsum paper plasterboard	10:55	11.0	234	7210
11.	FR extruded polystyrene foam	1:20	5.4	23.3	430
12.	Birch plywood	2:17	8.5	46.7	1170
13.	FR plywood	> 20	4.5	32.3	5400
14.	Melamine-faced particle board	3:02	11.1	51.5	2010
15.	FR polystyrene	> 20	6.6	67.8	7880
16.	Particle board	2:30	11.3	66	1700
17.	Insulating wood fiber board	1:07	9.3	55	620
18.	Medium-density wood fiber board	2:14	7.5	58	1000
19.	Wood panel, spruce	2:18	7.2	61	1000
20.	Melamine-faced particle board	7:45	33.3	136	15500
21.	Plastic wallcovering on gypsum board	10:15	3.6	140	2200
22.	Textile wallcovering on gypsum board	10:37	0.3	28	210
23.	Textile wallcovering on rockwool	0:55	21.8	84	1200
24.	Paper wallcovering on particle board	2:22	12.0	67	1700
25.	Rigid polyurethane foam	0:14	214	305	3000
26.	Expanded polystyrene	2:12	34.1	95	4500
27.	Paper wallcovering on gypsum board	> 20	0.5	10	200
28.	Gypsum board	> 20	0	1	200

RSP Rate of smoke production.
TSP Total smoke production.

Table 5a. **Cone calorimeter data** with retainer frame at 50 kW/m^2 and horizontal orientation. All data are from start of test (incl. time to ignition) **to end**, i.e. to the mass loss criterium is reached (SE).

Products	Time to ignition s	Average RSP $\cdot 10^3$ m^2/s	Max RSP $\cdot 10^3$ m^2/s	TSP m^2
1. Painted gypsum paper plasterboard	47	3.1	17	0.9
2. Ordinary birch plywood	30	37.0	157	19.2
3. Textile wallcovering on gypsum paper plasterboard	25	8.8	135	3.3
4. Melamine-faced high-density non-combustible board	29	16.9	130	7.9
5. Plastic-faced steel sheet on mineral wool	53	82.9	272	5.0
6. FR particle board, type B1	21	14.9	86	16.0
7. Combustible-faced mineral wool	5	43.3	88	0.65
8. FR particle board	700	27.8	88	26.8
9. Plastic-faced steel sheet on polyurethane foam	19	232	476	41.7
10. PVC-wallcarpet on gypsum paper plasterboard	15	18.5	297	11.3
11. FR extruded polystyrene foam	31	462	913	47.3
12. Birch plywood	28	28.4	86	16.6
13. FR plywood	469	14.2	46	7.6
14. Melamine-faced particle board	34	10.6	45	8.3
15. FR polystyrene	25	298	774	35.7
16. Particle board	34	24.3	73	14.1
17. Insulating wood fiber board	12	19.4	67	7.5
18. Medium-density wood fiber board	31	37.6	103	27.3
19. Wood panel, spruce	20	20.9	68	12.0
20. Melamine-faced particle board	44	24.2	209	27.9
21. Plastic wallcovering on gypsum board	10	14.9	366	4.9
22. Textile wallcovering on gypsum board	20	7.4	150	2.9
23. Textile wallcovering on rockwool	11	74	317	2.6
24. Paper wallcovering on particle board	35	20.2	77	14.2
25. Rigid polyurethane foam	2	391	665	26.2
26. Expanded polystyrene	39	262	513	44.6
27. Paper wallcovering on gypsum board	21	5.4	47	1.4
28. Gypsum board	34	4.1	30	1.1

RSP Rate of smoke production.
TSP Total smoke production.

Table 5b. **Cone calorimeter data** with retainer frame at 50 kW/m^2 and horizontal orientation. All data are from start of test (incl. time to ignition) **to 300** s **after ignition** (S 3).

Products	Time to ignition s	Average RSP $\cdot 10^3$ m^2/s	TSP m^2
1. Painted gypsum paper plasterboard	47	2.9	1.0
2. Ordinary birch plywood	30	22.6	7.5
3. Textile wallcovering on gypsum paper plasterboard	25	9.8	3.2
4. Melamine-faced high-density non-combustible board	29	22.7	7.5
5. Plastic-faced steel sheet on mineral wool	53	17.8	6.3
6. FR particle board, type B1	21	16.5	5.3
7. Combustible-faced mineral wool	5	3.7	1.1
8. FR particle board	700	26.8	26.8
9. Plastic-faced steel sheet on polyurethane foam	19	139	44.4
10. PVC-wallcarpet on gypsum paper plasterboard	15	35.2	11.1
11. FR extruded polystyrene foam	31	149	49.2
12. Birch plywood	28	14.9	4.9
13. FR plywood	469	10.9	8.3
14. Melamine-faced particle board	34	13.1	4.4
15. FR polystyrene	25	118	38.5
16. Particle board	34	22.0	7.4
17. Insulating wood fiber board	12	17.1	5.3
18. Medium-density wood fiber board	31	36.8	12.2
19. Wood panel, spruce	20	11.0	3.5
20. Melamine-faced particle board	44	38.6	13.3
21. Plastic wallcovering on gypsum board	10	15.6	4.8
22. Textile wallcovering on gypsum board	20	8.5	2.7
23. Textile wallcovering on rockwool	11	9.7	3.0
24. Paper wallcovering on particle board	35	13.5	4.5
25. Rigid polyurethane foam	2	89.6	27.1
26. Expanded polystyrene	39	135	45.8
27. Paper wallcovering on gypsum board	21	4.8	1.5
28. Gypsum board	34	3.6	1.2

RSP Rate of smoke production.
TSP Total smoke production.

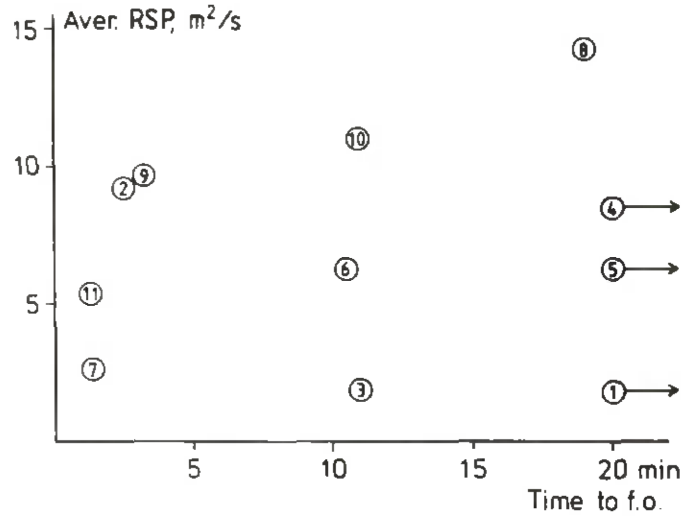
4. SMOKE CRITICAL FOR CLASSIFICATION

Products which release large amounts of smoke often have a rather short time to flashover in the room fire test. In these cases there is no problem to classify the products according to their fire behaviour. However, some products may release large amounts of smoke even if they have a considerably long time to flashover or do not reach flashover within 20 minutes. In these cases, it is important to consider the smoke production in a classification system.

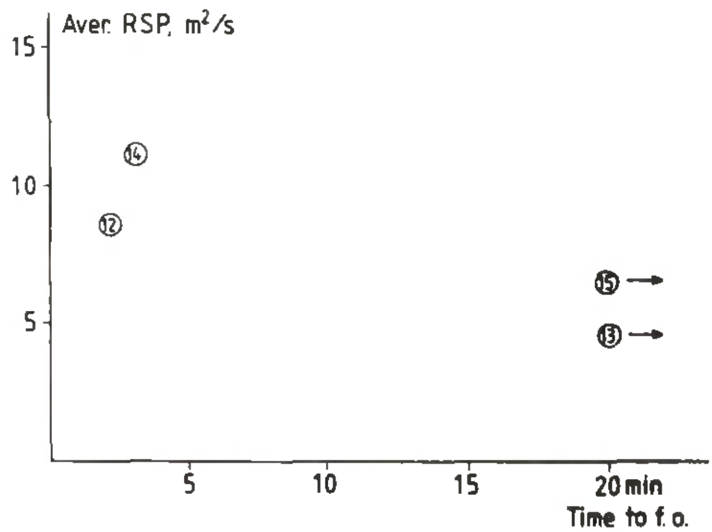
The situation is illustrated by Figure 1, from which it is obvious that several of the EUREFIC products with long time to flashover release large amounts of smoke, while all the Scandinavian products (Nos. 16-28) with long time to flashover release only small amounts of smoke. The Nordic round robin products (Nos. 12-15) are intermediate.

If the classification system proposed in EUREFIC /21/ is applied, it is obvious that smoke release is critical for seven products, see Table 6. Among these, there are five EUREFIC products and two Nordic round robin products with high smoke release, while all the products from the old set (Nos. 16-28) have a relatively low smoke release in relation to their heat release.

EUREFIC products



Nordic RR products



Scandinavian products

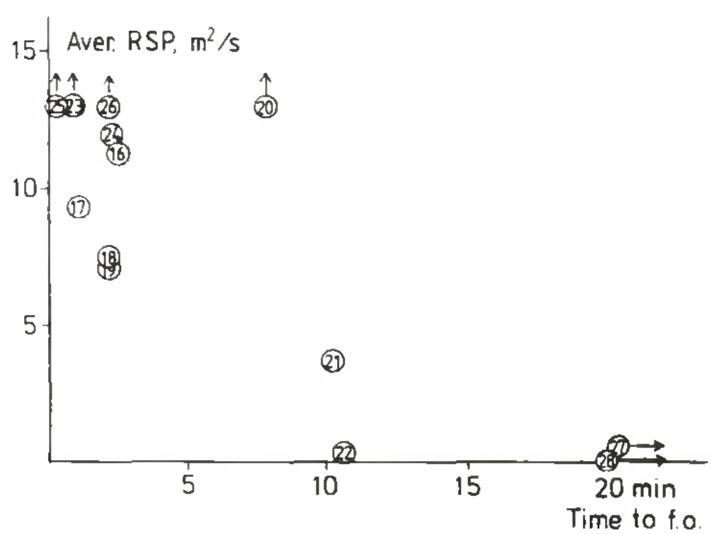


Figure 1. Average rate of smoke production, RSP, vs time to flashover in the room fire test for all products tested. Above for the EUREFIC products, in the middle for the Nordic round robin products and below for the Scandinavian products. Several of the products with long time to flashover have a high release of smoke.

Table 6 Critical factors for classification

Products	Heat release (flashover)	Smoke release
1. Painted gypsum paper plasterboard	both	
2. Ordinary birch plywood	both	
3. Textile wallcovering on gypsum paper plasterboard	x	
4. Melamine-faced high-density non-combustible board		x
5. Plastic-faced steel sheet on mineral wool		x
6. FR particle board, type B1		x
7. Combustible-faced mineral wool	x	
8. FR particle board		x
9. Plastic-faced steel sheet on polyurethane foam	both	
10. PVC-wallcarpet on gypsum paper plasterboard		x
11. FR extruded polystyrene foam	x	
12. Birch plywood	both	
13. FR plywood		x
14. Melamine-faced particle board	both	
15. FR polystyrene		x
16. Particle board	both	
17. Insulating wood fiber board	x	
18. Medium-density wood fiber board	both	
19. Wood panel, spruce	both	
20. Melamine-faced particle board	both	
21. Plastic wallcovering on gypsum board	x	
22. Textile wallcovering on gypsum board	x	
23. Textile wallcovering on rockwool	both	
24. Paper wallcovering on particle board	both	
25. Rigid polyurethane foam	both	
26. Expanded polystyrene	both	
27. Paper wallcovering gypsum board	x	
28. Gypsum board	both	

5. CORRELATIONS OF MEASURED AND CALCULATED PARAMETERS

Several available smoke parameters from the room fire test and the cone calorimeter have been correlated in order to get an overview of possible useful relations. The same parameters from both tests have been used to ensure a sound physical basis for the correlations.

5.1 Two groups of products

For safety reasons, it is most essential to predict the smoke production from products with rather long time to flashover. Therefore, the products have been divided into two groups: those which reach flashover in the room fire test in **less than 10 minutes** and those which have **more than 10 minutes** to flashover. This is justified since the heat source in the room fire test is increased from 100 to 300 kW after 10 minutes. Correlations including all products have been less successful in most cases, see below.

There are 15 products with less than 10 minutes to flashover and 13 products with more than 10 minutes to flashover.

5.2 Regression analyses of different smoke parameters

The following smoke parameters from the room fire test and the cone calorimeter have been correlated by a simple linear regression analysis:

- o Average rate of smoke production (Average RSP)
- o Maximum rate of smoke production (Max RSP)
- o Total smoke production (TSP)
- o Ratio between total smoke production and total heat release (TSP/THR)
- o Specific extinction area (SEA)
- o Smoke parameter (RHR SEA)
- o Smoke factor (RHR TSP)

In addition to that, smoke indices as defined in Eq. (3) for data from the cone calorimeter have been correlated with average rate of smoke production in the room fire test to give an indication of their usefulness. This means:

- o Smoke index (cone) vs Average RSP (room)

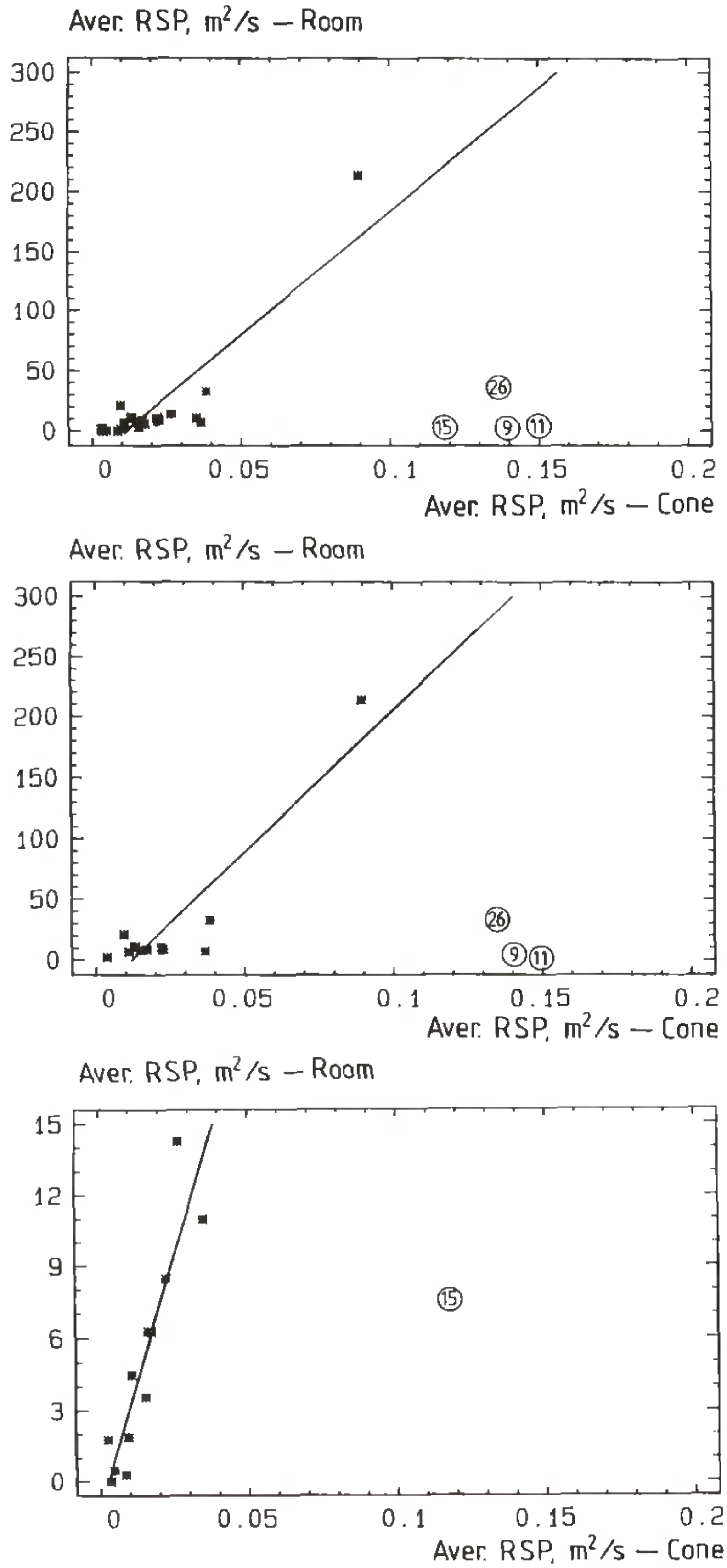
In most cases one or a few products have been identified as outliers and therefore rejected from the correlation analysis. The correlation coefficients obtained for different smoke parameters and for different numbers of products included in the correlations are given in Tables 7 to 12. Correlations with the same or nearly the same number of products included have been plotted in Figures 2 to 9.

Table 7. **Average rate of smoke production** in the cone calorimeter and the room fire test.
Correlation coefficients for different times to flashover in the room fire test, different time periods in the cone calorimeter at 50 kW/m² and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients Average rate of smoke production			
		Time period for cone data [x]			
		SE	S3	IE	I3
all	28				
times	27				
	26		0.28		
	25				
	24		0.88		
< 10 min	15	0.52	0.26	0.38	0.21
	14	0.78		0.70	
	13	0.87		0.80	
	12		0.91		0.89
> 10 min	13	0.21	0.39	0.15	0.27
	12	0.40	0.91	0.29	0.56
	11	0.94	0.94	0.61	0.83

[x] SE: from start to end of test.
S3: from start to 300 s after ignition.
IE: from ignition to end of test.
I3: from ignition to 300 s after ignition.

Underlined correlation coefficients are plotted in Figure 2.



Time to f. o. in room fire	Corr. coeff.
all times	<u>0.88</u> (24 prod.)
$<$ 10 min	<u>0.91</u> (12 prod.)
$>$ 10 min	<u>0.91</u> (12 prod.)

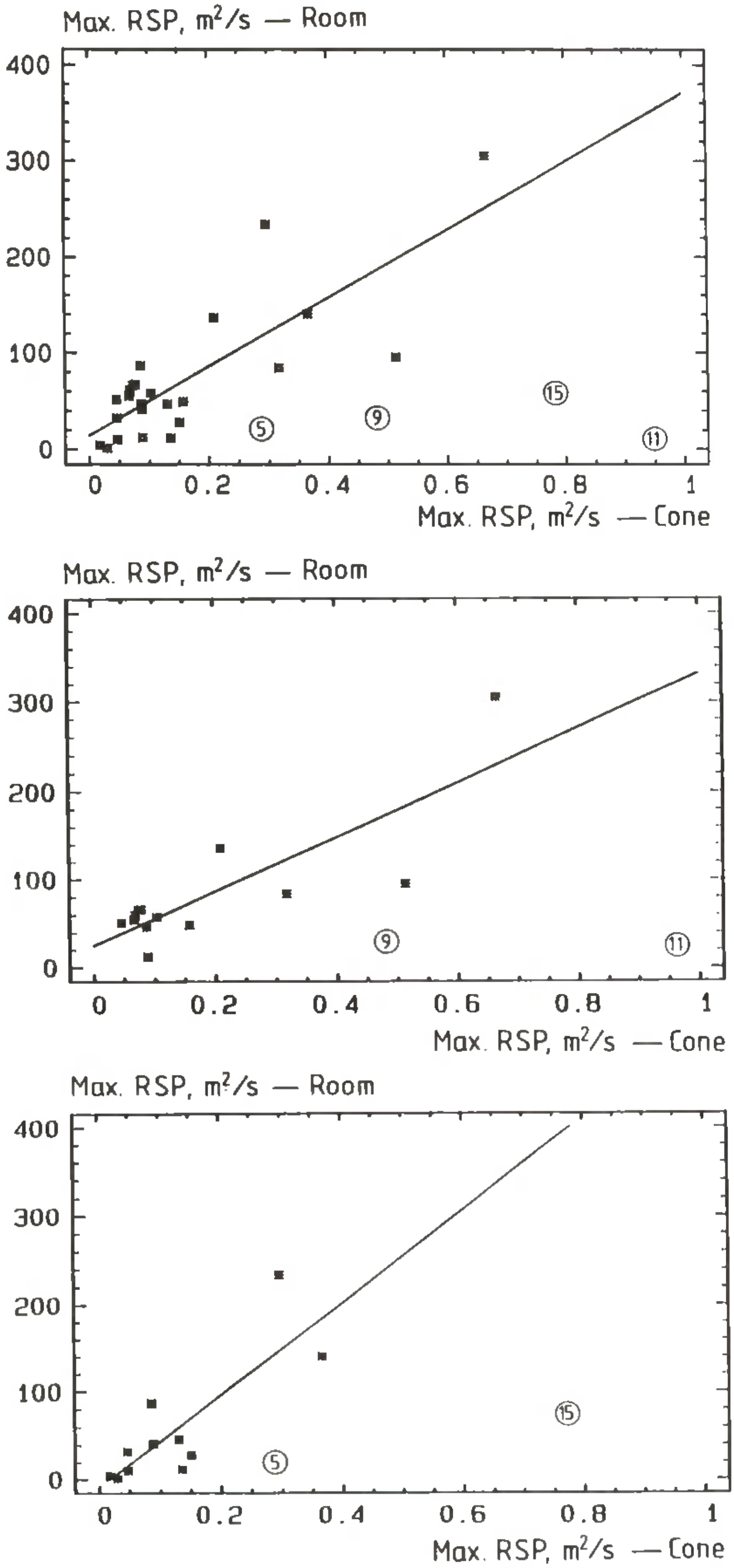
<u>Figure 2.</u> Average rate of smoke production, RSP, in the room fire test and the cone calorimeter from start of test to 300 s after ignition (S 3).
Note: Different scales.
Outliers not included in the correlations are identified by product numbers.

Table 8. **Maximum rate of smoke production** in the cone calorimeter and the room fire test.
Correlation coefficients for different times to flashover in the room fire test, different time periods in the cone calorimeter at 50 kW/m^2 and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients Max rate of smoke production — Time period for cone data[x] SE
all times	28	
	27	
	26	0.48
	25	
	24	0.80
	23	0.83
	22	0.90
< 10 min	15	0.34
	14	0.68
	13	0.82
	12	
> 10 min	13	0.41
	12	0.70
	11	0.82

[x] SE: from start to end of test.

Underlined correlation coefficients are plotted in Figure 3.



Time to f. o. in room fire	Corr. coeff.
all times	0.80 (24 prod.)
< 10 min	0.82 (13 prod.)
> 10 min	0.82 (11 prod.)

Figure 3. Maximum rate of smoke production, RSP, in the room fire test and the cone calorimeter (SE).
Outliers not included in the correlations are identified by product numbers.

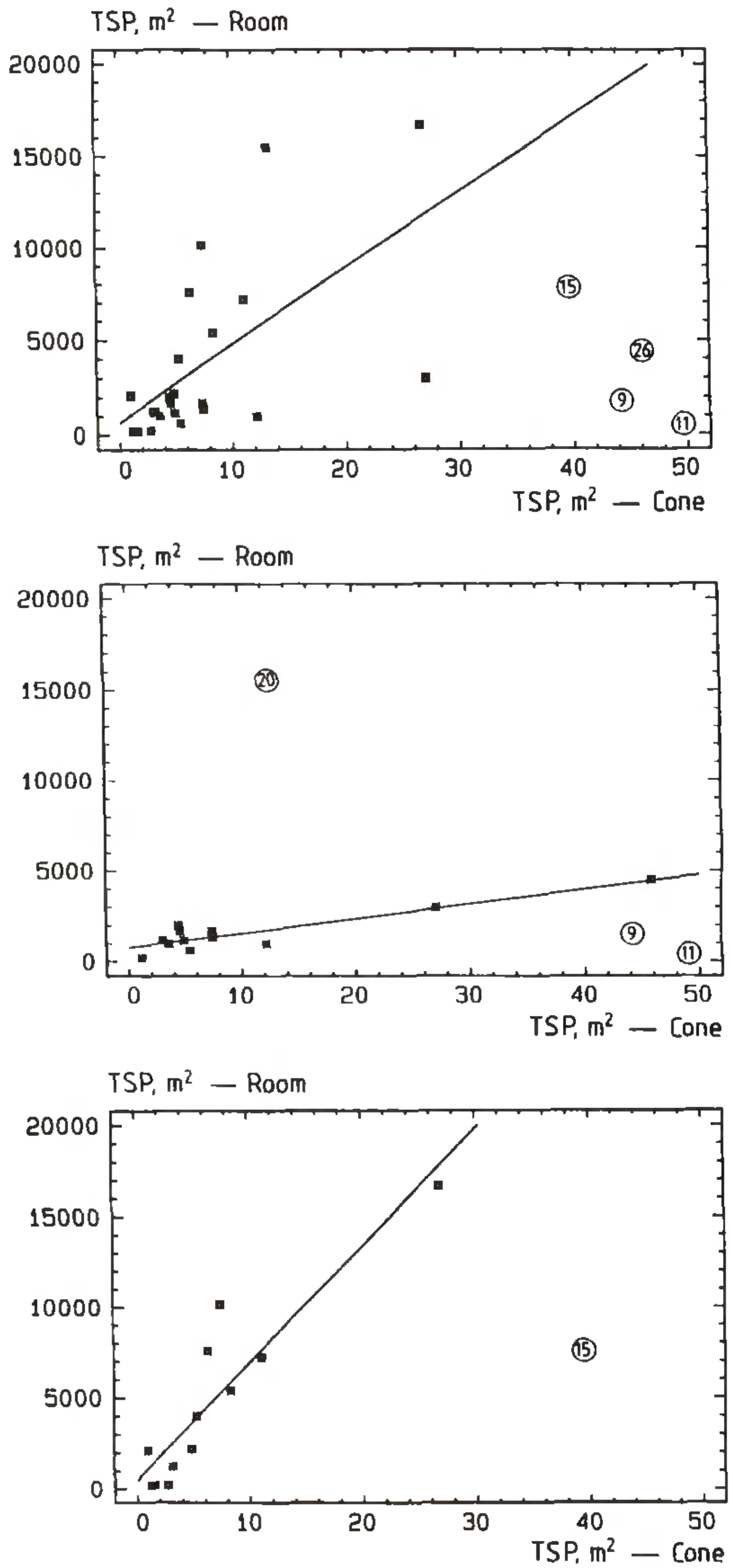
Table 9. **Total smoke production** in the cone calorimeter and the room fire test.

Correlation coefficients for different times to flashover in the room fire test, different time periods in the cone calorimeter at 50 kW/m^2 and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients Total smoke production	
		Time period for cone data[x]	
		SE	S3
all times	28	0.26	0.24
	27		
	26		
	25	0.49	0.57
	24	0.58	<u>0.62</u>
	23	0.63	0.80
	22	0.68	0.86
< 10 min	15	0.25	0.10
	14	0.44	0.46
	13	0.72	0.76
	12	0.78	<u>0.91</u>
> 10 min	13	0.68	0.69
	12	0.83	<u>0.91</u>
	11	0.91	0.96

[x] SE: from start to end of test.
S3: from start to 300 s after ignition.

Underlined correlation coefficients are plotted in Figure 4.



Time to f. o. in room fire	Corr. coeff.
all times	0.62 (24 prod.)
<10 min	0.91 (12 prod.)
>10 min	0.91 (12 prod.)

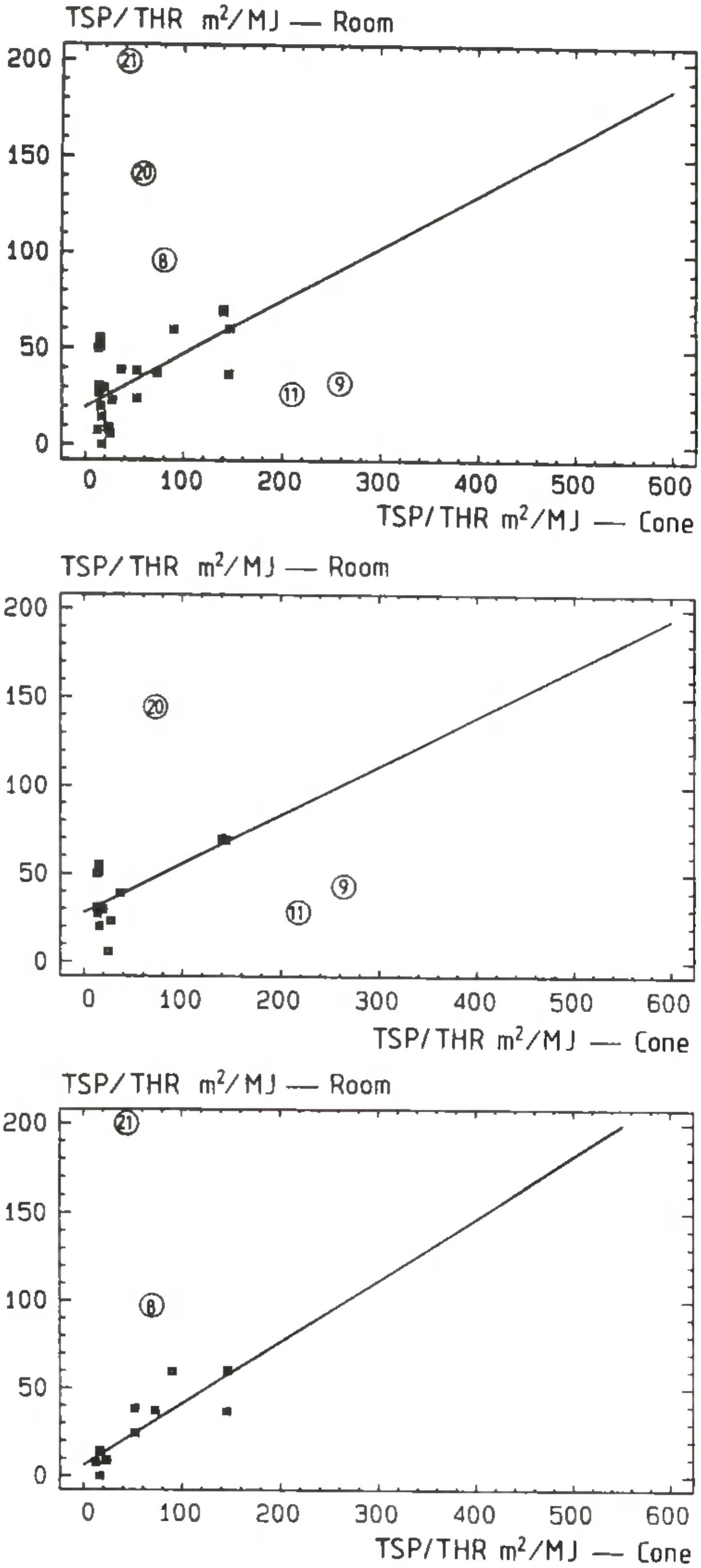
Figure 4. Total smoke production, TSP, in the room fire test and the cone calorimeter (S 3).
Outliers not included in the correlations are identified by product numbers.

Table 10. **TSP/THR** (calculated as the ratio between integrated data) in the cone calorimeter and the room fire test.
Correlation coefficients for different times to flashover in the room fire test, different time periods in the cone calorimeter at 50 kW/m^2 and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients TSP/THR			
		Time period for cone data [x]			
		SE	S3	IE	I3
all	28	0.03	0.17	0.04	0.12
times	26	0.23	0.38		
	25	0.34		0.42	0.45
	24		0.60		
	23	0.54	0.64		0.72
	22	0.59	0.71	0.66	0.78
< 10 min	15	0.03	0.15	0.06	0.13
	14	0.27	0.25	0.33	0.26
	13				
	12	0.57	0.67	0.64	0.69
> 10 min	13	0.03	0.26	0.03	0.16
	12	0.28	0.65	0.24	
	11	0.64	0.84	0.52	0.89

[x] SE: from start to end of test.
S3: from start to 300 s after ignition.
IE: from ignition to end of test.
I3: from ignition to 300 s after ignition.

Underlined correlation coefficients are plotted in Figure 5.



Time to f. o. in room fire	Corr. coeff.
all times	<u>0.64</u> (23 prod.)
< 10 min	<u>0.67</u> (12 prod.)
> 10 min	<u>0.84</u> (11 prod.)

<u>Figure 5</u>. Ratio between total smoke production and total heat release, TSP/THR, (calculated as the ratio between integrated data) in the room fire test and the cone calorimeter (S 3).
Outliers not included in the correlations are identified by product numbers.

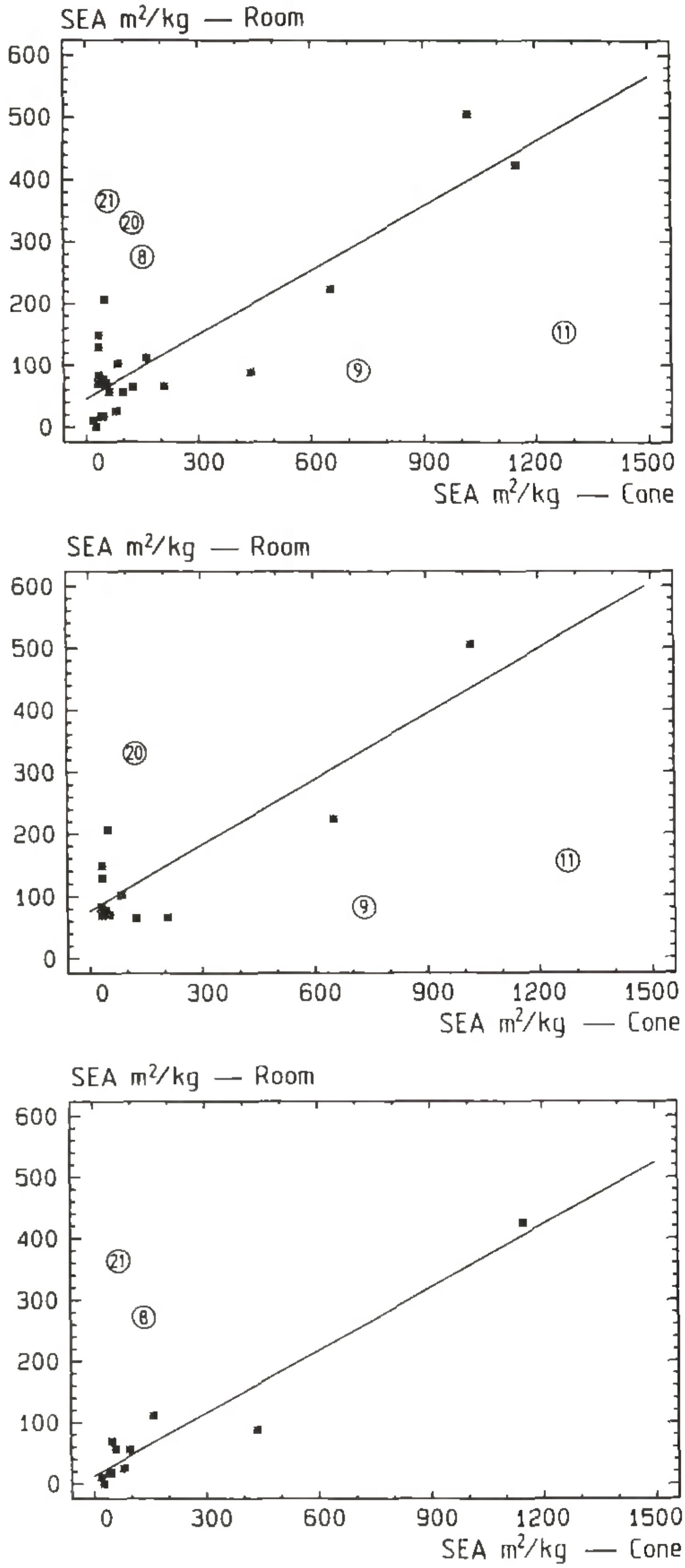
Table 11. **Specific extinction area**, SEA (to the left), **smoke parameter** (in the middle) and **smoke factor** (to the right) in the cone calorimeter and the room fire test.

Correlation coefficients for different times to flashover in the room fire test, different time periods in the cone calorimeter at 50 kW/m^2 and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients					
		SEA		Smoke parameter		Smoke factor	
		Time period for cone data ˣ					
		S3	I3	S3	I3	S3	I3
all	28	0.55	0.54	0.47	0.46	0.24	0.19
times	27				0.61		
	26	0.68		0.68		0.33	0.23
	25		0.72	0.87	0.87		
	24	0.82				0.47	0.46
	23	0.88		0.96	0.96	0.62	0.61
	22	0.91	0.91	0.97	0.97	0.69	0.68
< 10 min	15	0.47	0.46	0.46	0.44	0.19	0.17
	14	0.57	0.63		0.63		
	13			0.88	0.88	0.61	0.62
	12	0.88	0.89	0.95	0.95	0.82	0.82
> 10 min	13	0.66	0.65	0.50	0.47	0.34	0.07
	12	0.83	0.82	0.54	0.69	0.71	0.42
	11	0.96	0.98	0.86	0.89	0.85	0.52

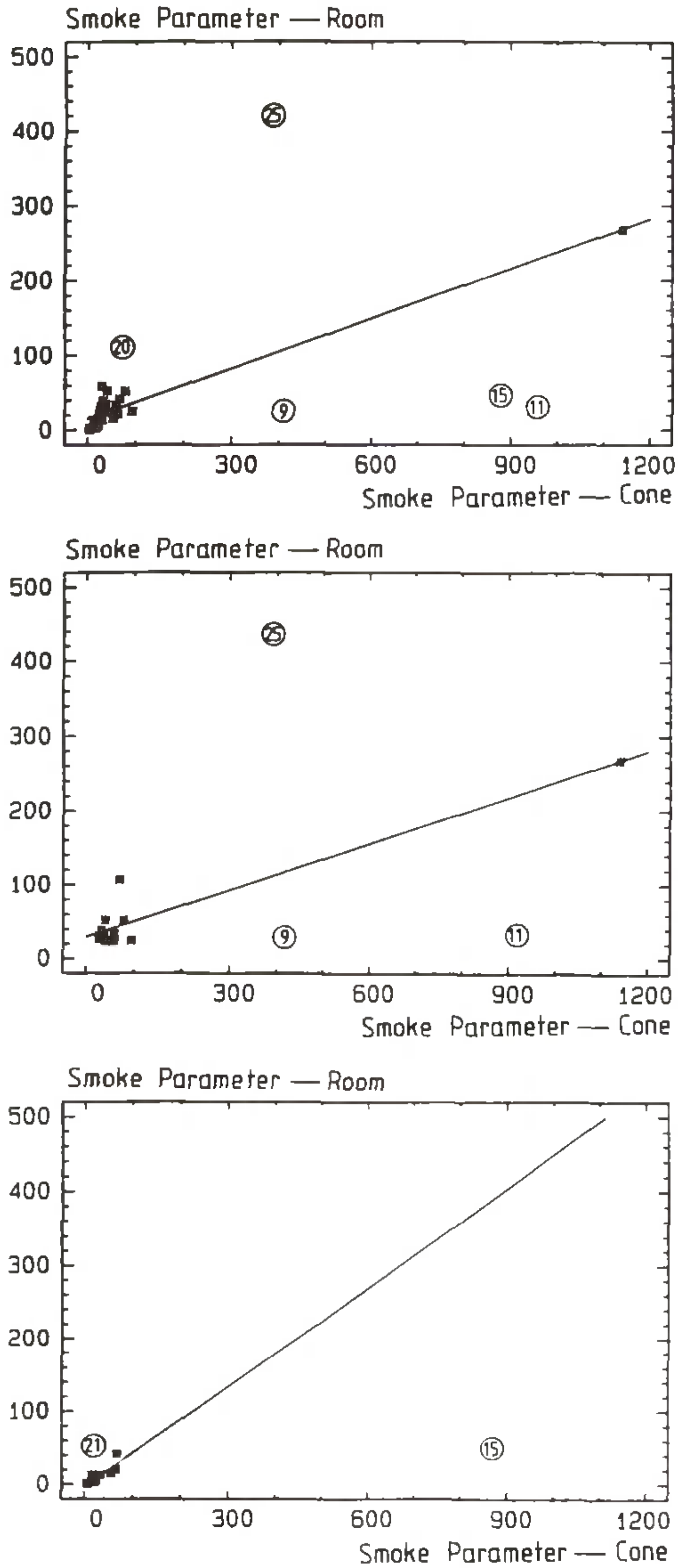
ˣ S3: from start to 300 s after ignition.
I3: from ignition to 300 s after ignition.

Underlined correlation coefficients are plotted in Figures 6 to 8.



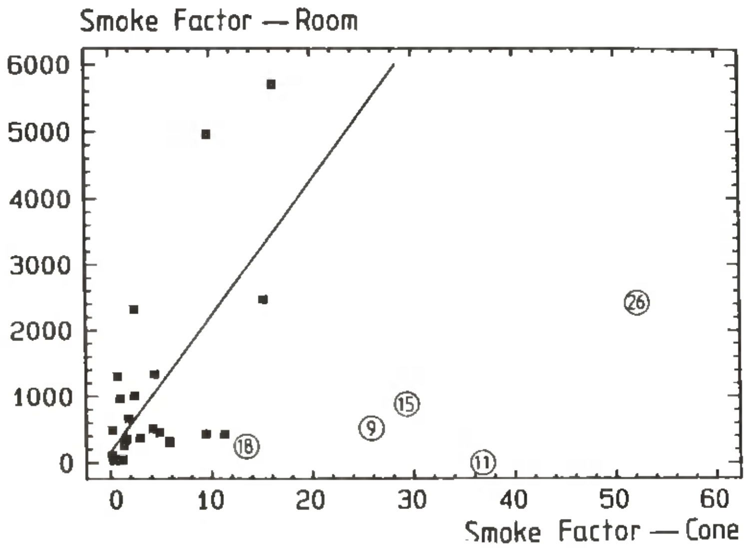
Time to f. o. in room fire	Corr. coeff.
all times	<u>0.88</u> (23 prod.)
< 10 min	<u>0.88</u> (12 prod.)
> 10 min	<u>0.96</u> (11 prod.)

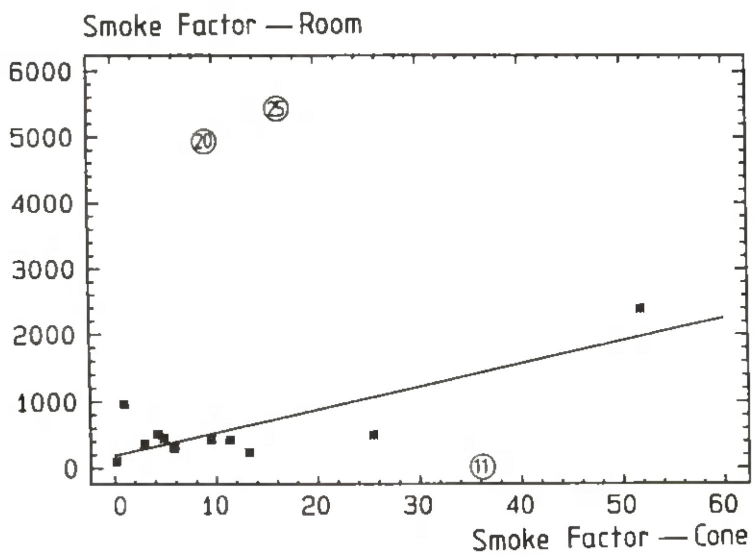
<u>Figure 6</u>. Specific extinction area, SEA, in the room fire test and the cone calorimeter (S 3).
Outliers not included in the correlations are identified by product numbers.

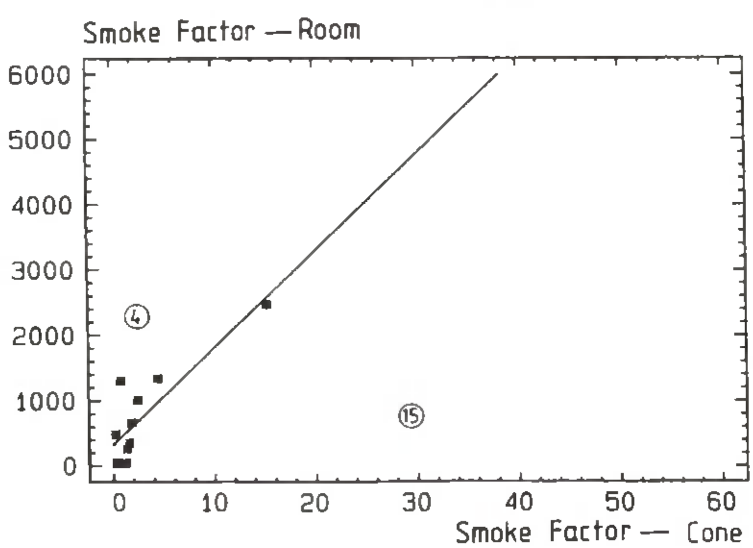


Time to f. o. in room fire	Corr. coeff.
all times	0.96 (23 prod.)
< 10 min	0.95 (12 prod.)
> 10 min	0.86 (11 prod.)

Figure 7. Smoke parameter, i.e. product of SEA and RHR, in the room fire test and the cone calorimeter (S 3).
Outliers not included in the correlations are identified by product numbers.







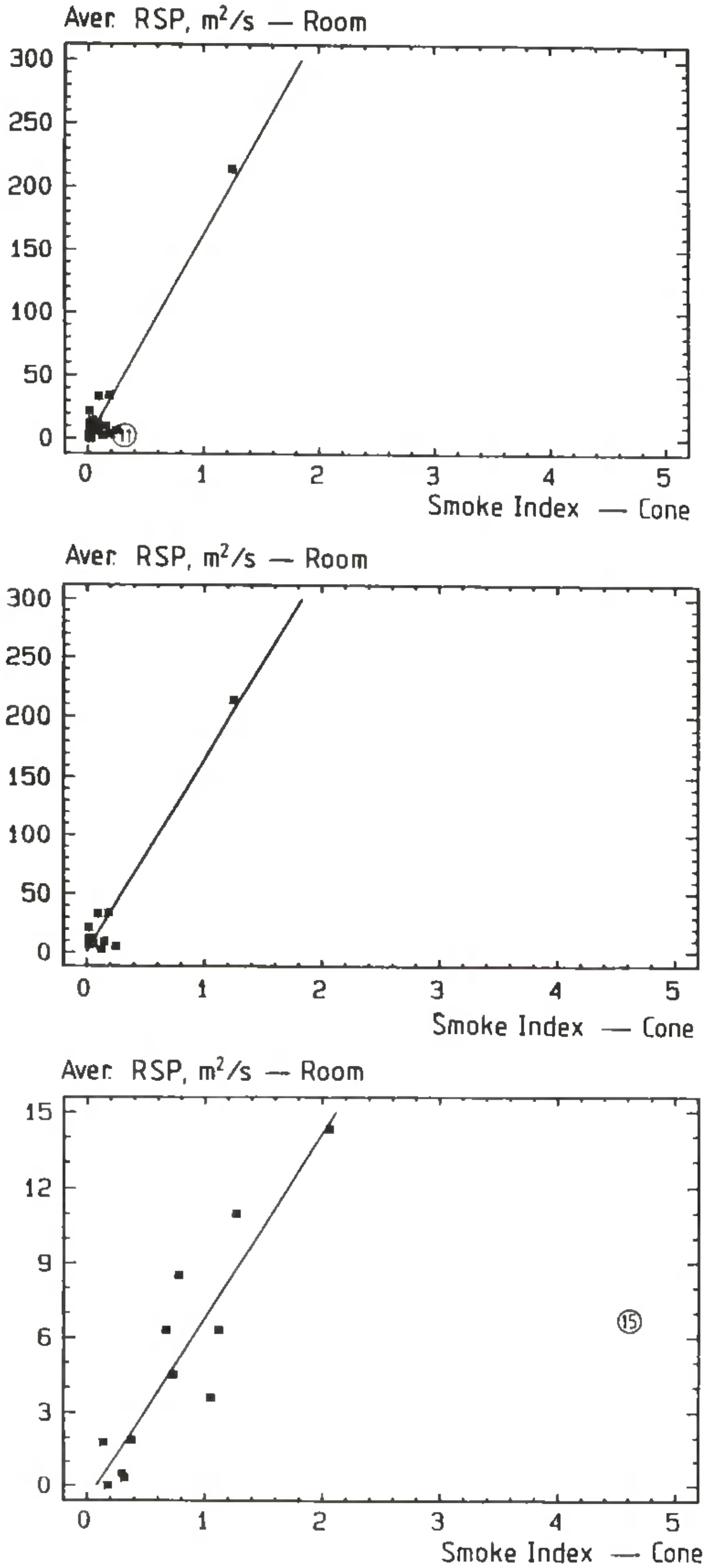
Time to f. o. in room fire	Corr. coeff.
all times	<u>0.62</u> (23 prod.)
< 10 min	<u>0.82</u> (12 prod.)
> 10 min	<u>0.85</u> (11 prod.)

<u>Figure 8</u>. Smoke factor, i.e. product of total smoke production, TSP, and RHR in the room fire test and the cone calorimeter (S 3).
Outliers not included in the correlations are identified by product numbers.

Table 12. **Smoke index** in the cone calorimeter compared with **average rate of smoke production** in the room fire test.
Correlation coefficients for different times to flashover in the room fire test, different exponents "n" in Eq. (3) and different number of products included in the correlation.

Time to flashover in room fire	Number of products	Correlation coefficients Smoke index vs average rate of smoke production				
		Exponent n in eq (3)				
		1.0	0.9	0.7	0.5	0.4
all	28	0.94	0.91	0.73	0.48	
times	27	0.95				
	26		0.96			
	25					
	24					
	23		0.98	0.96		
	22		0.99	0.97		
< 10 min	15	0.96	0.94	0.78	0.49	
	14	0.98	0.97			
	13					
> 10 min	13		0.26	0.37	0.46	0.51
	12			0.59	0.85	0.91
	11		0.66			

Underlined correlation coefficients are plotted in Figure 9.



Time to f. o. in room fire	Corr. coeff.
all times	<u>0.95</u> (n=1.0) (27 prod.)
< 10 min	<u>0.96</u> (n=1.0) (15 prod.)
> 10 min	<u>0.91</u> (n=0.4) (12 prod.)

Figure 9. Smoke index in the cone calorimeter vs average rate of smoke production in the room fire test. Note: Different scales and exponents, n.
Outliers not included in the correlations are identified by product numbers.

5.3 Useful correlations for predictions

Some of the correlations seem to be useful in order to predict the smoke production in the room fire test from cone calorimeter data. This is true mainly for products with more than 10 minutes to flashover in the room fire test.

5.3.1 Products with **more** than 10 minutes to flashover

Average rate of smoke production and **total smoke production** have both a correlation coefficient of 0.91 with only one outlier, product No. 15, a FR polystyrene, see Figure 10. This product is on the 'safe' side, i. e. its smoke production is lower in the room fire test than should have been predicted from the cone calorimeter data. It had a special behaviour in the room fire test. Droplets fell to the floor and did not produce much smoke, but may cause other hazards. A room fire test can be performed for such products to possibly reach a better classification. All other products with more than 10 minutes to flashover agree fairly well with the regression lines in Figure 10.

The average rate of smoke production in the room fire test can thus be predicted by

$$\text{Aver. RSP}_{\text{room, >10 min to f.o.}} = 419 \ \text{Aver. RSP}_{\text{cone, S3}} - 1.2 \tag{8}$$

This means that if the average rate of smoke production in the room fire test should not exceed 3 m^2/s as suggested /21/, the average rate in the cone calorimeter should not exceed about 0.01 m^2 /s.

The total smoke production in the room fire test can be predicted similarily by

$$\text{TSP}_{\text{room, >10 min to f.o.}} = 644 \ \text{TSP}_{\text{cone, S3}} + 486 \tag{9}$$

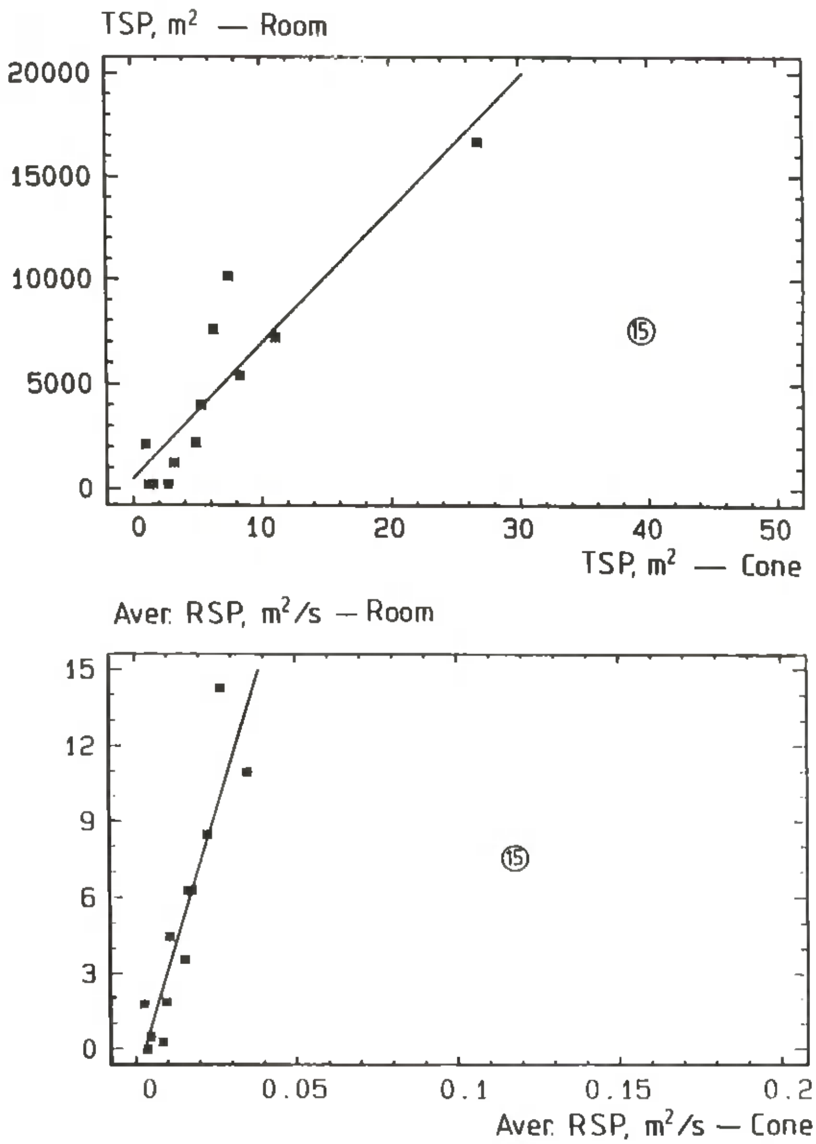
For total smoke production no classification limits have been suggested so far.

Another possibility is to use a **smoke index** which can predict the average rate of smoke production with the same correlation coefficient of 0.91 and the same outlier, product No. 15 on the 'safe' side as above, see Figure 9. This relation can be written

$$\text{Aver. RSP}_{\text{room, >10 min to f.o.}} = 7.4 \ I_{s,\, n=0.4,\, \text{cone}} - 0.59 \tag{10}$$

This relationship seems to be as reliable as Eq. (8), but does not seem to offer any obvious advantages compared to Eq. (8).

In other cases several products are on the 'unsafe' side as for TSP/THR in Figure 5 and for SEA in Figure 6. These are not useful correlations.



Corr. coeff.

0.91

(12 prod.)

0.91

(12 prod.)

Figure 10. The best correlations for products with more than 10 minutes to flashover.

5.3.2 Products with less than 10 minutes to flashover

For these products there are no obvious useful correlations. The best choice might be to use the maximum rate of smoke production, where different rates are available in both scales, see Figure 3. The correlation coefficient is quite low, 0.82, for 13 products when excluding 2 outliers, products Nos. 9 and 11. Higher correlation coefficients have been obtained for average RSP, but here only one product is determining the correlation coefficient. All other products are gathered closely, which makes the correlation less reliable.

5.3.3 All products included

Very good correlation coefficients have been obtained in some cases, e.g. for smoke index predicting average rate of smoke production for all products with a correlation coefficient of 0.94 without any outliers at all. However, the plot in Figure 9 shows that only one product is determining the regression line, while all other products are gathered without any clear tendency. This is therefore not a useful or reliable correlation.

Better correlations in this respect are obtained for maximum RSP and TSP, but the correlation coefficients are quite small even if several products are excluded from the correlation analysis. However, the regression lines for all products are rather similar to those for

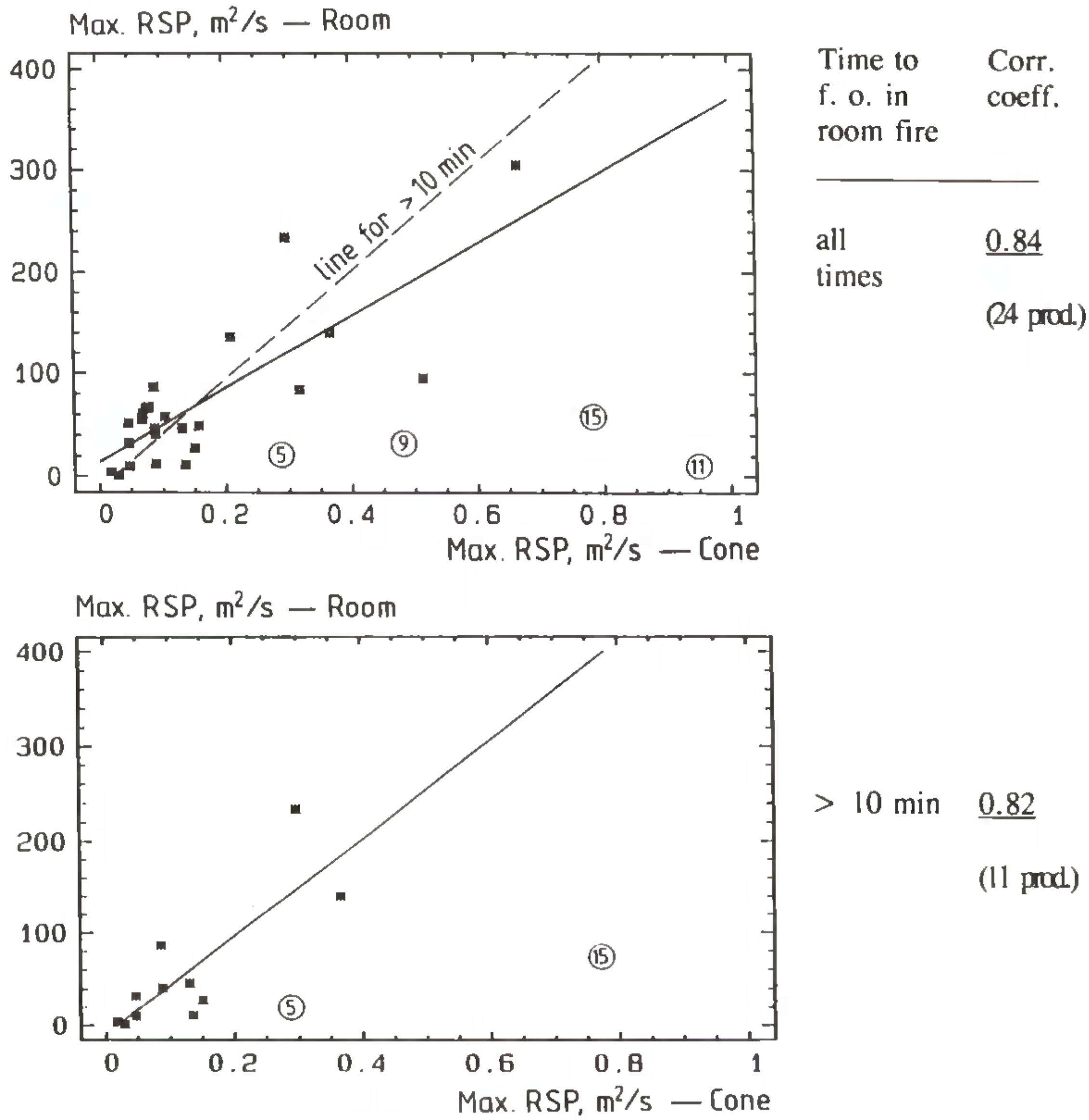
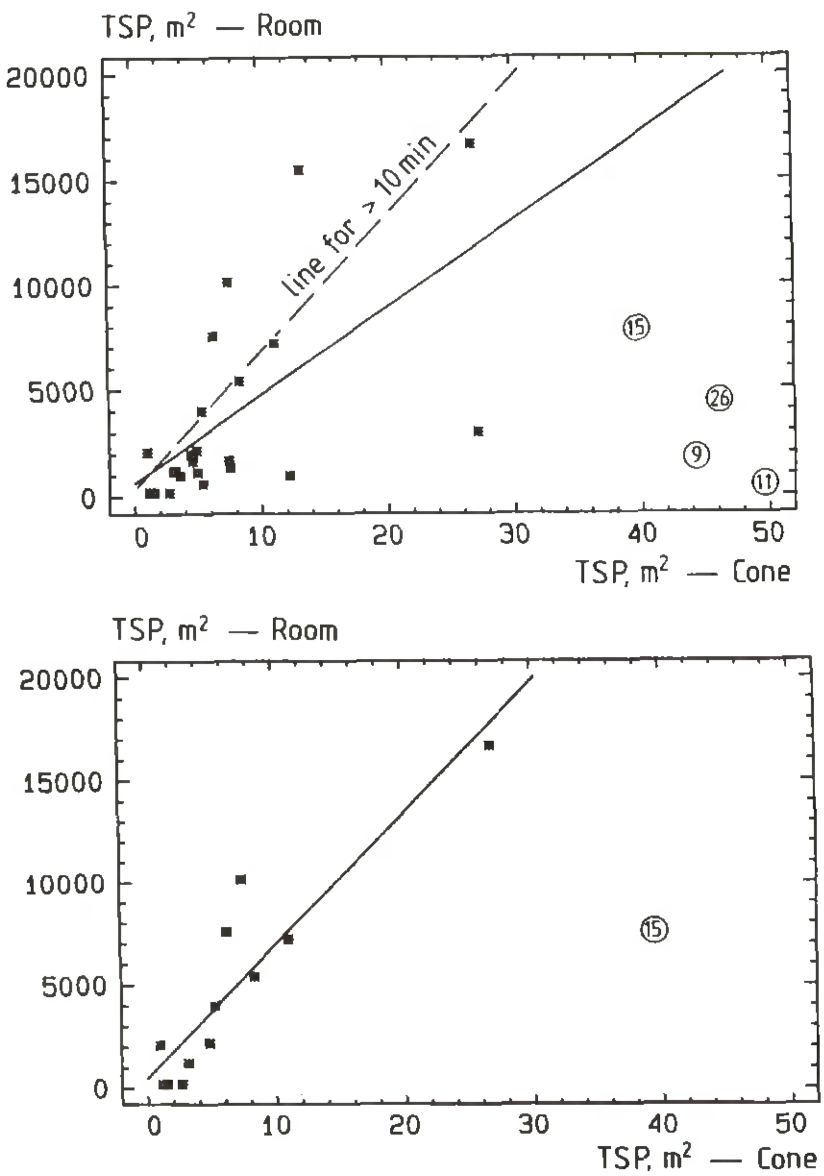


Figure 11. Maximum rate of smoke production for all products and for products with more than 10 minutes to flashover in the room fire test. The same regression line as for products with **more** than 10 minutes to flashover can be used also for **all** products but with less accuracy.

products with more than 10 minutes to flashover except for the much larger scatter for all products, see Figures 11 and 12. Therefore, the quite safe regression lines obtained for products with more than 10 minutes to flashover might be used also for all products as a first rough estimate. The total smoke production is probably the most suitable parameter to use since it has higher correlation for products with more than 10 minutes to flashover, although the correlation with all products included is smaller. Eq. (9) can be generalized and simplified to

$$TSP_{room} = 640 \ \ TSP_{cone,\ S3} \qquad (9a)$$



Time to f. o. in room fire	Corr. coeff.
all times	0.62 (24 prod.)
> 10 min	0.91 (12 prod)

Figure 12. Total smoke production for all products and for products with more than 10 minutes to flashover in the room fire test. The same regression line as for products with **more** than 10 minutes to flashover can be used also for **all** products but with less accuracy.

5.3.4 Time period for cone calorimeter data

Cone calorimeter data from start of test to 300 s after ignition (called S3) seem to be most useful since they give the highest correlation coefficients generally speaking, see Table 13. It also seems safe to include the time before ignition, since some products release much smoke in that stage. On the other hand it does not seem to be necessary to include data exceeding 300 s after ignition.

5.4 Outliers in the correlation analyses

Some products seem to be outliers when correlating most smoke parameters, see Table 14. These are mainly product No. 9 Plastic faced steel sheet on polyurethane foam, No. 11 FR extruded polystyrene foam and No. 15 FR polystyrene. Other frequent outliers are products No. 20 Melamine-faced particleboard, No. 21 Plastic wallcovering on gypsum board, No. 25 Rigid polyurethane foam and No. 26 Expanded polystyrene. Some of these products are known to be difficult in fire testing generally and may not even be possible to test at all in many standard fire tests.

Table 13. "Optimum" correlation coefficients between data in the room fire test and the cone calorimeter.

Time to flashover	Number of products	Aver RSP	Max RSP	TSP	TSP/ THR	SEA	Smoke para- meter	Smoke factor	Smoke index vs Aver RSP
all	28			0.26	0.17[x]	0.55[x]	0.47[x]	0.24[x]	0.94°
times	27				0.38[x]				0.95°
	26	0.28[x]	0.48			0.68[x]	0.68[x]	0.33[x]	
	25			0.57[x]			0.87[x]		
	24	0.88[x]	0.80	0.62[x]		0.82[x]		0.47[x]	
	23		0.83	0.80[x]	0.72	0.88[x]	0.96[x]	0.62[x]	
	22		0.90	0.86[x]	0.78	0.91[x]	0.97[x]	0.69[x]	
< 10	15	0.52	0.34	0.25	0.15[x]	0.47[x]	0.46[x]	0.19[x]	0.96°
min	14	0.78	0.68	0.46[x]	0.33	0.63	0.63		0.98°
	13	0.87	0.82	0.76[x]	0.69		0.88[x]	0.62	
	12	0.91[x]		0.91[x]		0.89	0.95[x]	0.82[x]	
> 10	13	0.39[x]	0.41	0.69[x]	0.26[x]	0.66[x]	0.50[x]	0.34[x]	0.51°°
min	12	0.91[x]	0.70	0.91[x]	0.65[x]	0.83[x]	0.69	0.71[x]	0.91°°
	11	0.94[x]	0.82	0.96[x]	0.89	0.98	0.89	0.85[x]	
Table		7	8	9	10	11	11	11	12
Figure		2	3	4	5	6	7	8	9

[x] as calculated for cone data from start of test to 300 s after ignition (= S 3)

° for n = 1.0 in Eq. (3)
°° for n = 0.4 in Eq. (3)

RSP = Rate of smoke production
TSP = Total smoke production
RHR = Rate of heat release
SEA = Specific extinction area

Underlined correlation coefficients indicate useful regression lines.

Table 14. Outliers in correlation analyses.

Product No.	Aver RSP	Max RSP	TSP	TSP/ THR	SEA	Smoke para- meter	Smoke factor	Smoke index vs Aver RSP
1								
2								
3								
4							c	
5		a c						
6								
7								
8				a c	a c			
9	ab	ab	ab	ab	ab	ab	a	
10								
11	ab	ab	ab	ab	ab	ab	ab	a
12								
13								
14								
15	a c	a c	a c			a c	a c	c
16								
17								
18							a	
19								
20			b	ab	ab	a	b	
21				a c	a c	c		
22								
23								
24								
25						ab	b	
26	ab		a				a	
27								
28								

a Among all products.
b Among products with < 10 min to flashover
c " " " > 10 min " "

6. CORRELATIONS OF PREDICTED PARAMETERS

6.1 Smoke data and smoke parameters

In this study SINTEF NBL has used data for the 11 EUREFIC products shown i Table 1. The products have been tested at the four Nordic fire research laboratories. The following smoke and burning parameters reported by Thureson /26/ (cone calorimeter data) and by Söderbom /22/ (room fire test data) were used:

	Cone calorimeter	Room fire test
- Rate of heat release (RHR):	x	x
- Mass loss rate (MLR):	x	
- Specific extinction area (SEA):	x	
- Rate of smoke production (RSP):		x

Specific extinction area, SEA, and total smoke production, TSP, in the room fire test were calculated from the data listed above.

The cone calorimeter results are obtained with a horizontal sample and at a heat flux of 50 kW/m^2. It should also be noted that all products have been tested without the retainer frame except product No. 7 which was tested by Trätek with a retainer frame.

6.2 Prediction model

Babrauskas /4/ has proposed a model to correlate predicted and measured values of total smoke production, i.e. the smoke produced over the entire period ending at either end of test (i.e. to 20 min. if 1000 kW is not reached), or else at the time when 1000 kW is just reached in the room fire test. The intention is not to achieve any instantaneous, time-resolved value of smoke, but rather, simply the total smoke production up to the end of the room fire test (single number).

The proposed model is given by the following expression:

$$TSP_{pred} = \frac{THR_{\text{Cone Tool}}\ SEA}{EHC} \quad (m^2) \qquad (11)$$

where

	$THR_{\text{Cone Tool}}$	is predicted total heat release up to the effective end of the room fire test by using the Cone Tools fire simulation program (MJ)
	SEA	is average specific extinction area as determined in the cone calorimeter (m^2/kg)
	EHC	is average heat of combustion determined in the cone calorimeter (MJ/kg)

Eq. (11) can also be expressed as

$$TSP = TBM \;\; SEA \qquad (12)$$

where TBM is total burned mass (kg)

However, this equation can not be used since there are no means of measuring or predicting TBM, total burned mass, in the room fire test for the time being.

Cone Tools /14/ is a computer program which can predict, among other things, the RHR in the room fire test on the basis of heat release data from the cone calorimeter by using the correlation of Wickström and Göransson /27/. The results from the Cone Tools simulation program are revised so that they express the value of total heat release up to the effective end.

The validity of this model can be tested by calculating TSP_{meas} on the basis of measured smoke data in the room fire test. For each room fire test, the total smoke production TSP_{meas} at the effective end is calculated. The effective end is the actual end (i.e. after 20 minutes test time) if no flashover occurs, or else the time to flashover. This is carried out according to:

$$TSP_{meas} = \Sigma k \; V \; \Delta t \qquad (m^2) \qquad (13)$$

where
- k is the extinction coefficient $k = (1/L) \cdot \ln(I_o/I)$ (m^{-1})
- V is the actual duct volumetric flow rate at the temperature of the thermocouple near the photometer (m^3/s)
- Δt is the time-scanning interval (s).

Both TSP_{pred} and TSP_{meas} are single values representing the total predicted and measured smoke production in the room fire test.

The total smoke production can also be calculated according to Eq. (11) by using the measured total heat release instead of the predicted value based on the cone calorimeter result and the Cone Tools fire simulation model. The new parameter is termed TSP'_{pred}.

$$TSP'_{pred} = \frac{THR_{meas} \;\; SEA}{EHC} \qquad (m^2) \qquad (14)$$

where THR_{meas} is measured total heat release in the room fire test (MJ)

The smoke parameters TSP_{pred}, TSP'_{pred} and TSP_{meas} for the 11 products in the room fire test are shown in Table 15.

As it appears from Table 15, the difference between TSP_{pred}, where THR in Eq. (11) is predicted by means of the Cone Tools, and TSP'_{pred}, where THR is measured, is quite large for some products. From Eq. (11) it can be seen that these differences are solely due to differences in predicted and measured THR, because SEA and EHC have the same values in both cases.

Table 15. **Total smoke production,** TSP_{pred} , TSP'_{pred} and TSP_{meas} for the 11 EUREFIC products in the room fire test.

Product No.	TSP_{pred} m^2	TSP'_{pred} m^2	TSP_{meas} m^2
1	356	305	488
2	193	181	298
3	125	315	279
4	1240	519	2337
5	855	0.2	1744
6	365	558	921
7	42	63	48
8	3236	5317	3840
9	1631	4435	436
10	452	823	1168
11	367	955	99

6.3 Regression analysis

A linear relationship between corresponding smoke parameters of the two test methods is presupposed to be represented by the general formula:

$$y = c\,x \tag{15}$$

where x and y are the smoke parameters predicted on the basis of the data from the cone calorimeter and those measured in the room fire test, respectively, and c is a constant of proportionality. That is, it is presupposed that there is a constant ratio between the smoke parameters measured in the room fire test and the cone calorimeter. When knowing this constant of proportionality 'c' in Eq. (15), the corresponding smoke parameter in full scale for a certain product can be predicted by means of tests with the cone calorimeter only by using the equation above.

Table 16 shows the correlation coefficient, r, and the constant of proportionality, c, with all the 11 products included in the regression analysis as well as with only the products that reached flashover before or after 10 minutes separately.

Table 16 The coefficient of correlation, r, and the constant of proportionality, c, for prediction of total smoke production, TSP, in the room fire test based on small scale results according to: y = c x, where y is the smoke parameter measured in the room fire test and x is predicted from the cone calorimeter. (t_{fo} is the time to flashover in the room fire test).

No. of products included in the analysis		TSP_{pred} [1]	TSP'_{pred} [2]	
All 11 products	r	0.84	0.20	0.69 [3]
	c	1.14	0.51	0.48 [3]
The 4 products that have t_{fo} < 10 min.	r	0.61	0.41	
	c	0.085	0.10	
The 7 products that have t_{fo} > 10 min.	r	0.93	0.44	0.96 [3]
	c	1.33	0.79	0.75 [3]

[1] Based on THR determined from Cone Tools according to Eq. (17).
[2] Based on THR measured in the room fire tests according to Eq. (18).
[3] Products Nos. 4 and 5 are excluded from the regression analysis.

It appears from Table 16 that the predicted and measured smoke production TSP show a reasonable correlation for all 11 products included (r = 0.84) as well as for the 7 products that have t_{fo} > 10 minutes (r = 0.93). The correlation appears not to be satisfactory for the 4 products that have t_{fo} < 10 minutes.

The following relationship applies for the 7 products that have t_{fo} > 10 minutes:

$$TSP_{meas} = 1.33 \ TSP_{pred} \quad (m^2) \tag{16}$$

Figure 13 shows smoke production data from the room fire test and the cone calorimeter as well as the relationship shown in Eq. (16).

Consequently, the following calculation model may be established by using Eq. (11):

$$TSP_{meas} = 1.33 \frac{THR_{Cone\ Tool} \ SEA}{EHC} \quad (m^2) \tag{17}$$

where

$THR_{Cone\ Tool}$ is predicted total heat release in the room fire by using Cone Tools (MJ)

SEA is average specific extinction area as determined in the cone calorimeter (m^2/kg)

EHC is average heat of combustion determined in the cone calorimeter (MJ/kg)

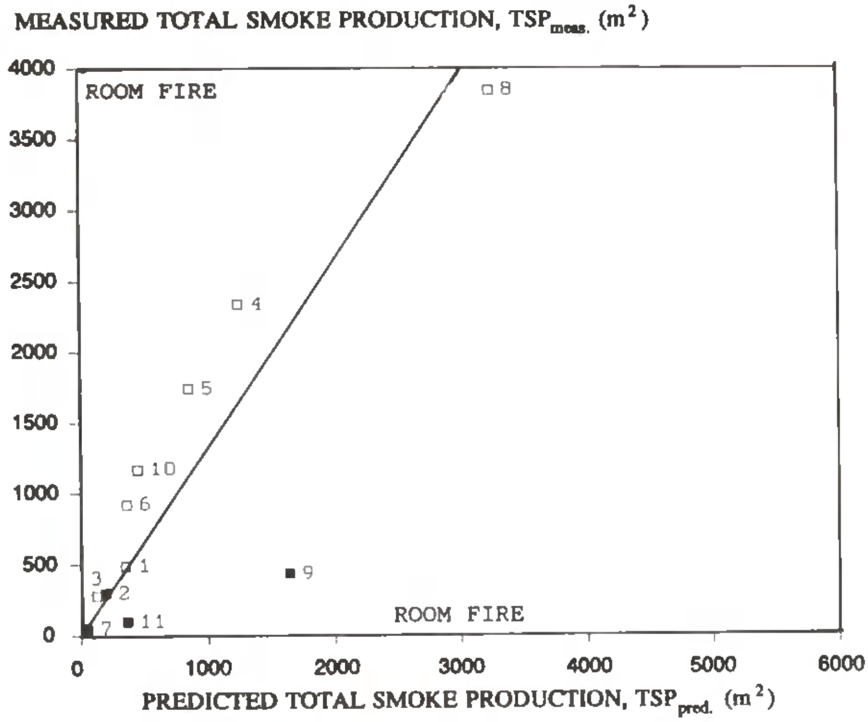


Figure 13. Total smoke production in the room fire test. Predicted data are based on predicted $THR_{Cone\ Tool}$ according to Eq. (11).
The line and unfilled symbols are for products with $t_{fo} > 10$ minutes.

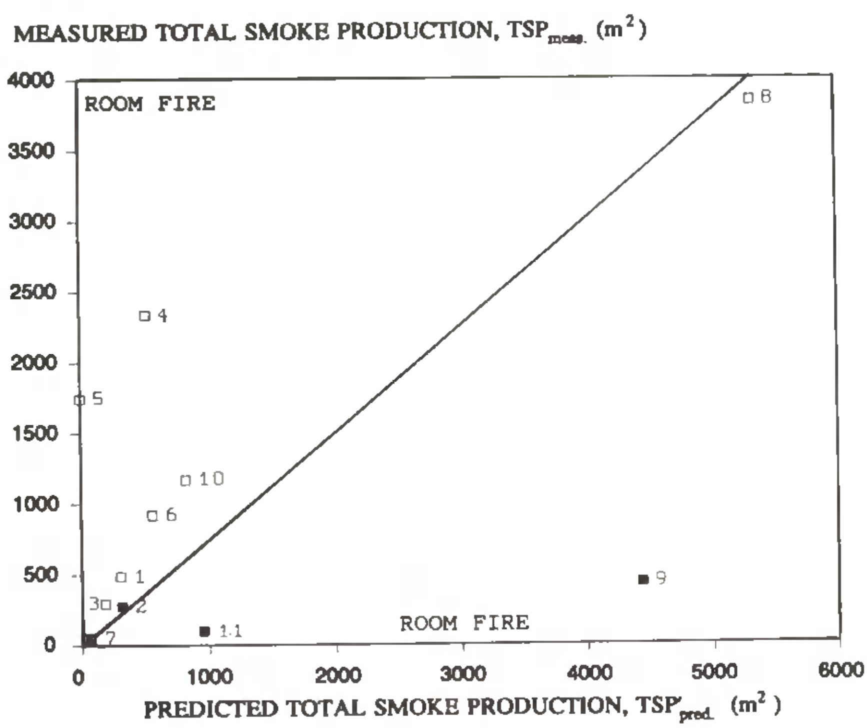


Figure 14. Total smoke production in the room fire test. Predicted data are based on measured THR_{meas} according to Eq. (14). The line and unfilled symbols are for products with $t_{fo} > 10$ minutes, but excludes products Nos. 4 and 5.

Table 16 also shows the correlation between TSP_{meas} and TSP'_{pred}. This correlation is, however, not so good when including all the 7 products (i.e. also products Nos. 4 and 5) as in the case when using TSP_{pred}. However, as can be seen from Figure 14, this bad correlation is mainly due to products Nos. 4 (melamine faced high density non-combustible board) and 5 (plastic faced steel sheet on mineral wool). When excluding these two products, a much better correlation is achieved (r = 0.96). The following relation may be established

$$TSP_{meas} = 0.75 \; \frac{THR_{meas} \; SEA}{EHC} \qquad (m^2) \qquad (18)$$

where THR_{meas} is measured total heat release in the room fire test (MJ)

The only difference between Eqs. (17) and (18) is that Eq. (17) is based on predicted total heat release in the room calculated by Cone Tools, while Eq. (18) is based on the measured total heat release in the room. Otherwise the equations are equal. The constants of proportionality are 1.33 and 0.75, respectively, and the corresponding correlation coefficients are 0.93 and 0.96. The better correlation achieved when using THR_{meas} may be due to the fact that Eq. (18) is based on 5 products only, while Eq. (17) is based on 7 products. From Figure 13 it appears that products Nos. 4 and 5 deviate the most from the correlation of Eq. (17) represented by the straight line.

Since the equations are equal apart from the total heat release, these deviations have to be attributed solely to deviations in this parameter. The ratio of average specific extinction area to average heat of combustion is the same in both correlations. From Table 15 it appears that TSP_{pred} and TSP'_{pred} deviate quite a lot from each other for most of the 11 products. This must solely be due to deviations between $THR_{Cone\ Tool}$ and THR_{meas}, respectively. Hence, the rather large difference between the constant of proportionality of Eqs. (17) and (18) must also be due to these deviations. However, the differences are not only due to problems with calculating the heat release for some of the combined, multilayered products by use of Cone Tools. There were also some problems with the measured data for heat release in the room fire test for some of the products, especially Nos. 4 and 5 as mentioned above.

7. SUMMARY AND CONCLUSIONS

7.1 Smoke critical for classification

The smoke production is critical for the fire classification of surface products since some products produce large amounts of smoke in the room fire test even if they do not reach flashover within 20 minutes. This is especially true for the set of 11 EUREFIC products. Those products must be identified in a simple way in order to get a safe classification system for wall and ceiling linings.

7.2 Smoke parameters analysed

Several smoke parameters from the cone calorimeter and the room fire test have been analysed in order to get an overview of all possibilities to obtain simple relationships between the two scales. The same parameters from the two tests have been used to ensure a sound physical basis for the coorelations. The smoke parameters analysed are:

* Average rate of smoke production (Aver. RSP)
* Maximum rate of smoke production (Max RSP)
* Total smoke production (TSP)
* Ratio between total smoke production and total heat release (TSP/THR)
* Specific extinction area (SEA)
* Smoke parameter (RHR SEA)
* Smoke factor (RHR TSP)

In addition to that, smoke indices defined for data from the cone calorimeter have been correlated with average RSP from the room fire test, i.e.

* Smoke index (cone) vs Average RSP (room)

Three sets with a total of 28 building products have been analysed to be able to draw some statistical conclusions.

7.3 Two groups of products - correlations

Good correlations were obtained only if the products were divided into two groups: those which reached flashover in **less** than 10 minutes and those which had **more** than 10 minutes to flashover in the room fire test.

The best correlations were obtained for products with **more** than 10 minutes to flashover, which is promising since their smoke production may be decisive for their fire classification. The **average rate of smoke production** and the **total smoke production** seem to be the most suitable parameters to use. In both cases the correlation coefficient is 0.91 for 12 of the 13 products with more than 10 minutes to flashover, i.e. only one product, a melting material, had to be excluded and regarded as an outlier. The smoke production of that product did not fit the regression, but is on the "safe" side, i.e. the smoke production is smaller in the room fire test than predicted from the cone calorimeter data. Tests in room scale can be used in such a case to reach a better classification.

For products with **less** than 10 minutes to flashover there is no really good correlation. The best choice might be to use the maximum rate of smoke production, but the correlation coefficient is quite low. The maximum rate is also a rather variable parameter and should not be recommended.

If **all** products are included in the correlation analysis, the best choice is probably the total smoke production, but again the correlation coefficient is quite low, 0.62, for 24 products, i.e. when 4 products are excluded from the regression analysis.

Not only the correlation coefficient must be considered when choosing the best regression lines. The spread of data points along the line must also be considered. If only one point is determining the correlation and all other points are gathered at similar values, the correlation can not be considered to be reliable.

7.4 Time intervals for test data

For the cone calorimeter data, different time periods can be used to calculate the different smoke parameters, e.g. starting either at the beginning of the test or at the time for ignition and ending either after some fixed time period or at the end of the test. Such different time periods have been analysed and it has been found that the time period from start of test to 300 s after ignition (called S3) seems to give the best correlations. It seems to be essential to include the time before ignition, since some materials produce much smoke before ignition, which should be included to get a safe system.

For the room fire test the time period for calculation of smoke parameters is the same in all cases, i.e. from start of test to flashover or to 20 minutes for products not reaching flashover.

7.5 Prediction model

In a separate study, the total smoke production in the room fire test for the 11 EUREFIC products has been predicted from cone calorimeter data by a simple model. Cone data on specific extinction area and effective heat of combustion have been used together with total heat release in the room fire test. The total heat release can either be determined from cone calorimeter data by using the fire simulation model Cone Tools or by using the measured total heat release in the room fire test. In both cases, good correlation coefficients, 0.93 and 0.96, have been obtained for products with more than 10 minutes to flashover, but for predictions based on measured THR two products out of the 7 reaching flashover had to be excluded. However, the constants of proportionality were quite different in the two cases, 0.75 and 1.33. The prediction model therefore seems to be quite sensitive to the use of Cone Tools. More products have to be evaluated and tested in order to verify the smoke prediction model.

7.6 Outliers

The same products are identified as outliers in most correlations. These are products Nos. 9, 11 and 15. Among these, only one product, No. 15 a fire retardant polystyrene, has more than 10 minutes to flashover in the room fire test and is on the "safe" side in the regression analysis as mentioned above. All outliers are either composite products or thermoplastics which are known to be difficult to handle in fire testing generally and may not even be possible to test at all in most standard fire tests. It is important to be aware of this fact, because problems with special products must be related to product properties and not used for concluding that good correlations between small and full scale can not be achieved. One have to realize that some products have to be tested in full scale.

7.7 Main conclusion

The **main conclusion** of this study is that the smoke production in the room fire test can be predicted from cone calorimeter data **only** for building products with **more** than 10 minutes to flashover in the room fire test. However, the regression lines for **all** products are rather similar to those for products with more than 10 minutes to flashover except for the much larger scatter for all products. This is true mainly for the total smoke production. Therefore, the quite safe regression line obtained for products with more than 10 minutes to flashover might be used also for all products as a first rough estimate. Otherwise, criteria for smoke production have to be omitted for products with less than 10 minutes to flashover. Some smoke criteria also for these products seems to be desirable for a safe classification system.

7.8 First estimate

As a first estimate the following two relationships can be used to predict the smoke production in the room fire test from cone calorimeter data. Both have a correlation coefficient of 0.91 and are applicable to products with an estimated time to flashover of **more** than 10 minutes:

$$RSP_{\text{room, >10 min to f.o.}} = 420 \ RSP_{\text{cone, S3}} \qquad (8a)$$

$$TSP_{\text{room, >10 min to f.o.}} = 640 \ TSP_{\text{cone, S3}} \qquad (9a)$$

where RSP is average rate of smoke production (m^2/s)
TSP is total smoke production (m^2)

The second relationship can also be used with less accuracy to estimate the smoke production in the room fire test for **all** products independent of their estimated time to flashover:

$$TSP_{\text{room}} = 640 \ TSP_{\text{conc, S3}} \qquad (9b)$$

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