Fire safety of EPS ETICS in residential multi-storey buildings

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Summary

Effect of EPS insulation used in facade on fire safety of building has been studied by using fire safety engineering methods. The study covers residential multi-storey buildings up to eight floors with main emphasis on safety of people.

Fire risk analysis was used utilising statistical data and modelling of the spreading of a flash-over room fire through breaking window to the facade. The probabilities of the spread of the fire to apartments above the room-of-fire-origin were assessed by calculating heat exposures and consequences caused by the external flaming both for the EPS ETICS facade and for façade made of at least A2-s1, d0 materials.

The estimated maximum overall probabilities for window breaking at floors above the fire room were about 2 % (2.3 % for EPS ETICS and 1.9 % for at least A2-s1, d0 façade per ignited fire). The estimated overall probability values for the window breaking in the floors above are on the upper limit compared to statistical data (0.7-2 %) for which conservative values were used. Thus a safety factor is included in the results.

Concerning consequences for life safety, the fire death probability for EPS ETICS system was found to be within tolerable limits of F-N-curve which illustrates the probability of an event and consequences in terms of number of deaths. Special concern should be paid to fire safety during installation phase when EPS is unprotected without reinforced rendering. Main principles and actions concerning construction site fire safety are summarised in this report.

Confidentiality	Public

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Contents

1. Introduction

Energy efficiency and overall needs for sustainable buildings are increasing the renovation of old buildings and bringing demand for effective thermal insulations both for new and old buildings. In national regulations and guidelines limitations or protection requirements may be specified for the use of combustible insulation materials and products in facades. Alternatively, there may be performance based requirements for products or for the whole facade system defining fire performance levels for different applications.

The use of EPS (expanded polystyrene) in building applications is expanding because of the good thermal insulation properties. At elevated temperatures EPS starts to shrink and melt. If the fire exposure is high enough, ignition will occur and heat will be released. Because of the low density of EPS, the total amount of heat released is quite small when the EPS insulation is protected from all sides (rendering outside and fire separating construction inside). To compare with widely acceptable reference scenarios of facades made of of at least A2-s1, d0 (or nearly the same fire performance) building materials and products, the increase in fire exposure caused by the EPS insulation and the consequences for safety are assessed.

2. Goal

This study aims to determine the effect of EPS insulation used in external wall on the fire safety of the building and to use fire safety engineering to produce justification for required protective methods. The EPS insulation systems (ETICS, External Thermal Insulation Composite Systems) have defined reinforced rendering setups as outer layer and fire stops/barriers (at least A2-s1, d0 mineral wool) in the insulation layer. The study covers residential multi-storey buildings (new and renovated) up to eight floors with the main emphasis on the safety of people in everyday use. In addition, an assessment concerning the construction or renovation time is also done. The statistical data utilised cover Finland and Sweden.

3. Scope and methods

3.1 Scenarios and techniques used

The analysis focuses on fires starting inside of buildings and uses data on room areas and fire loads of typical dwellings in multi-storey buildings. It is also assumed that distance between buildings will be at least 5-8 m (according to commonly used national requirements) and thus effects from possible fires in neighbouring buildings are not considered (risks of ignition the neighbouring buildings are low and within nationally accepted limits). External ignitions do not cause more severe exposures on the facade than flashover room fires. Thus, the extent of their effects can be considered to be covered by the fires started inside (see section 6.1.3). Also the number of external ignitions is substantially lower compared to those ignited inside buildings (approximately ten per cent).

A prerequisite for using fire safety design approach is that there are validated methods and input data on which to base the design. In this study, state-of-the-art techniques of fire risk analysis are used utilising also statistical data on e.g. ignition frequencies and spread of fires to facades. Modelling of the spreading of a flash-over room fire takes into account the development of fire in the room-of-fire-origin, spreading through breaking window to the facade and external flaming. Using the Monte Carlo technique [1], the probabilities of the spread of the fire to apartments above the room-of-fire-origin are assessed on the basis of the magnitude of the heat exposure caused by the external flaming both for the EPS insulated facade and for at least A2-s1, d0 facade. Also detection of fire, first-aid extinguishing, self-extinction as well as fire brigade intervention are taken into account in the analysis. The calculated probabilities are compared with data from fire statistics.

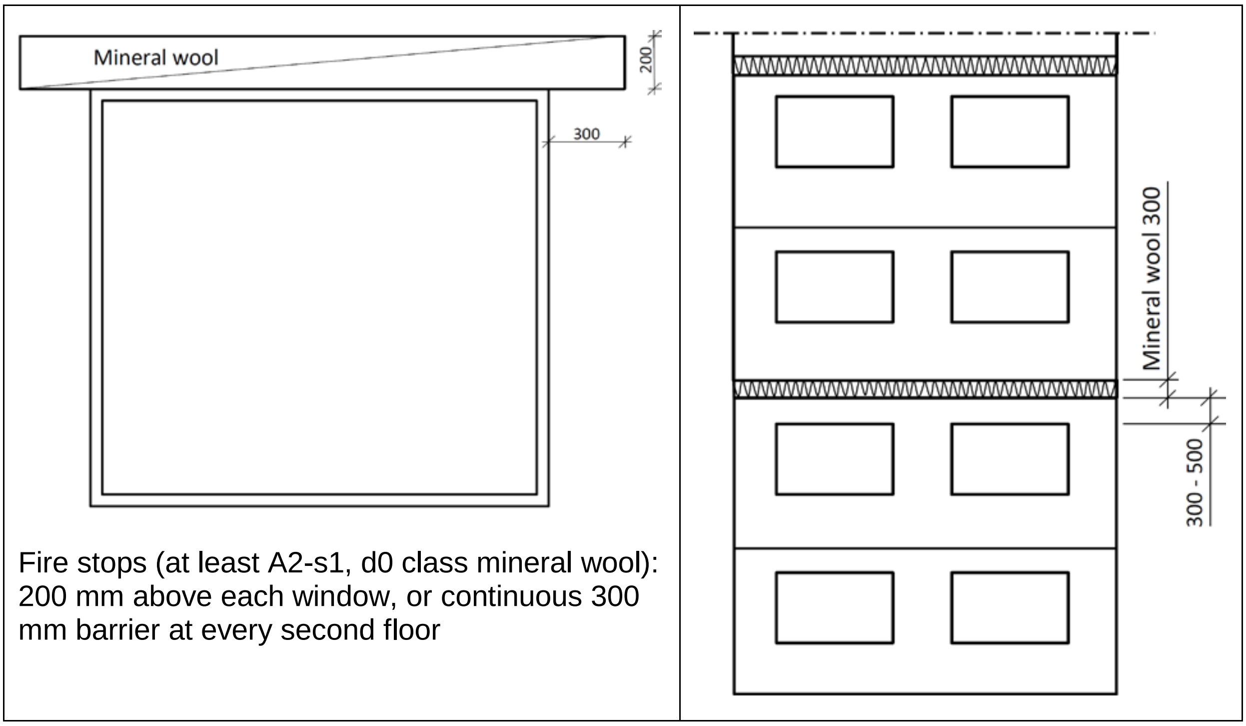
3.2 Use of EPS insulation in external walls

The following types of EPS insulation are included in this study: with and without flame retardant as white and grey (=graphite containing) qualities. The densities of the different qualities vary between 15 and 22 kg/m^3. In renovation, the additional new insulation may be 50 mm as a minimum thickness, and in new buildings the thickness can be up to 300 mm.

In the end use, EPS insulation is protected against direct fire exposure from all sides. In this study it is assumed that in the multi-storey apartment buildings EPS insulation is protected from internal fires by structures with fire separating function of at least EI 30 and reaction to fire class at least A2-s1, d0. If the external side is protected in a similar way (e.g. using fire separating EPS sandwich elements) EPS will not contribute to fire spread on facade.

When EPS insulation is protected from external side with approved reinforced rendering system (ETICS - External Thermal Insulation Composite Systems, which fulfil requirements of ETAG 004 [2] including fire performance of components and the system according to possible national provisions (e.g. on the basis of large scale testing)), fire stops described in Figure 1 are used to prevent fire spread in the insulation layer in buildings with more than two floors.

Fire spread from fire room window to windows above is the main concern for life safety. Fire spread on façade areas without windows are less important for life safety.



Fire stops (at least A2-s1, d0 class mineral wool): 200 mm above each window, or continuous 300 mm barrier at every second floor

Figure 1. Examples of fire stop/barrier alternatives for buildings with more than two floors when EPS insulation is used in external walls [3].

3.3 Typical buildings used in the analysis

Buildings considered in this study are residential multi-storey buildings which can be new or renovated. The maximum number of floors assumed is eight (with possible basement floor which can be aboveground). Loadbearing structures are assumed to be stone based material (concrete, bricks, etc.) forming a fire separating structure on inner side of external wall.

In Finland, the average size of apartments is 56.5 m^2 for multi-storey dwelling buildings and about 80 m^2 for all apartments [4]. These floor area numbers have been slowly increasing during years. There are also differences between the different parts of the country, e. g. in Helsinki the average floor area of new apartments in multi-storey buildings is just above 70 m^2 and about 10 % of new buildings have floor area of at least 100 m^2 [5].

In Sweden, the average floor area is about 93 m^2 for all apartments [6]. Thus, for multi-storey dwelling buildings the average size of apartments is estimated to be 65 - 70 m^2.

In the analysis the area of individual rooms has been taken to be between 7 and 30 m^2 and the width and depth of the rooms are also variable. Window heights vary between 1.2 and 1.4 m (and 1.8 m in sensitivity analysis) and widths between 1.0 and 3.0 m.

3.4 Event tree analysis

Development and spreading of fire, breaking of windows above the fire room and interdependence of the different phases are illustrated in Figure 2 by using an event tree. Probabilistic branching values for this event tree are obtained partly from fire statistics and partly from simulations of room fire development and spreading which are described and reported in the following sections. Simulation results and practical experience indicate that the window two floors above can break only if the window below it breaks. On this basis, breakage of the window two floors above was added as a continuum to the event tree in Figure 2.

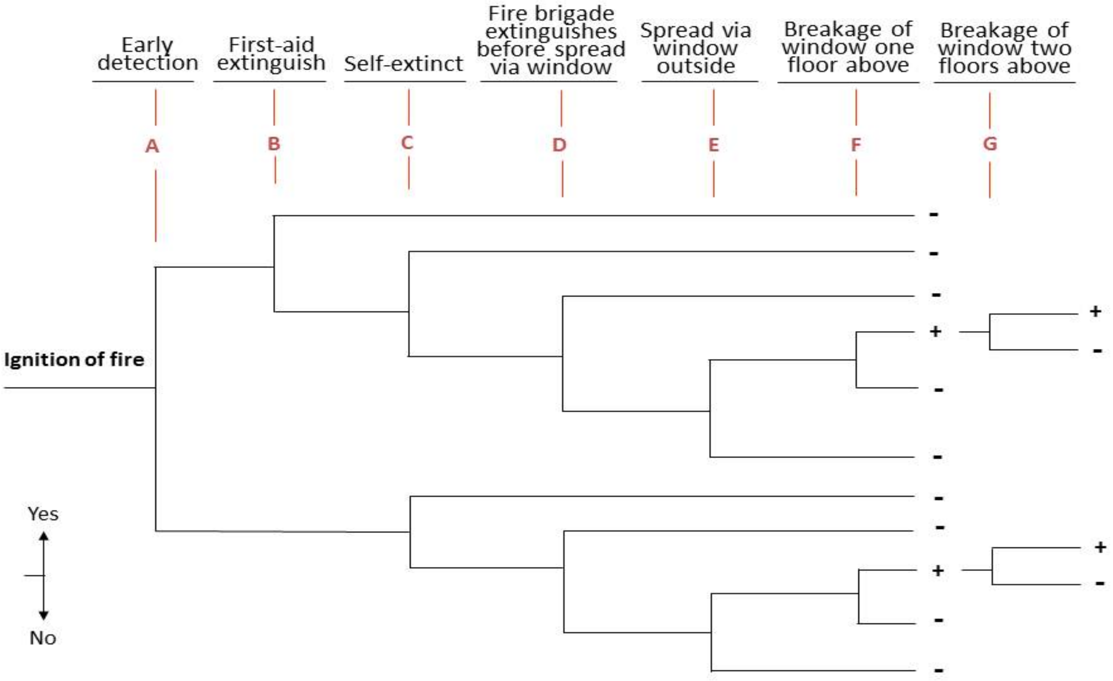


Figure 2. Event tree describing spread of fire from ignition to apartments above. Breakage of window is indicated by '+' and no breakage by '-'.

4. Statistical background for facade fires

4.1 Statistical data sources

To establish the statistical basis for studying the effect of EPS insulation used in external wall on the fire safety of the building, a statistical survey was carried out on the data stored in the Statistics system of the Finnish rescue services (PRONTO) and in the Statistics database of the Swedish Civil Contingencies Agency (IDA). The survey concerned fires in residential multi-storey buildings and the role of the façade material in these fires. The years covered in the survey are 2004–2012 for PRONTO and 2004–2011 for IDA. It is noted that personal user codes are required for the use of the databases.

4.2 External and internal ignitions

Finland

The total number of fires in residential multi-storey buildings stored in PRONTO in 2004–2012 is 4575, which corresponds to an average number of fires of 508 per year (with 95 % confidence interval equalling 465–553 fires). The numbers and proportions of external and internal ignitions in residential multi-storey buildings of different fire classes are presented in Table 1. Load-bearing constructions in buildings of fire class P1 are assumed to withstand fire without collapsing and in buildings with more than two floors the load-bearing constructions are made of least A2–s1, d0 class materials. P2 class residential buildings can have maximum eight floors (four floors until spring 2011), load-bearing structures need not to be at least A2-s1, d0 and the buildings are sprinklered if there are more than two floors. P3 class buildings can have maximum two floors. The main interest of the statistical survey is in the residential multi-storey buildings of fire class P1, which are typically concrete-framed apartment buildings.

Table 1. Proportions of external and internal ignitions in residential multi-storey buildings of different fire classes during 2004–2012 in Finland. (See text for fires classes P1, P2 and P3)

Fire class	**External ignitions**		**Internal ignitions**		**Unknown**		**Total**
	number	percent-age	number	percent-age	number	percent-age	
P1	318	8 %	3412	91 %	15	0 %	3745
P2	28	9 %	265	90 %	2	1 %	295
P3	51	10 %	479	90 %	5	1 %	535
Total	397	9 %	4156	91 %	22	0 %	4575

In the beginning of the year 2009, the accident type “building fire” was divided to two accident types “building fire” and “building fire hazard” in the PRONTO system. The building fire hazard is defined as an incident which could have developed into a larger building fire but which has not spread beyond the object or place of fire origin for some reason. In this study, only building fires were extracted from the database in the data acquisition, because the main interest is in fires having the potential to spread to the facade by breaking windows. Consequently, the number of building fires includes also minor incidents during 2004–2008, but excludes them during 2009–2012.

In 2004–2008, the total number of fires in residential multi-storey buildings stored in PRONTO is 3119, which corresponds to 624 fires per year in average (with 95 % confidence interval equalling 576–674 fires). The numbers and proportions of external and internal ignitions in 2004–2008 are presented in Table 2.

Table 2. Proportions of external and internal ignitions in residential multi-storey buildings of different fire classes during 2004–2008 in Finland.

Fire class	**External ignitions**		**Internal ignitions**		**Unknown**		**Total**
	number	percent-age	number	percent-age	number	percent-age	
P1	199	8 %	2351	92 %	9	0 %	2559
P2	21	10 %	196	90 %	0	0 %	217
P3	34	10 %	308	90 %	1	0 %	343
Total	254	8 %	2855	92 %	10	0 %	3119

According to PRONTO statistics in 2009–2012, the total number of building fires in residential multi-storey buildings is 1456, which corresponds to 364 building fires per year in average (with 95 % confidence interval equalling 328–402 fires). The numbers and proportions of external and internal ignitions in 2009–2012 are presented in Table 3. Minor incidents classified as building fire hazards are excluded from these numbers. The total number of building fire hazards in residential multi-storey buildings is 4061 during 2009–2012, which corresponds to 1015 building fire hazards per year in average (with 95 % confidence interval equalling 954–1078 fire hazards).

Table 3. Proportions of external and internal ignitions in residential multi-storey buildings of different fire classes during 2009–2012 in Finland. Building fire hazards are excluded.

Fire class	**External ignitions**		**Internal ignitions**		**Unknown**		**Total**
	number	percent-age	number	percent-age	number	percent-age	
P1	119	10 %	1061	89 %	6	1 %	1186
P2	7	9 %	69	88 %	2	3 %	78
P3	17	9 %	171	89 %	4	2 %	192
Total	143	10 %	1301	89 %	12	1 %	1456

The average number of building fires per year in residential multi-storey houses during 2004–2008 (624) is significantly lower than the sum of average numbers of building fires and building fire hazards per year in residential multi-storey houses during 2009–2012 (1379). The reason for this is most probably the progress in the compilation of the PRONTO statistics. Since the accident types “building fire” and “building fire hazard” were separated, a larger number of minor cases (i.e. building fire hazards) has been input to the database. Furthermore, the fire authorities responsible for data input have been systematically trained during the recent years, which has improved the comprehensiveness and reliability of the data.

As shown in Tables 1–3, the proportion of external ignitions residential multi-storey buildings is ca. 10 %, independently of the fire class (P1, P2 or P3) of the building.

Ignitions on the balcony in the Finnish statistics were studied related to only fire class P1 residential multi-storey buildings. According to PRONTO data, 290 fires ignited on the balcony in these buildings during 2004–2012. 236 cases were recorded as external ignitions and 54 cases as internal ignitions. According to PRONTO instructions, an ignition on a balcony is considered internal if the balcony is glazed, and external in other cases.

The total number of external ignitions in class P1 residential multi-storey buildings during this period is 318. Since 236 (74 %) of these fires ignited on the balcony, the number of actual external ignitions is 82 (26 %). Considering the total number of fires in this building type (3745), the proportion of actual external ignitions is 2.2 %.

Sweden

In the information retrieval of the IDA database, data on fires in residential multi-storey buildings (“flerbostadshus” in Swedish) during 2004–2011 was searched in terms of the room or space of ignition, the ignited object, the reason for ignition, the fire extent at the arrival of the fire brigade, and the total fire extent. It is noted that the search output of the IDA database is the number of cases classified according to the selected search criteria, and more detailed information on individual cases cannot be obtained. For instance, the data cannot be sorted according to the fire class of the building, or the descriptions in text fields cannot be studied.

The total number of fires in residential multi-storey buildings stored in IDA in 2004–2011 is 21914, which corresponds to an average number of fires of 2739 per year (with 95 % confidence interval equalling 2637–2843 fires).

Table 4 shows the numbers and proportions of fires in residential multi-storey buildings during 2004–2011 classified according to the room or space of ignition. The original data includes 40 options which have been classified for Table 4 by assessing whether the original option refers to an internal or external ignition. The option “other” probably includes mostly internal ignitions.

Table 4. Proportions of external and internal ignitions in residential multi-storey buildings during 2004–2011 in Sweden.

Room or space of ignition	Number of cases	Percentage
Internal ignition	19548	89 %
External ignition		
other than balcony	615	3 %
balcony	1297	6 %
Other or unknown	454	2 %
Total number of fires	21914	

For the ignited object, there are 38 options in IDA data input. One of the options is “outside the building”, which has been selected in 410 cases. The ignited object has been a vehicle in 134 cases, and it is probable that a great majority of these cases are external ignitions. Summing up these options, we get a lower limit estimate for external ignitions (which occur outside balconies): 544 cases out of 21914 fires, i.e. 2.5 %.

During 2004–2011 in Sweden, hot works was the reason for ignition in 110 fires of residential multi-storey buildings, i.e. in 14 fires per year in average.

Comparison of Finnish and Swedish data

The average number of fires per year in residential multi-storey buildings in Sweden was 2739 during 2004–2011. In Finland, the average numbers of building fires and building fire hazards in residential multi-storey buildings in 2009–2012 were 364 and 1015, respectively, i.e. an average of 1379 cases per year in total. Taking into account the larger population and larger number of residential buildings in Sweden, these averages are in proportion. This refers to similarities in compilation of building fire statistics in Finland and in Sweden, and thus to reasonable comparability of the statistical data.

As presented above, the proportion of actual external ignitions is 2.2 % according to the Finnish statistics, and a lower limit estimate for external ignitions is 2.5 % according to the Swedish statistics. These numbers are of the same order, giving further indication of the congruence between the building fire statistics of Finland and Sweden.

In summary, the statistics indicate that at least 2–3 % of fires in residential multi-storey buildings are external ignitions other than balcony fires, approximately 5–6 % are external ignitions on the balcony, and the proportion of internal ignitions is of the order of 88–92 %.

4.3 Fire development and fire spread

Finland

The fire development phase and fire extent at the arrival of the fire brigade, and fire extent after the operations of fire brigade according to the PRONTO database are presented in Tables 5–7. Only residential multi-storey buildings of fire class P1 are included, since they are of main interest in this study. The data covers the years 2004–2012, but the period 2009–2012 (excluding minor cases classified as building fire hazards) is presented also separately.

The spread of fire outside the compartment of ignition can be determined by summing up the options “spread from compartment of ignition”, “spread to more than one compartment of building”, “spread to whole building”, and “whole building destroyed” in Tables 6 and 7. When the fire brigade arrived, the fire had spread outside the compartment of ignition in 367 cases (10 %) in 2004–2012, and in 38 cases (3 %) in 2009–2012. After the operations of the fire brigade, the corresponding numbers were 527 cases (14 %) in 2004–2012, and 40 cases (3 %) in 2009–2012.

During 2009–2012, the fire spread from the room of ignition in 179 cases (see Table 7), that is, in 45 cases per year. In 2004–2012, the respective numbers were 977 cases in total, and 109 cases per year. These correspond to 26 % and 15 %, respectively.

It is probable that the data of 2009–2012 is more reliable than the data of the whole period 2004–2012 due to improvements in the data input in recent years.

Table 5. Fire development phase at the arrival of the fire brigade according to Finnish statistics 2004–2012, residential multi-storey buildings of fire class P1.

Fire development phase when fire brigade arrived	2004–2012		2009–2012	
	Number	Percentage	Number	Percentage
Ignition phase	1274	34 %	330	28 %
Fully developed fire	1359	36 %	615	52 %
Decay phase	237	6 %	59	5 %
Fire extinguished or self-extinct before fire brigade arrival	874	23 %	181	15 %
Unknown	1	0 %	1	0 %
Total	3745		1186	

Table 6. Fire extent at the arrival of the fire brigade according to Finnish statistics 2004–2012, residential multi-storey buildings of fire class P1.

Fire extent when fire brigade arrived	2004–2012		2009–2012	
	Number	Percentage	Number	Percentage
Confined to room of ignition	2174	58 %	775	65 %
Spread from room of ignition	421	11 %	129	11 %
Spread from compartment of ignition	156	4 %	32	3 %
No spread to inside of building	152	4 %	83	7 %
Spread to one compartment of building	27	1 %	20	2 %
Spread to more than one compartment of building	64	2 %	0	0 %
Spread to whole building	142	4 %	6	1 %
Fire extinguished or self-extinct before fire brigade arrival	603	16 %	140	12 %
Whole building destroyed	5	0 %	0	0 %
Unknown	1	0 %	1	0 %
Total	3745		1186	

Table 7. Fire extent after the operations of the fire brigade according to Finnish statistics 2004–2012, residential multi-storey buildings of fire class P1.

Fire extent after fire brigade operations	2004–2012		2009–2012	
	Number	Percentage	Number	Percentage
Confined to room of ignition	2052	55 %	788	66 %
Spread from room of ignition	423	11 %	119	10 %
Spread from compartment of ignition	331	9 %	33	3 %
No spread to inside of building	187	5 %	80	7 %
Spread to one compartment of building	27	1 %	20	2 %
Spread to more than one compartment of building	78	2 %	2	0 %
Spread to whole building	110	3 %	5	0 %
Fire extinguished or self-extinct before fire brigade arrival	528	14 %	138	12 %
Whole building destroyed	8	0 %	0	0 %
Unknown	1	0 %	1	0 %
Total	3745		1186	

Sweden

The fire extent at the arrival of the fire brigade and the total fire extent according to the IDA database are presented in Tables 8 and 9. The data covers the years 2004–2011. Differently from the respective Finnish data, all residential multi-storey buildings are included independently of their fire class.

The spread of fire outside the compartment of ignition can be determined by summing up the options “in several compartments”, “in the building of ignition”, and “spread to other buildings” in Tables 8 and 9. When the fire brigade arrived, the fire had spread outside the compartment of ignition in 135 cases (1 %). The total fire extent was beyond the compartment of ignition in 656 cases (3 %).

During 2004–2011, the fire spread from the room of ignition in 2906 cases (see Table 9), that is, in 363 cases per year. This corresponds to 13 %.

Table 8. Fire extent at the arrival of the fire brigade according to Swedish statistics 2004–2011, all residential multi-storey buildings.

Fire extent when fire brigade arrived	Number	Percentage
In the object of ignition	4540	21 %
In the room/space of ignition	3759	17 %
In several rooms	675	3 %
In several compartments	135	1 %
Fire extinguished or self-extinct	6783	31 %
Only smoke production	6001	27 %
Unknown	21	0 %
Total	21914	

Table 9. Total fire extent according to Swedish statistics 2004–2011, all residential multi-storey buildings.

Total fire extent	Number	Percentage
In the object of ignition	13636	62 %
In the room/space of ignition	5349	24 %
In the compartment of ignition	2250	10 %
In the building of ignition	620	3 %
Spread to other buildings	36	0 %
Unknown	23	0 %
Total	21914	

Comparison of Finnish and Swedish data

Based on the Finnish and Swedish statistics it seems that fire spreads outside the compartment of ignition in about 3 % of residential multi-storey building fires.

Fire spread outside the room of ignition took place in 45 cases per year (2009–2012) in Finland and in 363 cases per year (2004–2011) in Sweden. These numbers correspond to 15 % and 13 % of the fire cases, respectively, showing a reasonable agreement between the countries.

Fire spread due to window breaking

Information on fire spread due to window breaking was available only in the Finnish statistics. The study was concentrated on residential multi-storey buildings of fire class P1 in Finland.

Of the 3745 fire cases of fire class P1 residential multi-storey buildings in Finland during 2004–2012, the compartmentation endured in 3276 cases (87 %) and failed in 388 cases (10 %). No information was provided in 81 cases (2 %). The separating element which failed was a window in 26 cases (7 % of the failures).

It is noted that a window is typically not a fire-separating building element, i.e. it is not usually required that a window should meet fire resistance time requirements in terms of integrity and insulation.

In the description fields of separating structures, there are 5 cases in which an internal fire has spread out of the ignition compartment through a broken window, and 5 cases in which an external fire has spread inside a building through a broken window.

Fire spread on façade, to eaves or to attic

Fire spread on façade, to eaves or to attic was studied on the basis of text fields “Insulation, its position and effect on fire” and “More detailed description of reason for ignition” in the Finnish PRONTO database. The study was concentrated on residential multi-storey buildings of fire class P1 during 2004–2012.

Six relevant cases comments were found on the basis of the text field comments. The information obtained was the following:

1. The surface of wind shield board in the air gap burned over five storeys.
2. The fire spread to roof structures via the balcony. The balcony door was open. [Room of ignition: living room]
3. The fire entered the air gap of the façade.
4. The surface of the wind shield board ignited due to hot work on the roof. The surface layer ignited and spread the fire seven storeys downwards. The surface layer formed droplets running down and further igniting the material.
5. The plastic moisture barrier spread the fire inside the outer wall.
6. As a consequence of hot work on the [balcony] roof, the hardboards and their battening installed for sandblast protection ignited on the third storey. The fire spread fiercely over the façade between the third and the seventh storey.

Information concerning casualties was available in the database for cases 2, 3, 5 and 6. In cases 3, 5 and 6, there were not any fatalities or injuries. In case 2, one person died in the fire. This casualty occurred inside the compartment of ignition, since it was reported that the fire did not spread inside the building (i.e. the fire spread from the living room via the balcony to the roof structures, but not inside into other fire compartments). There were no injuries in case 2. For cases 1 and 4, information on casualties cannot be retrieved from the database.

Effects of first-aid extinguishing

Information on the effects of first-aid extinguishing was available only in the Finnish statistics. The study was concentrated on residential multi-storey buildings of fire class P1 in Finland. In the Swedish IDA database, data on the existence, use and effect of first-aid extinguishers is entered, but the information cannot be retrieved in the data search.

The fields for information on first-aid extinguishing were added to PRONTO in the beginning of 2008 in their current format. The total number of fires in fire class P1 residential multi-storey buildings during 2008–2012 was 1944. The use and effects of first-aid extinguishing equipment are summarized in Table 10.

Table 10. Information on first-aid extinguishing in fire class P1 residential multi-storey buildings in Finland during 2008–2012.

Question in PRONTO	Answers	Number	Percent-age
Did the building have actual first-aid extinguishing equipment?	Yes No Unknown	305 1334 305	16 % 69 % 16 %
Was first-aid extinguishing tried?	Yes No Unknown	482 1318 144	25 % 68 % 7 %
Effect of first-aid extinguishing?	Extinguished the fire Limited the fire No effect Unknown	267 128 87 1462	14 % 7 % 4 % 75 %
The reason for not trying first-aid extinguishing?	No equipment available Nobody present People present did not use equipment Fire was too large No able people present Able people present did not use equipment No actual ignition/fire self-extinct Other reason Unknown	497 253 177 149 35 12 2 193 626	26 % 13 % 9 % 8 % 2 % 1 % 0 % 10 % 32 %

4.4 Fire contribution of insulation

The contribution of insulation to fire was studied on the basis of the information in the Finnish PRONTO database, concentrating on residential multi-storey buildings of fire class P1.

Contribution of façade to fire

The contribution of façade to fire was evaluated on the basis of two fields added to PRONTO in the beginning of 2008. The total number of fires in residential multi-storey buildings of fire class P1 in 2008–2012 is 1944. The results are shown in Table 11.

The external walls had an accelerating effect on fire in 13 % of the cases in which they were reported to have an effect, and in 1 % of all cases. It cannot be determined in detail in how many cases the façade insulation has been the accelerating factor. It is also noted that the information on the effect of external walls is missing in the majority of cases.

Table 11. Effect of external walls on fire in fire class P1 multi-storey residential buildings in 2008–2012.

Question in PRONTO	Answers	Number
Did the external wall surfaces of the building have an effect (decelerating or accelerating) on fire in initial phases?	Yes	163
	No	1632
	Not known	149
Effect of external walls on fire	Decelerated the fire	116
	No effect	23
	Accelerated the fire	22
	Cannot be estimated	2
	Unknown	1781

Fires in which EPS involved

The involvement of EPS in fires was studied using the inputs in the following text fields of PRONTO:

- Insulation, its position and effect on fire
- More detailed description of reason for ignition
- Description of separating structures

Reference to EPS was found in 7 cases: 4 related to EPS as building insulation, and 3 related to food containers. Two of the cases described above were related to construction or renovation work and only one to wall insulation.

In an earlier study [7], information has been retrieved from the PRONTO database related to fires into which EPS has contributed. The search covered years 1999–2004, and 103 building fires with reference to EPS were found. In 42 of these fires, EPS was base floor, roof or wall insulation. In 14 of these cases (i.e. in 33 %), the reason for ignition was hot work. No information is available whether these incidents occurred during construction, renovation or normal use of the building.

Even though the ignition of insulation seems to be relatively rare, the adequate protection of combustible insulation materials during construction and renovation work is of crucial importance in avoiding fire damages.

4.5 Conclusions of statistical survey

The statistical survey was performed on the data stored in the Statistics system of the Finnish rescue services (PRONTO) and in the Statistics database of the Swedish Civil Contingencies Agency (IDA). The survey concerned fires in residential multi-storey buildings and the role of the façade material in these fires. The years covered in the survey were 2004–2012 for PRONTO and 2004–2011 for IDA.

According to the Finnish statistics, first-aid extinguishing could extinguish or limit the fire in 21 % of the fires (Table 10). The fire extent when the fire brigade arrived was “fire extinguished or self extinct” in 12–16 % of the cases in Finland (Table 6) and 31 % of the cases in Sweden (Table 8). In summary, it can be concluded that the fire is extinct without fire brigade intervention (and thus not capable of spreading out of the compartment of fire origin) in about 15–30 % of the fires.

By the arrival of the fire brigade, the spread of fire outside the fire compartment occurs in 3–4 % of the fires according to the Finnish statistics (Table 6) and in 1 % according to Swedish statistics (Table 8).

In residential multi-storey buildings of fire class P1, the compartmentation failed in 10 % of the cases. In 7 % of these cases, the failing element was a window. This results in a probability estimate of 0.7 % for fire spread through a window.

A limited amount of data is available about the involvement of EPS insulation in fires, and only a few incidents were found related to construction or renovation work. The ignition of EPS insulation seems to be relatively rare, indicating that an adequate protection is usually provided. Nevertheless, protecting combustibles during construction and renovation is an issue of crucial importance.

5. Fire performance of EPS under different conditions

5.1 Cone calorimeter results for EPS

Fire performance parameters for white and grey (containing carbon/graphite) EPS with and without flame retardants were measured using the Cone Calorimeter method [8]. This bench-scale method is commonly used for determining fire performance properties of materials and products, especially for the purposes of fire simulations because of defined fire exposure levels and expression of results per unit area of exposure surface.

In this study experiments were carried out at 50 kW/m^2 exposure level to compare with earlier literature values and to see possible differences of the white and grey EPS qualities. The results of the Cone Calorimeter measurements are summarised in Table 12 and Table 13 together with earlier results which also include results for steel and steel + fibre-cement board protected specimen. In Table 12 and Table 13 the variable RHR$_{max}$ is the maximum value of rate of heat release and RHR$_{60s}$ is the mean value of rate of heat release during 60 seconds after ignition. Note that there are two thicknesses of the specimen. EPS melts before ignition and thus the distance of the melted substance to the radiant heater is different depending on the specimen thickness. Effective burning time of an initially 50 mm thick specimen is about 1.5 minutes. The heat of combustion of EPS is about 42 MJ/kg at maximum.

Table 12. Cone Calorimeter results for grey EPS compared with earlier results for white EPS at 50 kW/m^2 exposure level.

EPS without flame retardant						
	Grey EPS		White EPS			
			[9]	[10]	[11, 12][1]	[11, 12][2]
Density ρ (kg/m^3)	18	18	20	15	16	16
Thickness d (mm)	25	50	50	25	25	25
Time to ignition (s)	41	35	37	18	26	68
RHR$_{max}$ (kW/m^2)	411	343	410	407	507	477
RHR$_{60s}$ (kW/m^2)	218	306	345	158	-	-
THR (MJ/m^2)	13.3	26.5	-	-	16.9	17.3
Smoke; SEA (m^2/kg)	-	-	1120	1346	1174	977

[1] No protection

[2] Steel sheet (0.6 mm) protection

The results in Table 12 and Table 13 indicate that present and earlier results (up to 20 years ago) are quite similar. At this reasonably high heat flux level of 50 kW/m^2 there are only small differences between the products with and without flame retardant. The efficiency of flame retardant come more significant at lower heat fluxes: With flame retardant EPS did not ignite at 20 kW/m^2 but ignited at 15 kW/m^2 without flame retardant [11].

The experimental results also show very clearly the protective effect of thin steel sheet (0.6 mm) and 4.5 mm thick fibre-cement board. This information can be used in the façade fire simulations.

Table 13. Cone Calorimeter results for grey and white EPS with flame retardant compared with earlier results for white EPS at 50 kW/m^2 exposure level.

EPS with flame retardant									
	Grey EPS		White EPS						
					[9]	[10]	[11,12]		
							1	2	3
Density ρ (kg/m^3)	19	19	22	22	22	15	16	16	16
Thickness d (mm)	25	50	25	50	50	25	25	25	20
Time to ignition (s)	48	46	56	46	46	24	37	83	198
RHR_{max} (kW/m^2)	325	329	265	330	380	379	306	97	77
RHR_{60s} (kW/m^2)	172	290	202	293	320	173	-	-	-
THR (MJ/m^2)	13.9	27.6	16.5	32.7	-	-	14.9	18.6	20.2
Smoke; SEA (m^2/kg)	-	-	-	-	1220	1297	1394	1004	609

[1] No protection
[2] Steel sheet (0.6 mm) protection
[3] Steel sheet (0.6 mm) + 4.5 mm fibre-cement board protection

5.2 Ignition and burning of EPS covered by reinforced rendering

The EPS insulation is protected with reinforced rendering (5 - 8 mm) which does not ignite or whose contribution to fire is limited. The rendering can contain limited amounts of organic substances, but this cannot cause burn through of the rendering layer and the reaction to fire classification needs to be at least B level or fire performance shown by large scale evidence.

According to reference [11] ignition of steel sheet (0.6 mm) + 4.5 mm fibre-cement board protected EPS takes about 2.5 minutes at heat flux level 60 kW/m^2, about 4 minutes at 40 kW/m^2 and more than 15 minutes at 30 kW/m^2. Similarly, RHR_{max} is 91 kW/m^2 at heat flux level 60 kW/m^2, 65 kW/m^2 at heat flux level 40 kW/m^2 and almost zero at 30 kW/m^2 for this mechanically protected specimen. Thus, the average rate of heat release from steel sheet (0.6 mm) + 4.5 mm fibre-cement board protected EPS can be assumed to be not more than 50 kW/m^2 for heat flux levels up to 60 kW/m^2. 5 – 8 mm thick reinforced rendering can be assumed to be as good protection for EPS as the thin steel + 4.5 mm thick fibre-cement board because the heat transfer through fibre-cement board and rendering are quite similar. The thin steel sheet in the tests for fibre-cement board delays heat transfer only very short time and in the small scale testing the steel sheet does not prevent pyrolysis gases releasing and igniting. Additonally, in real façade applications the reinforced rendering will stay in place without tearing according to large scale experiments. Thus, in the following analysis 50 kW/m^2 is used as an average value for rate of heat release from rendering protected EPS. In the sensitivity analysis a double of the value, 100 kW/m^2 is used to cover possible worst case situations. It is also assumed that only when the heat flux level is at least 30 kW/m^2, ignition of rendering protected EPS can occur and EPS will start contributing to fire development.

There is also large scale experimental evidence on fire performance of EPS-rendering systems made in the following scale/conditions: specimen size above fire room 5 – 6 m and fire load 300 – 600 MJ/m^2 [7]. Maximum heat flux at the window above fire room, maximum temperature at the upper edge level of the specimen and limitation of burnt area to the lower edge of the window two floors up from the fire room are examples of acceptance criteria in these tests. In successful experiments EPS has contributed to the fire only on a limited area and no fire spread beyond the two floors above the fire room has occurred.

6. Analysis of room fire spread via facade to compartments above

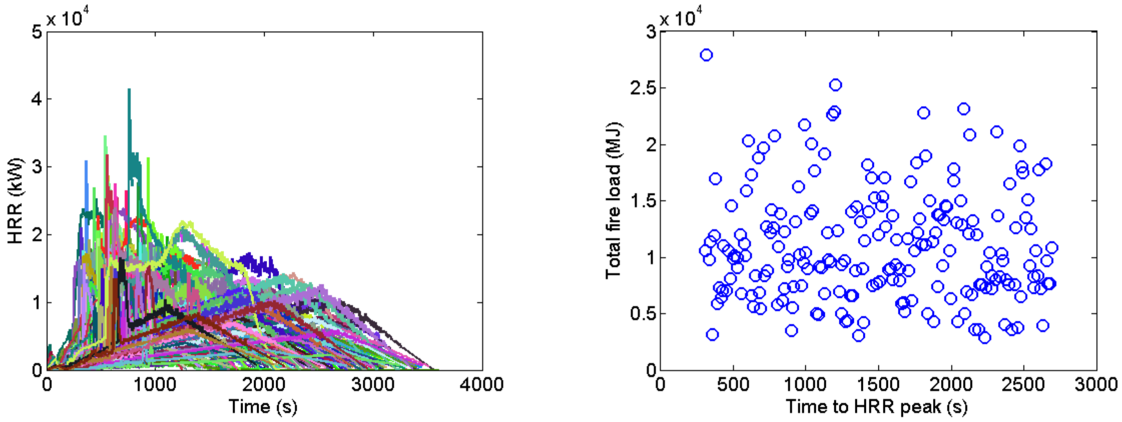
6.1 Probability based fire simulations

The fire is assumed to start from an apartment and spread to the facade through a broken window. The doors inside the fire room were closed, but a little leakage of air was assumed (0.2 m^2 gap in the door) in order to maintain enough oxygen for the fire to develop. The room height was 2.5 m. The grid cell size of the simulations was 0.2 m and the simulations were done using Fire Dynamics Simulator (FDS) program [13] version 6 (Release Candidate 4 Serial). The resolution is relatively coarse, but 0.2 m is chosen as a compromise with the calculation time and accuracy of the results. The statistical study was made using *Monte Carlo simulations* (MC). 200 random cases (using Latin Hypercube sampling) were simulated using the parameters and distributions listed in Table 14. An example of an input file is seen in Appendix A (including contribution of EPS to fire).

Table 14. Random variable distributions in Monte Carlo-simulations.

Variable	Distribution	Parameters
Room area (m^2)	Uniform	7, 30
Window wall length (proportional)	Uniform	0.25, 0.75
Window height (m)	Uniform	1.2, 1.4
Window width (m)	Uniform	1, 3
Fire load (MJ/m^2)	Triangular	200, 600, 1000
Time delay to window break (min)	Log-normal	1.099, 0.610
Time to fire peak (s)	Uniform	300, 2700

The room dimensions depended on the room area and the proportional length of the window wall. The proportional length means the wall length relative to the sum of two adjacent (x and y) walls. Each room has one window that is located in the middle of the wall. The dimensions of the window are also random variables, with an exception that the window cannot be wider than the wall. The window breaks in the temperatures above 500 °C. The time it takes to break is treated as a random number . This variable has an average of 3 minutes and 80 % fractal at 5 minutes [14]. The fire in the room starts at t = 0 and the heat release has a triangular shape. The peak is reached at the time determined by the random variable (between 300 and 2700 s) and after that the fire decreases linearly so that it is fully extinguished 15 minutes after the peak (Figure 3a). The actual heat release rate of the fire depends on the available oxygen in the room. The window breaking also cause a peak in heat release rate due to the fast effects in oxygen and pressure levels. The peak heat release rate is calculated so that the total fire load (determined by the random variable between 200 and 1000 MJ/m2) is consumed. The fire load is calculated per floor area of the room, and the fire is spread uniformly to half of the total surface area of the room. The total fire loads of the rooms as a function of peak time of the heat release rate are shown in Figure 3b.



a)

b)

Figure 3. Heat release of the room fire. a) Heat release rates of room fire. b) Total fire load (fire load/m^2 x room area) as a function of fire peak time.

6.1.1 Fire loads for apartments

Experimental data on real fire loads in apartment buildings are available in the literature. A Finnish study [15] on fire loads covered details of 165 dwellings in multi-storey apartment buildings. These fire load distributions together with earlier Finnish and international results [16, 17,18] are shown in Figure 4. It is to be noted that the Eurocode 1 (EN 1991-1-2) curve [19] in Figure 4 differs from the experimental findings because it is a design fire load curve including safety factors.

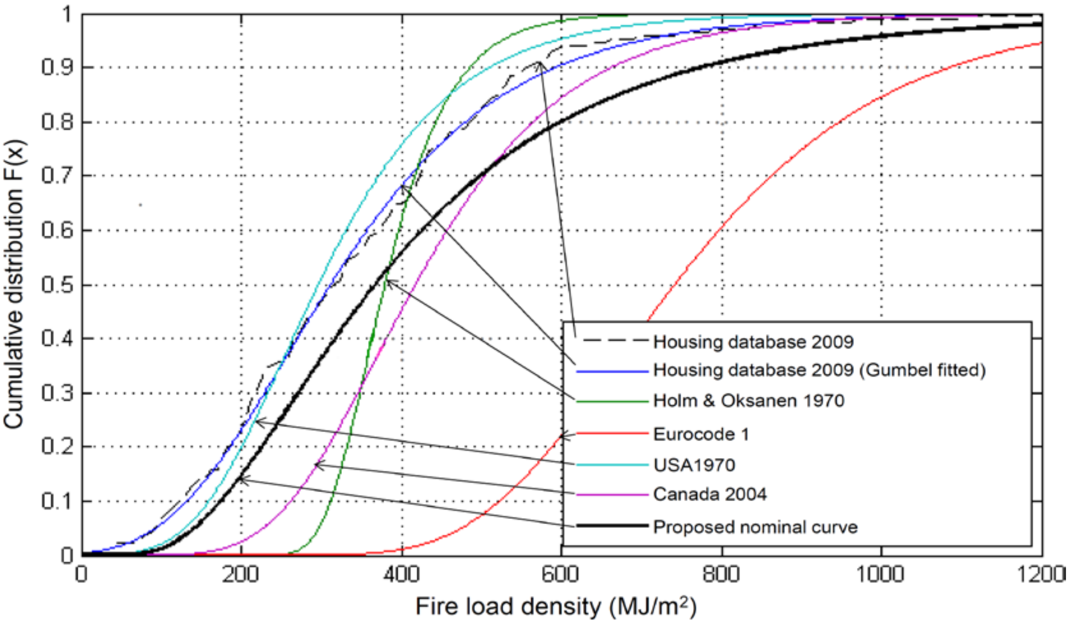


Figure 4. Housing data base [15] fire load density distributions compared with Holm & Oksanen [16], USA 1970 [17] and Canada 2004 [18] results. Eurocode 1 [19] distribution is also given together with a proposed nominal curve [20].

The proposed nominal curve [20] in Figure 4 is intended for use in multi-storey apartment buildings. 80 % fractal of this curve coincides with the assumed fire load maximum of 600 MJ/m^2 defined in the Finnish fire regulations for apartment buildings. In Sweden for residential buildings the assumed design value is 800 MJ/m^2 (80 % fractal) [21].

The assumed fire loads for the analysis of this work were defined to be between 200 and 1000 MJ/m^2 with mean value at 600 MJ/m^2 to simplify the fire load distributions presented in Figure 4.

6.1.2 Fire spread through window on facade

The occurrence of breakage and fallout of the windows of the room-of-fire-origin is estimated on the basis of the hot gas layer temperature. As explained earlier, it was assumed that the window breaks in the fire room when the window temperature at any point of the window area exceeds 500 °C during a time defined by a random variable. The variable has an average of 3 minutes and 80 % fractal at 5 minutes [14]. These assumptions are based on windows having double glazing. Triple glazing may further delay the fire to spread through the window and this can be taken as a safety factor for this type of windows. The fire exposure at the windows at upper floors are considered to be able to cause window breakage if the heat flux exceeded 35 kW/m^2 for at least 3 minutes [14] (this criterion is based on window breaking dependence on heat flux). The conservative assumption is, that the three minutes need not be consecutive, but it is enough if the heat flux exceeds 35 kW/m^2 cumulatively during the fire.

Some of the fires can be extinguished or limited by first-aid extinguishing, and some of the fires may self-extinguish before being able to spread out of the compartment of fire origin. According to statistics, these amount to 15-30 % of the total number of ignited fires. In most cases fire brigade can be in time to extinguish or limit the fire before it can spread through the window on the facade. Simulation can be used to assess the probabilities of window breakage above the fire room caused by flash-over room fires spread on facade. Comparing the overall probabilities of these window breakages from the event tree analysis with statistical estimates, validity of the assumptions made can be verified for façade systems made of at least A2-s1, d0 or nearly the same fire performance materials.

6.1.3 Fire exposure and fire spread on facade

Flashover room fires

In a facade fire test method SP Fire 105, the rate of heat release has been measured to be about 2.5 MW at maximum [22] according to Figure 5 when 60 l of heptane is burnt as a fire load and the heat flux levels one floor above the fire room are over 30 kW/m^2 in this test.

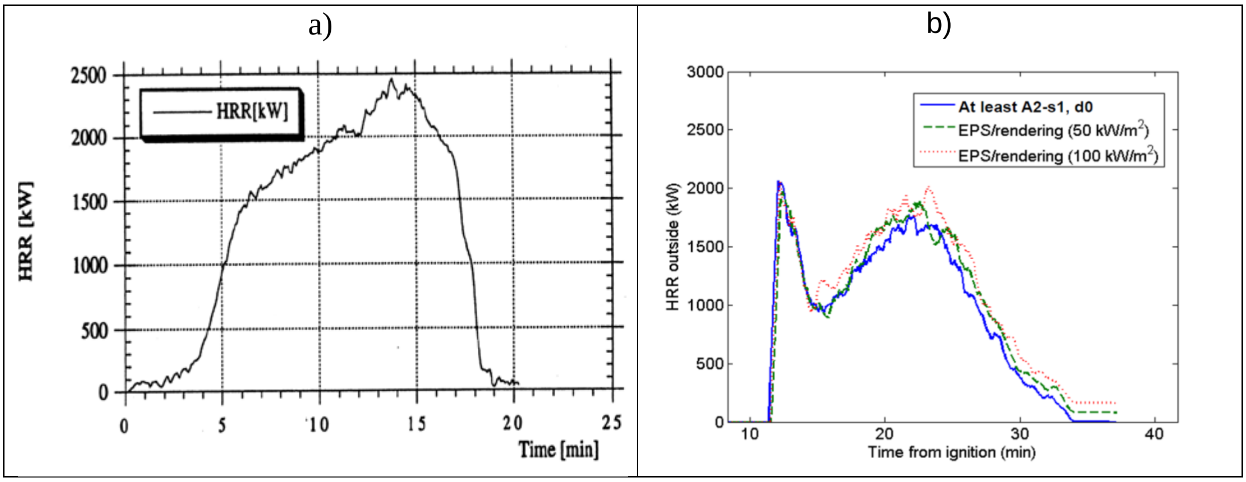


Figure 5. Heat release rate as a function of time a) in SP Fire 105 façade test [22] and b) in an example of simulations (case of room fire which breaks the 2nd floor window but not the 3rd floor window).

Experimental results for typical dwelling room flash-over fires show that at the window one floor above the fire room heat fluxes can be as a short-term up to 70-75 kW/m^2 [23, 24, 25]. In the VTT measurements [24, 25] the fire load has been up to 920-1200 MJ/m^2 per floor area and the window width has been 2.3 - 3.0 m and height 1.2 m. In the simulations the maximum heat fluxes have found to be about 80 kW/m^2 (except immediately after window breaking when the heat flux can be much higher for a short period, see Figure 6) which is in line with the experimental findings. Note that in the experiments there has been no window in place. Thus, in the testing results the first peak seen in the simulations is missing.

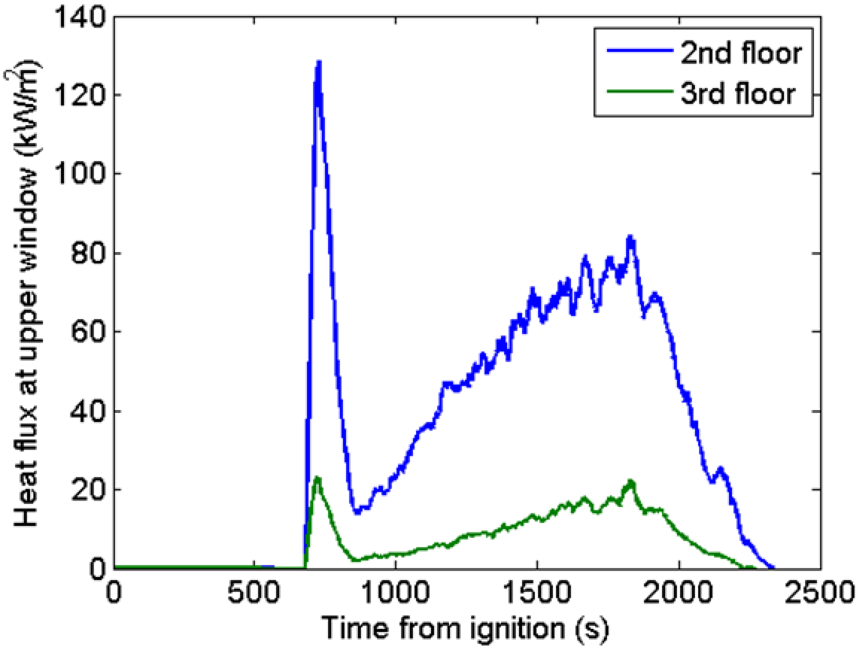


Figure 6. Example of maximum simulated heat fluxes at 2nd and 3rd floor window level.

At windows two floors above the fire room the heat flux levels have been typically at maximum one third of the values at one floor above [25]. From the experimental façade fire results [25] it can be also concluded that three floors above the fire room windows do not break because of the heat exposure is quite low (well below 10 kW/m^2), when the facade materials are at least A2-s1, d0 class.

The criteria for window breaking above the fire room is heat flux of 35 kW/m^2 for at least 3 minutes and at 10 kW/m^2 level window there will be no window breakage. Thus, rendering protected EPS will not ignite in the wall area which is above the window one floor above fire room when this window does not break. In the wall area immediately above the fire room EPS can be ignited if the exposure level is 30 kW/m^2 for about 15 minutes, or 40 kW/m^2 for about 4 minutes.

External ignitions

Fires ignited near the external wall can cause the main hazards for façade. Common objects of causing these hazards are different type of waste, motor vehicles, shelters, etc. In Figure 7 an example is given to indicate the level of exposure from a touring car [26]. It shows that at a distance of one meter the heat fluxes can be 30-40 kW/m^2. This intense fire can be estimated to cover typical fires of waste burning near a facade. In reference [26] the heat flux from a shelter with a moderate fire load at a distance of 5 m has been estimated to be maximum about 10 kW/m^2. As a conclusion it can be assessed that external ignitions do not cause more severe exposures on the facade than flashover room fires.

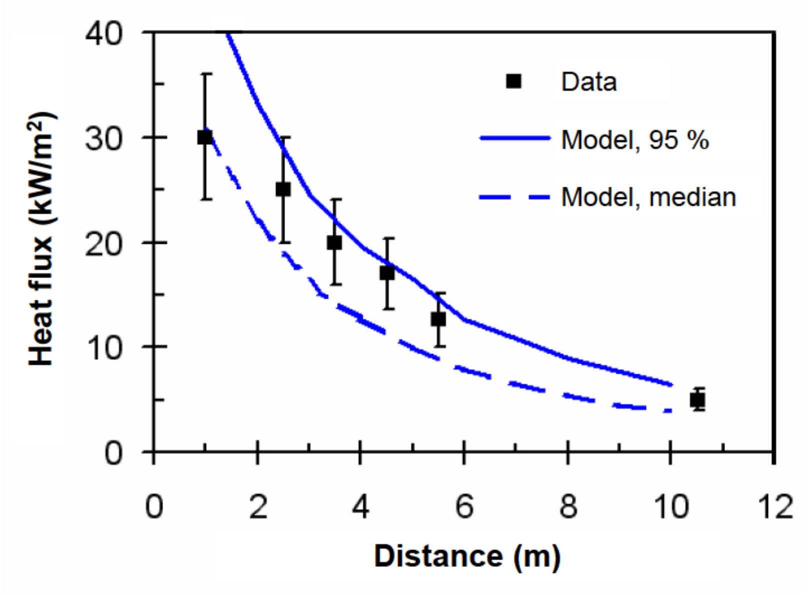


Figure 7. Heat flux from touring car fire as a function of distance [26].

Simulation of façade fires

In order to evaluate the effect of EPS, the fire simulations are performed two times. First, the wall is at least A2-s1, d0 class and in the second time the rendering protected EPS in the wall may ignite. The ignition occurs if the heat flux anywhere between the windows exceeds 35 kW/m^2 at least for 3 minutes (this criterion was set for the simulation to be on the conservative side). The average heat release rate of burning EPS was estimated to be 50 kW/m^2 or 100 kW/m^2 as a worst case [11] and the burning to continue for 15 minutes. An example of a facade fire is shown in Figure 8 when EPS has not yet ignited.

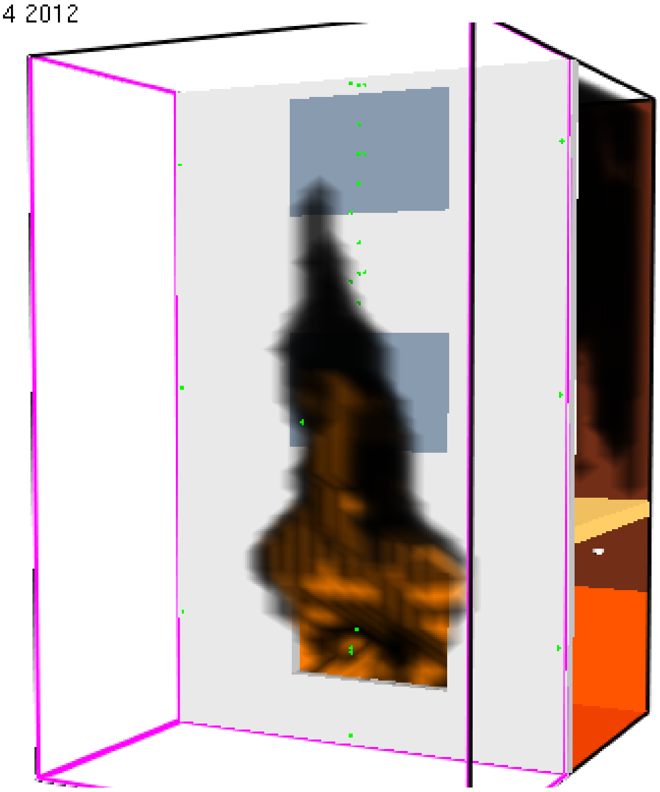


Figure 8. A flash-over room fire on facade (EPS not ignited).

6.2 Simulation results of fire spread

The window of fire room was broken in 146 cases of 200 (73 %). Of these 146 cases, the probabilities of times of window breaking and fire spreading to the facade are shown in Figure 9. The results are listed in numbers in Table 15.

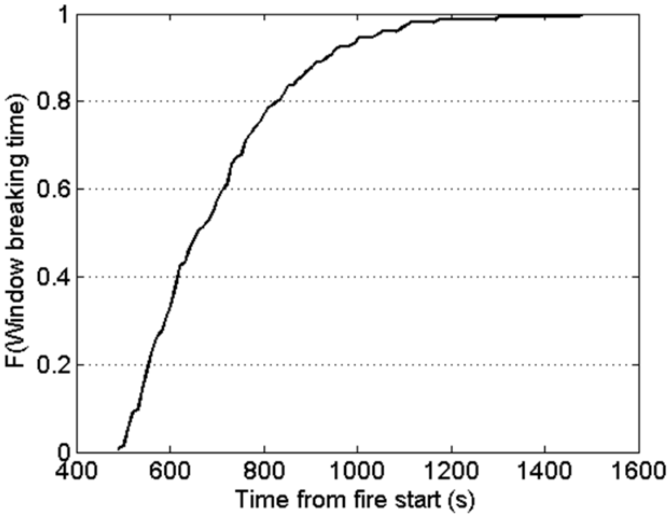


Figure 9. Cumulative probabilities for time of window break.

Table 15. Results of window breaking times (in seconds).

Minimum	Maximum	Mean value	25 %	50 %	75 %
486	1490	708	571	662	792

The window is breaking above the fire room if the heat flux is at least 35 kW/m^2 during 3 minutes (cumulative). For at least A2-s1, d0 facade, the second floor window was broken in 31 % and the third floor window in 5 % of the cases when the fire spread to the facade (146). The cumulative probabilities of the times of breaking upper floor windows are shown in Figure 10. The minimum times of window breaks at upper floors are above 700 s from the ignition.

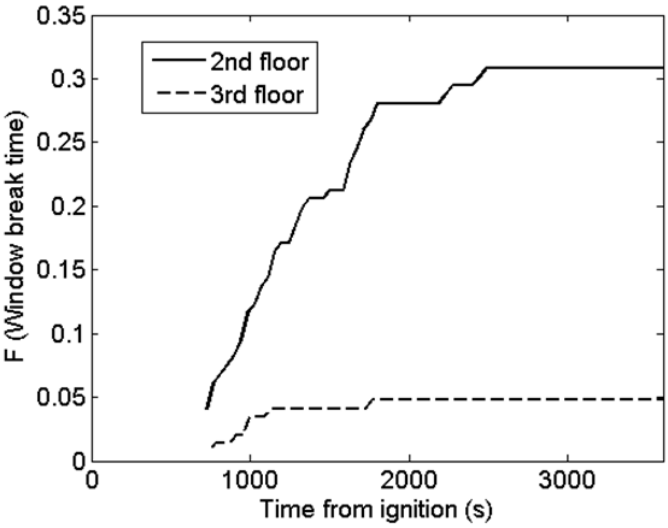


Figure 10. Cumulative probabilities for times of upper floor window breaking for at least A2-s1, d0 façade (of all the cases when fire spread through window to the facade).

The comparison of probabilities for at least A2-s1, d0 and EPS insulated facades are done in Figure 11 as cumulative probabilities. The second floor window was broken in 31±5 % with at least A2-s1, d0 facade and in 36±5 % of the cases with EPS insulation. Until about 25 minutes from the start of the fire the window breaking time probabilities for both façade types are very close to each other (within one minute difference). In third floor the final probabilities were the same (5±1 %), but with EPS insulation the window breaking tends to occur slightly earlier. These are relative numbers per fires which have spread through the fire room window to the facade. Overall probabilities for window breaking are estimated in section 6.4.

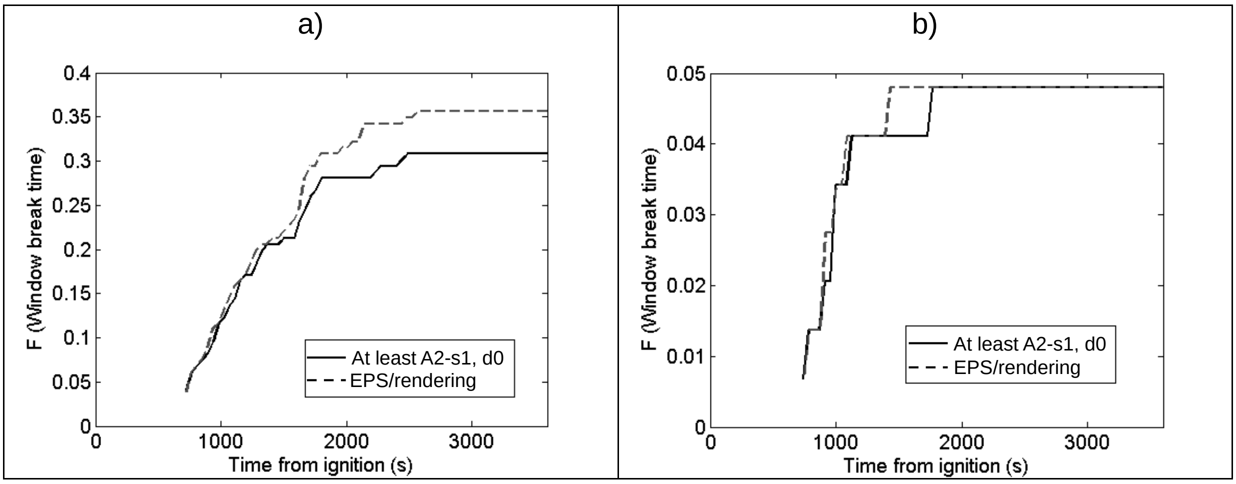


Figure 11. Window break results for at least A2-s1, d0 and EPS insulated facades. The probabilities are calculated from the cases where fire spread through window to the facade. a) Second floor. b) Third floor.

6.3 Effects of used fire performance data and building geometries

Sensitivity of the used input data and effects of building geometries were studied for the following parameters: Heat release from the rendering protected EPS, window breaking criteria, distance of window edge from an inner corner of a building, width of the fire room window, height of the fire room window, fire load density of the apartment, effects of balconies and exit applications, and fire stops/barriers in different façade layouts.

Contribution of EPS to fire development

The sensitivity of heat release rate from rendering protected EPS was studied by choosing four inputs in which the second window did not break, but EPS was ignited at least above the fire window. In none of these four cases did the window break in the third floor when heat release rate of the rendering protected EPS was increased from 50 kW/m^2 to 100 kW/m^2. The effect of this increase is demonstrated in Figure 12. In some borderline case the increase in heat flux may be enough to break a window, but not in general.

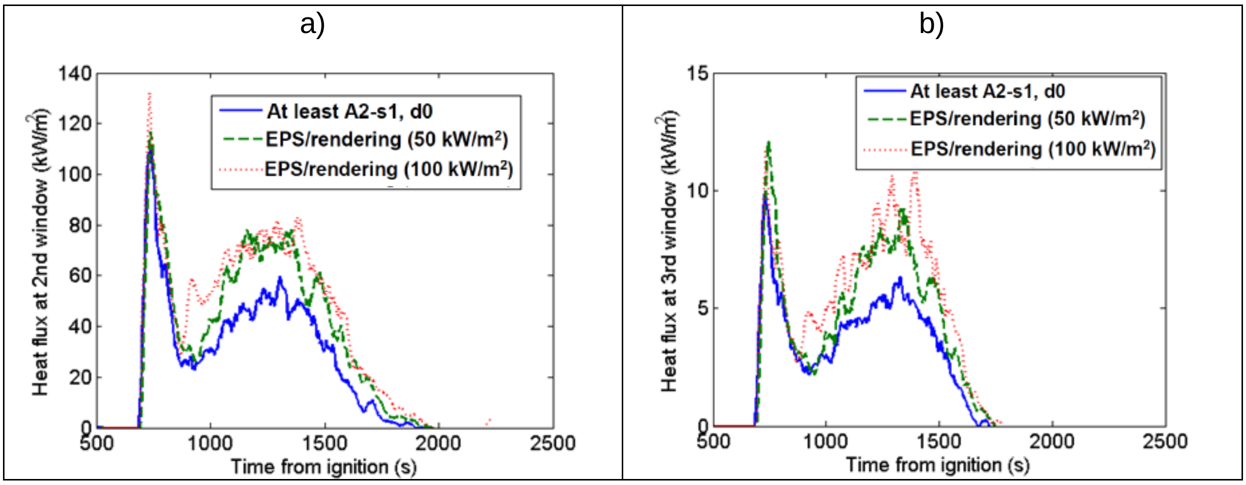


Figure 12. Simulation result examples of heat flux for at least A2-s1, d0 facade, and for EPS/rendering systems with rate of heat release of 50 kW/m^2 and 100 kW/m^2. a) Heat flux at 2nd floor window. b) Heat flux at 3rd floor window.

Window breaking criteria

The critical time of window break at upper floors was assumed to be 3 minutes (at least 35 kW/m^2 heat flux level). If less conservative values (which are likely to be expected with double or triple glazing) would be used, the results would change slightly. The probabilities of upper floor window break with different minimum exposure times are listed in Table 16 for at least A2-s1, d0 and EPS insulation facades.

Table 16. Window break sensitivity to the minimum exposure time.

Minimum exposure time	2nd floor		3rd floor	
	At least A2-s1, d0	EPS/rendering	At least A2-s1, d0	EPS/rendering
3 min	31 %	36 %	5 %	5 %
4 min	27 %	32 %	3 %	3 %
5 min	26 %	29 %	3 %	3 %

Width and height of fire room window

The width of the window is a significant factor when considering the fire spread to the upper floors. The window width was uniformly distributed between 1–3 m in the Monte Carlo simulations. At the second floor the window breaking probabilities are higher for wider fire room windows (about 60 % of window break cases occur for window widths 2–3 m and about 40 % for window widths 1–2 m). At the third floor no window was broken when the fire room window width was maximum 1.5 m.

Sensitivity of window height was studied by simulating one severe case with an increased window height of 1.8 m. The results showed that total burning time became shorter and flame height was increased causing increased maximum heat fluxes at the windows above (about 10 % increase at second floor and about 20 % increase at third floor compared to 1.4 m high window) for at least A2-s1, d0 facades. This increase can be estimated to cause not more than 10 % increase in the window breaking probabilities which is within the statistical uncertainties of the results. Similar changes in probabilities are estimated for the cases with EPS/rendering system.

Distance of fire room window from an inner corner

The effect of an inner corner of a building was studied by an example case (one of the worst cases of the simulations). The window edge was located either 0.5 m, 1.0 m or 1.5 m from the corner. Heat fluxes were measured at different heights and distances at the corner wall. The heat fluxes are in general highest at the level of second floor window (in the most distant measuring point from the corner (1.5 m) the highest heat flux was between 1st and 2nd floor window). The heat fluxes shown in *Figure 13* may increase above the critical point near the corner when the window edge is close to the corner. However, it is unlikely that the rendering protected EPS ignites if the window edge is located at least 1 m from the corner wall.

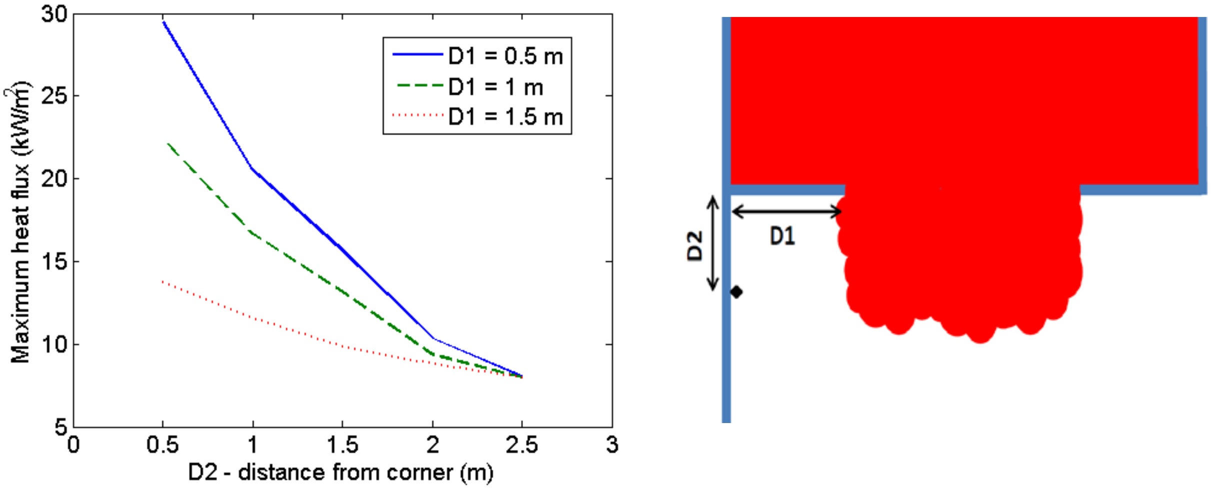


Figure 13. Inner corner close to window opening. Highest heat fluxes at a corner wall as a function of window distance from the corner.

Balconies and exit applications

Balcony layouts need to be considered when using EPS/rendering systems because of changed exposure conditions. In case of external balconies (which are outside the main façade plane) flames are usually directed further off from façade plane (see Figure 14) and thus the fire exposure on the façade surface will be lower than for normal window cases.

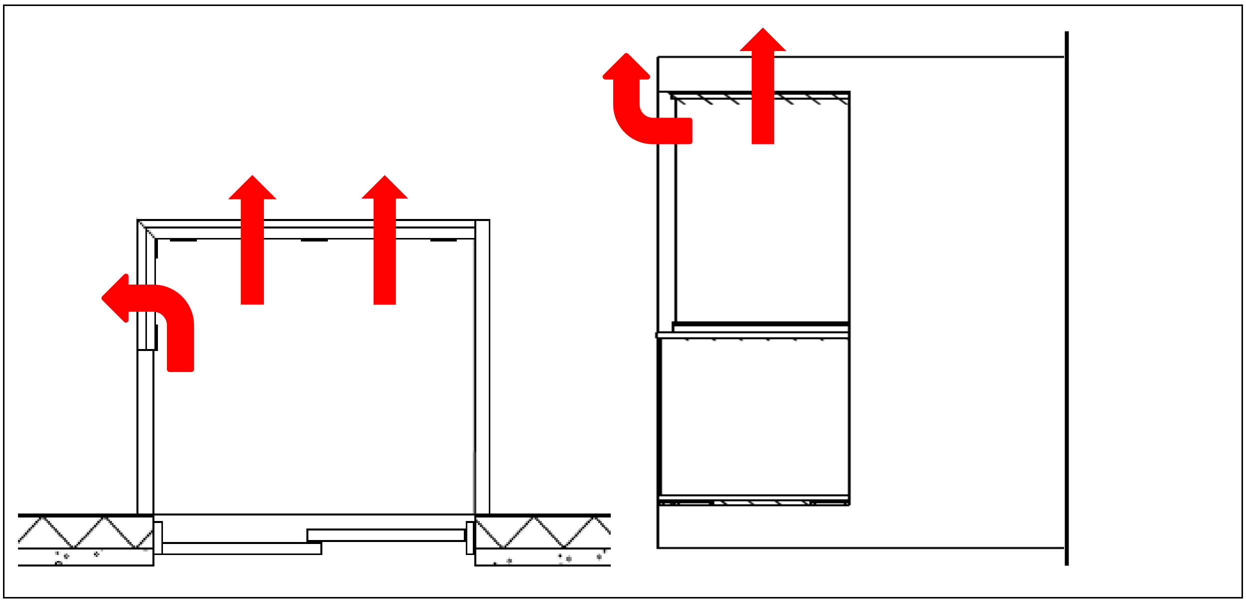


Figure 14. Example of an external balcony and main flame directions.

For recessed balconies the heat exposures to walls and ceiling can be as high as in room fires and the results of this study are not totally valid. Higher heat fluxes will mean an increased contribution of EPS to fire development. Thus in this case fire safety requirements for internal walls and ceilings should be applied.

For corridor type exits the situation is similar to recessed balconies and potential for flaming droplets should be taken into account. For these cases fire safety requirements for exits should be applied.

Fire stops/barriers

The assumed fire stops/barriers were defined in section 3.2, Figure 1. In practice there are many different façade/window layouts which may cause the need to use different fire barrier layouts in different parts of the building. When the windows are not in line above each other in successive floors continuous fire barriers at least on every second floor are recommended (see Figure 15). In general, structural detailing of facades and the associated constructions are of essential importance in decreasing potential fire hazards and resulting property losses.

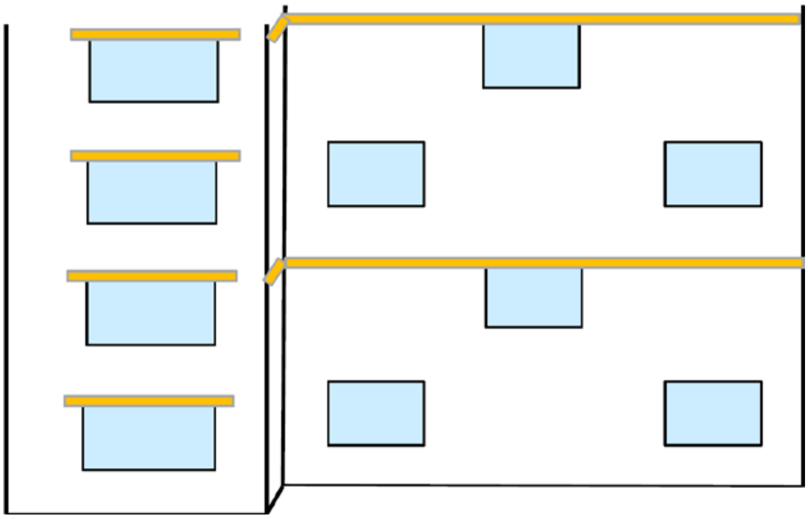


Figure 15. Examples of fire barriers for different façade layouts.

6.4 Conclusions on fire spread analysis

The event tree approach (see section 3.4) is used to summarise the results received from statistics and simulations and finally to compare the overall probabilities for window breaking at floors above the fire room. Branching probabilities for the event tree based on literature values, statistics and simulations are given in the upper part of Table 17.

According to statistics, the fire development situation at fire brigade arrival is as follows for spread of fire outside the fire compartment:
- Finland: 3–4%
- Sweden: 1 %.

Information on fire spread due to window breaking (according to Finnish statistics) indicated that 0.7 % of cases could lead to spreading through windows. In a previous study the upper limit for spreading through windows has been evaluated to be 2% [14]. These are in line compared with the above mentioned statistical data on fires spreading outside the fire compartment (1–4%). All fires do not spread through the window, thus the 0.7 to 2% share of spreading through windows can be taken as the upper limit based on statistics. These same values are used as conservative statistics based estimates of window breaking above the fire room in Table 17.

The accident statistics based limit for probability of fire spreading to the apartments above are compared with event tree estimates in the bottom part of Table 17. Using the event tree of Figure 2 the sum for probabilities of breakage of window 1 and 2 floors above were calculated to be 1.9 % for at least A2-s1, d0 façade and 2.3 % for EPS ETICS façade per ignited fire.

Table 17. Probabilities used in the event tree analysis and overall probabilities compared with statistical estimates.

Probabilities in the branches of event tree and overall probabilities	**Statistical data At least/nearly A2-s1, d0 facade**	**Data used and results of simulations At least A2-s1, d0**	**Data used and results of simulations EPS/rendering**
Early detection of fire		0.7[14]	0.7[14]
First-aid extinguishing successful	0.15–0.25	0.2	0.2
Self-extinction of fire	0.1–0.15	0.15	0.15
Fire brigade extinguishes before spread via window	0.8–0.95	0.9	0.9
Fire spreads via window		0.73	0.73
Breakage of window 1 floor above of fires spreading via window		0.31	0.36
Breakage of window 2 floors above of fires breaking window 1 floor above		0.16	0.16
		Overall probabilities	
Breakage of window 1 floor above		**1.66 %**	**1.95 %**
Breakage of window 2 floors above		**0.26 %**	**0.31 %**
Breakage of window 1 or 2 floors above	**< 0.7 %–2 %**	**1.9 %**	**2.3 %**

The probability of fire brigade to be able to extinguish the fire before spreading through windows to façade is high (up to 95 %) based on the estimates from the statistics. Figure 9 indicates that in 50 % of the cases it will take about 11 minutes for the window of fire room to break (in the simulations the fire was set initially on a large area which means that the estimated times may be underestimates). This value can be compared with time distributions of fire brigade interventions in urban areas where multi-storey apartment buildings are located.

The fire brigade response time in Finnish city areas has been reported to be maximum 5-8 minutes for 50 % of cases and 7-10 minutes for 80 % of cases [27]. A large majority of the residential buildings of urban areas in Finland have maximum eight floors. Cumulative distribution of response time in Helsinki is shown in Figure 16. At least 4-8 minutes must be added to these times to approximate fire brigade intervention times. Thus it will take at least about 10 minutes from the start of fire before fire brigade can be estimated to be able to extinguish or limit significant part of fires. As a conclusion, the fire brigade intervention times, statistical data on fire development situation at fire brigade arrival and simulation based window breaking times of fire room are at least roughly in line with each other.

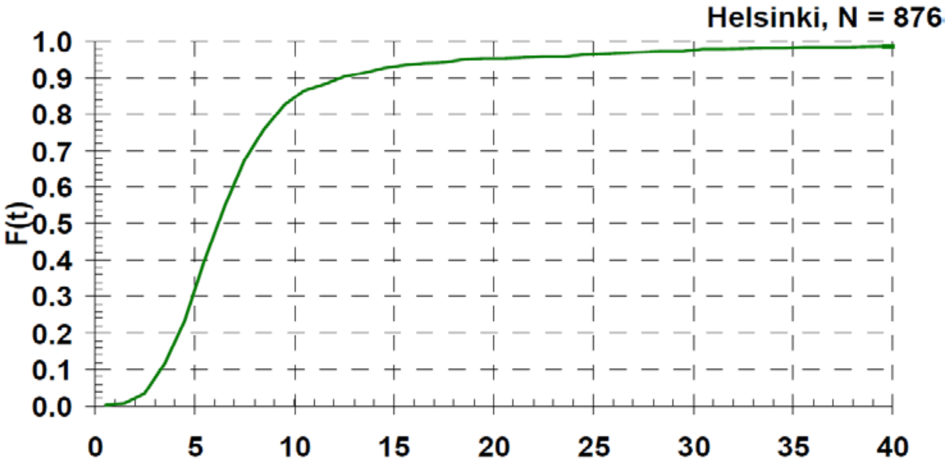


Figure 16. Cumulative distribution of fire brigade response time in Helsinki (in minutes) [27].

Taking into account uncertainties and sensitivity analysis results for the window breaking probabilities it can be concluded that there is a small difference between the two façade types: The overall window break probability in the floors above for EPS ETICS façade is 2.26 % and for at least A2-s1, d0 façade 1.92 % per ignited fire. The estimated overall probability values for the window breaking (Table 17) are on the upper limit compared to statistical data for which conservative values were used. Thus a safety factor is included in the results.

7. Performance criteria for life safety

7.1 Fire spread risks in multi-storey apartment buildings

Life safety risks caused by fires in residential buildings can be assessed by using ignition frequencies and estimated probabilities of spreading of fires. In Finnish residential multi-storey buildings ignition frequency per floor area according to accident statistics (Figure 17) is not more than 7.5×10^{-6} $1/m^2a$ [27, 28]. Using 70 m^2 as a mean value for apartments (this is a slightly larger area than the average for apartments in multifloor buildings), the average probability of ignition of a fire in an apartment will be 5×10^{-4} per year.

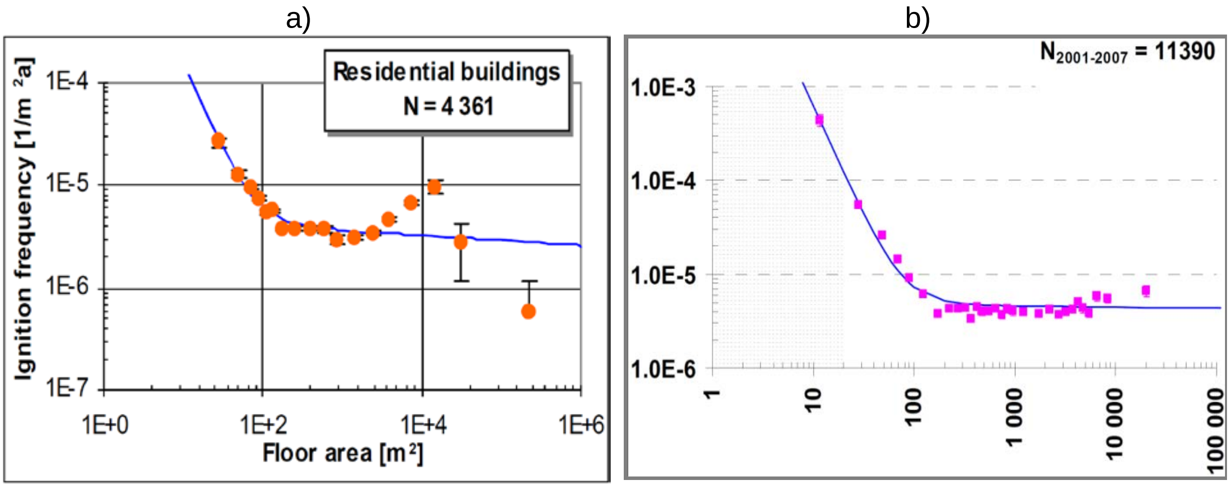


Figure 17. Ignition frequencies in residential buildings based in Finnish accident statistics for years 1996–1999 [28] and 2001–2007 [27].

In section 6.4 it was estimated that maximum 2 % of multi-storey apartment building fires may spread to apartments above the initial fire compartment through windows when the surface and insulation of an external wall is made of at least A2-s1, d0 or nearly the same fire performance (=at least B-s1, d0) materials. Thus, the probability of fire spreading through a window can be at maximum 1×10^{-5} per year for fires spreading though one window. If it is assumed that the initial fire is in a room or spreads to an apartment with 4 sufficiently large windows which break, then the probability of fire spread to apartments above will be (the worst case upper limit) 4×10^{-5} per year. For the rendering protected EPS ETICS façade this worst case upper limit of fire spread probability would be 4.8×10^{-5} per year.

7.2 Acceptance limits

A common way of expressing risk is an F-N curve, where the frequency of an incident is plotted as function of the number of fatalities for that incident. In other words, F-N curve shows the frequency (F) of an expected number of events per time period that a certain number of people (N) may die in the accident. F-N curves are commonly used when presenting e.g. societal risks.

An example of F-N curve of fire fatalities illustrating the significant differences in acceptance levels between single and multiple casualties is shown in Figure 18 [29]. It includes information on structural fires and fire deaths in the Nordic countries and USA. The fire death frequencies are normalized by number of fires. Analytical function was fitted to the data and these functions were summed. Upper (intolerable) and lower (tolerable) acceptance limits were proposed by plotting values 10 times higher and smaller than the summed curve. The frequencies higher than the upper limit have to be rejected, the ones below the lower limit can be taken as acceptable. Large majority of the observed frequencies lie between the two limits.

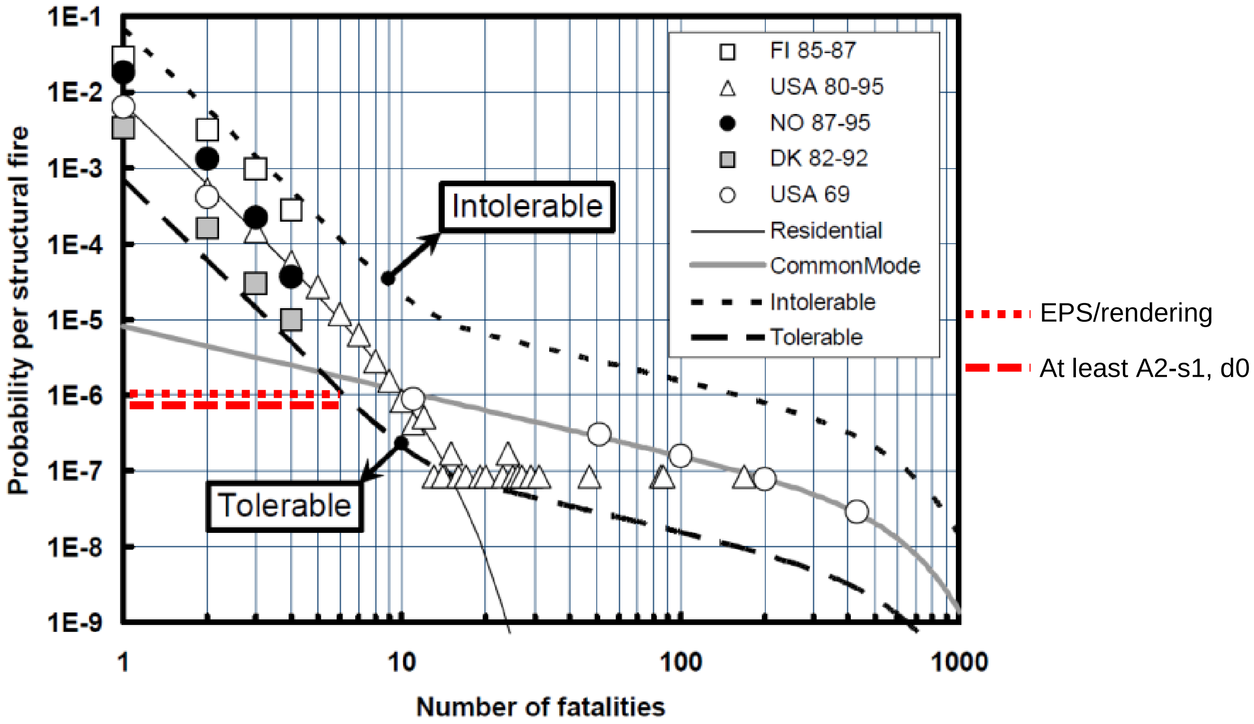


Figure 18. F-N curves based on statistical data, tolerable/intolerable limits [29] and present upper limit values for at least/nearly A2-s1, d0 facades and for EPS ETICS.

The number of fire deaths per apartment building fire according to Finnish [30] and Swedish [31] statistics is 1–2 $\times 10^{-2}$. Combining this with the estimated fire spread probabilities through windows leads to fire death probability upper limit of no more than 10^{-6} per building fire per year (0.8×10^{-6} for at least A2-s1, d0 facade and 1.0×10^{-6} for EPS/rendering systems). According to the F-N curves of Figure 18 [29] this frequency is tolerable to accidents of about 6 or less fatalities. Since the average number of persons per apartment e.g. in Finland is two, the number of deaths foreseen in three apartments (as a consequence of fire spreading through windows to upper floors) remains below 6 because apartments are not occupied all the time. Therefore, it can be concluded that life safety objectives are reached.

For higher buildings than eight floors an extended analysis would be needed to cover additional delays in fire brigade intervention time and also practical possibilities to extinguish fires on high facades.

8. Field of application of the results

8.1 Influence of general building characteristics

Buildings have variations according to their room and window sizes and shapes which may also change during the life cycle of a building. Most of the fire load in apartment buildings (i.e. movable property) is not controlled and thus may vary a lot. The influence of these factors has been included in this study and the conclusions are summarised in the following.

Fire load and room dimensions

In Finland according to the regulations the fire load in apartment buildings is assumed to be not more than 600 MJ/m^2 and according to a survey [15] nearly 95 % of multi-storey buildings are within this limit. In Sweden for residential buildings the assumed fire load design value is 800 MJ/m^2 (80 % fractal). In this study with fire load as a variable in the Monte Carlo simulations, a mean value of 600 MJ/m^2 and the maximum of 1000 MJ/m^2 were used. Thus, the high fire load values which are most critical concerning safety have been well covered compared to requirements and real measured fire loads. In addition, for the fire simulations it was assumed that the fire is spread uniformly to half of the total surface area of the room. This means that also apartments which have large areas of surfaces with combustible linings are well covered in this study.

Room sizes and shapes were random variables in the Monte Carlo simulations according to Table 14. These are parameters which can in principle have an effect on the flash-over flame height. These effects have been studied earlier and the conclusion has been that neither the room size nor the room shape has a notable influence on the flame height [14]. Thus, the present results can be applied to apartments which are in the same floor.

Windows

The width of the window is a factor affecting the fire spread to the upper floors. The window widths studied were between 1–3 m in the Monte Carlo simulations. Thus present results are applicable at least up to 3 meter wide windows. For wider windows the probabilities of fire spread will slowly increase, both for at least A2-s1, d0 and EPS ETICS facades.

Sensitivity of window height was studied by 1.8 m high windows. The flame heights were increased causing increased maximum heat fluxes at the windows above. This increase was estimated to cause not more than 10 % increase in the window breaking probabilities for both at least A2-s1, d0 and EPS ETICS facades. Results of the present study can be assessed to be applicable up to 1.8 meter high windows (with the above given 3 m limit for width).

As a conservative assumption for window breaking criteria it was assumed that the windows have maximum double glazing. Thus, if in practice triple glazing is used, fire spread will be further delayed and an additional safety factor will apply for this type of windows.

Façade areas without windows have quite low importance concerning life safety in fires, because fire spread from the fire room window to windows above is the main concern.

8.2 Influence of specific building characteristics and rescue

Windows close to inner corners

The effect of an inner corner was studied for one of the highest fire exposure cases measuring simulated heat fluxes at different heights and distances from an inner corner for different window distances from the corner. The results indicated that it is unlikely that the rendering protected EPS will ignite if the window edge is located at least 1 m from the corner wall.

Balconies

In case of an external balcony (protrusion from the main façade plane) flames are usually directed further off from façade plane and thus the fire exposure on the façade surface will be lower than for normal window cases. For recessed balconies or corridor shaped exits the heat exposures to walls and ceiling can be as high as in room fires. These higher heat fluxes will mean an increased contribution of EPS to fire development. Thus in these cases relevant fire safety requirements (for internal walls and ceilings or exits) should be applied.

Fire barriers in EPS insulation

The general option is to have fire stops (at least A2-s1, d0 class mineral wool) either above each window or continuous strips at every second floor in buildings with more than two floors. It is also possible to use different fire barrier layouts in different parts of the building. The main principle is to limit possible burning of the EPS insulation to a defined area in vertical direction.

Number of floors

Maximum eight floors (with possible basement floor which can be aboveground) has been assumed as the limiting height of buildings in this study. For higher buildings an extended analysis would be needed to cover realistic possibilities of fire brigade to prevent spreading of fire early enough (consequences of additional delays in intervention time and practical possibilities to extinguish fires on high facades).

Distance between buildings

The distance between buildings is assumed to be at least 5-8 m according to relevant national requirements to ensure risks of ignition of neighbouring buildings to be within nationally accepted limits.

EPS ETICS systems

The EPS insulation is assumed to be protected from external side with approved reinforced rendering system (ETICS fulfilling requirements of ETAG 004 including fire performance of components and the system according to possible national provisions (e.g. on the basis of testing)).

Fire brigade intervention

Multi-storey apartment buildings are usually located at urban areas and thus the fire brigade response times referred in this study are relevant. Also a large majority of the residential buildings of urban areas in Finland (and Nordic countries) have maximum eight floors. Thus, application area of the statistics used to estimate the situation at fire brigade arrival cover buildings up to this floor limit.

8.3 Summary of the field of application of the results

The analysis of the effects of different building characteristics and fire prevention measures show that the conclusions on the fire spread probabilities to upper floors presented in this report have general validity in typical multi-storey apartment buildings within the limitations given above.

9. Fire safety during construction and renovation

EPS is combustible material and therefore, when EPS is unprotected without reinforced rendering during the installation phase special concern should be paid to fire safety. Ignitability and fire behaviour of EPS with and without flame retardants as means of reducing fire hazards during installation phase are shortly described in the following.

EPS with flame retardant can resist small ignition sources such as cigarettes or small flames and is classified to reaction to fire class E. Also under radiant exposure at low heat flux levels EPS with flame retardant is superior to EPS without flame retardant in terms of fire behaviour: At 25 kW/m^2 EPS with flame retardant will ignite in more than 15 minutes whereas EPS without flame retardant ignites in less than 2 minutes [11]. Similarly, heat release rate values for EPS with flame retardant and EPS without flame retardant are close to zero and about 330 kW/m^2 [11], respectively. At higher heat fluxes these differences do reduce and at 50 kW/m^2 the differences are not very significant (see Table 12 and Table 13).

At 50 kW/m^2 exposure level the heat release rate of an unprotected EPS is about 350 kW/m^2. During installation phase flashover room fire and large external ignition sources should be avoided, because EPS can ignite under those conditions. When EPS is not covered by reinforced rendering, fire will also spread mainly upwards to an area covering up to approximately 100 m^2 in building with maximum 8 floors. Consequences of this kind of spreading fires should be avoided by minimising the time EPS is unprotected on the external wall and instructing the installation professionals on fire hazards.

In the statistical study a very limited amount of data was found about the involvement of EPS insulation related to construction or renovation work. The ignition of EPS insulation seems to be relatively rare, indicating that an adequate protection is usually provided.

In European level there is available CFPA Guideline No 21 - Fire prevention on construction sites [32] which is a general guidance for all construction sites and is very much valid also for sites where EPS insulation is installed. This guideline includes e.g. instructions concerning sites where construction contains combustible materials. It also gives guidance on site fire safety plan, which includes e.g. the following

- compliance with national fire safety legislation and fire risk assessment is undertaken
- the organisation and responsibilities for fire safety
- the arrangements for recording fire safety training given to all site operatives
- general site precautions, fire detection and alarm systems, portable fire extinguishers
- the requirements for a hot work permit regime
- an effective evacuation plan and procedures for calling the fire brigade

- fire brigade access, facilities and co-ordination
- the instructions given to those on site of the required actions in case of fire
- security measures to minimise the risk of arson
- the regime for the storage and control of waste materials
- the regime for the storage and control of flammable liquids and compressed gases.

Another European guideline related to the previous one is CFPA Guideline No12 – Fire safety basics for hot work operatives [33]. Examples of its contents are the following

- alternative working methods
- safety precautions before performance of hot work, during hot work and after completion of hot work
- hot work licence and safety examination.

In a Finnish guidance on fire safety during renovation of a building [34] instructions are given e.g. on fire compartmentation and fire loads, exits and emergency access roads, arson prevention, hot works, tarpaulins installed on scaffolds (including smoke venting) and emergency planning checklist. Similar guidance is available in Germany provided by insurance companies [35] and in Sweden for general guidance concerning requirements for fire protection work during construction [36] and for specific guidance concerning fire safety of EPS during construction [37].

The main principles and actions concerning construction site fire safety for the time when EPS is uncovered during installation phase can be summarised as follows:

- On construction sites there is a need, in general, to reduce the risks of ignition by minimizing the use of flammable liquids and gases and the amount of fire load (including waste material).
- Compliance with hot work instructions is of primary importance, and the construction site needs to be non-smoking area.
- Understanding of all fire safety instructions should be ensured by language versions whenever necessary.
- If apartments are occupied during the installation process, the time EPS insulation is uncovered should be limited and proper safety instructions and means for escape need to be provided. Otherwise it is recommended that the apartments should not be occupied.

10. Summary

Effect of EPS insulation used in external wall to the fire safety of the building has been studied by using fire safety engineering to assess required protective methods. The EPS insulation systems have defined rendering setups as outer layer (External Thermal Insulation Composite Systems, ETICS) and fire stops/barriers (at least A2-s1, d0 mineral wool) in the insulation layer. The study covers residential multi-storey buildings up to eight stories with the main emphasis on the safety of people in everyday use. In addition, an assessment concerning the construction or renovation time has been done.

The analysis focused on fires starting inside of buildings and used data on room areas and fire loads of typical dwellings in multi-storey buildings. It was assumed that distance between buildings will be at least 8 m and thus fires in neighbouring buildings were not considered. External ignitions do not cause more severe exposures on the facade than flashover room fires. Thus, the extent of their effects is considered to be covered by the fires started inside.

In this study fire risk analysis was used utilising also statistical data on e.g. ignition frequencies and spread of fires to facades. Modelling of the spreading of a flash-over room fire included the development of fire in the room-of-fire-origin, spreading through breaking window to the facade and external flaming. Using the Monte Carlo technique, the probabilities of the spread of the fire to apartments above the room-of-fire-origin were assessed on the basis of the magnitude of the heat exposure caused by the external flaming both for the EPS insulated facade and for at least A2-s1, d0 facade. Also detection of fire, first-aid extinguishing, self-extinction as well as fire brigade intervention were taken into account in the analysis. Finally, the calculated overall probabilities were compared with data from fire statistics.

The analysis of fires spreading from the room of fire origin through window to the façade and breaking windows of apartments above included also a sensitivity analysis of the used input data and effects of building geometries. The following parameters were studied: Heat release from the rendering protected EPS, window breaking criteria, distance of window edge from an inner corner of a building, width of fire room window, height of the fire room window, fire load density of the apartment, effects of balconies and exit applications, and fire stops/barriers in different façade layouts.

The estimated maximum overall probabilities for window breaking at floors above the fire room were about 2 % which is in agreement with statistical data. About 85 % of these window breaking cases occur one floor above the fire room and only about 15 % two floors above.

Taking into account uncertainties and sensitivity analysis it was estimated that there is a small difference between the two façade types: The overall window break probability in the floors above for EPS ETICS façade is 2.3 % and for at least A2-s1, d0 façade 1.9 % per ignited fire. The estimated overall probability values for the window breaking in the floors above are on the upper limit compared to statistical data for which conservative values were used. Thus a safety factor is included in the results.

Concerning consequences for life safety the fire death probability was found to be not more than 10^{-6} per building fire (0.8×10^{-6} for at least A2-s1, d0 façade and 1.0×10^{-6} for EPS ETICS systems). When this value is compared with tolerable limit of F-N-curves (probability of an event and consequences in terms of number of deaths), it can be concluded that life safety objectives are reached.

Structural detailing of the façade system and the associated constructions are of essential importance in decreasing fire hazards and potential property losses. The analysis of effects by inner corners indicated that it is unlikely that the rendering protected EPS ignites under room fire exposure if the window edge is at least 1 m from the corner wall. Another result was that two floors above no window was broken when the fire room window width was maximum 1.5 m. Simulations with 1.8 m window height showed that total burning times became shorter and flame heights were increased causing increased maximum heat fluxes at the windows above (about 10 % increase at second floor and about 20 % increase at third floor compared to 1.4 m high window) for at least A2-s1, d0 facades. This increase can cause no more than 10 % increase in the window breaking probabilities which is within the statistical uncertainties of the results. Similar changes are applicable also for EPS ETICS systems.

For recessed balconies fire safety requirements of internal walls and ceilings are recommended to be applied and for corridor type escape routes fire safety requirements of exits are recommended to be used.

The main principles and actions concerning construction site fire safety for the time when EPS is uncovered during installation phase can be summarised as follows: a)Reduce the risks of ignition by minimizing the use of flammable liquids and gases and the amount of fire load, b) follow the hot work instructions, c) make sure that everybody involved understands all fire safety instructions, and d) if the apartments are occupied during the installation process, limit the time EPS insulation is uncovered and provide proper safety instructions and means for escape.

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Appendix A: Example input file for FDS version 6

```
&HEAD CHID = 'EPS_room_fire_EPS_182' TITLE = 'Room fire for EPS facades project' / '

&MESH IJK= 29 27 40 XB =  -3 2.74 0 5.5 0 8 /

&TIME T_END = 3600 DT =  0.005 /

&ZONE XB =  -0.2 2.74 0 5.5 0 2.5 LEAK_AREA(0) =  0.2 /

&DUMP DT_RESTART = 3500 /

&REAC ID = 'PROPANE'  FUEL =  'PROPANE' SOOT_YIELD =  0.05 /

ceiling
&OBST XB =  0 2.74 0 5.5 2.5 2.7
 SURF_ID6 =  'INERT' 'INERT' 'INERT' 'INERT' 'WALL' 'INERT' / ceiling

 Outside open boundaries

&VENT XB = -3 -0.2 0 5.5 0 0 SURF_ID = 'OPEN' / down
&VENT XB = -3 -0.2 5.5 5.5 0 8 SURF_ID = 'OPEN' / left
&VENT XB = -3 -0.2 0 0 0 8 SURF_ID = 'OPEN' / right

&VENT MB =   'XMIN' SURF_ID =  'OPEN' /
&VENT MB =   'ZMAX' SURF_ID =  'OPEN' /

 Wall to outside
 Mesh 1
&OBST XB = -0.2 0 0 5.5 0 8 SURF_ID = 'WALL_OUT_WOOL' /
&VENT XB =  0 0 0 5.5 3.5 8 SURF_ID =  'WALL_UP' IOR = 1 /

 Window
&HOLE XB = -0.3 0.1 1.43 3.88 0.8 2.08 CTRL_ID =  'Time_delay' /
&VENT XB =  -0.2 -0.2 1.43 3.88 3.6 5 SURF_ID =  'WINDOW' IOR =  -1 /
&VENT XB =  -0.2 -0.2 1.43 3.88 6.4 7.8 SURF_ID =  'WINDOW' IOR =  -1 /

 EPS fire
&VENT XB =  -0.2 -0.2 1.43 3.88 2.08 3.6 SURF_ID =  'EPS_FIRE' IOR =  -1 CTRL_ID=  'EPS_CTRL_1' /
&VENT XB =  -0.2 -0.2 1.43 3.88 5 6.4 SURF_ID =  'EPS_FIRE' IOR =  -1 CTRL_ID=  'EPS_CTRL_2' /

&SURF ID=  'EPS_FIRE' HRRPUA =  50 /


&SURF ID = 'WINDOW'
 MATL_ID = 'GLASS'
 THICKNESS = 0.04
 COLOR = 'SLATE GRAY'
 BACKING =  'EXPOSED' /

 Walls are made of gybsum board

&SURF ID = 'WALL'
 MATL_ID = 'GYPSUM_BOARD'
 THICKNESS = 0.013
 DEFAULT = .TRUE.
 COLOR = 'SEPIA'
 BACKING =  'INSULATED'
 LEAK_PATH =  1,0 /

&SURF ID = 'WALL_OUT_EPS'
 MATL_ID(1,1) = 'GYPSUM_BOARD'
 MATL_ID(2,1) =  'EPS'
 MATL_ID(3,1) =  'GYPSUM_BOARD'
 THICKNESS = 0.006 0.2 0.006
 BACKING =  'EXPOSED'
 COLOR = 'SLATE GRAY' /

&SURF ID = 'WALL_OUT_WOOL'
 MATL_ID(1,1) = 'GYPSUM_BOARD'
 MATL_ID(2,1) =  'ROCK_WOOL'
 MATL_ID(3,1) =  'GYPSUM_BOARD'
 THICKNESS = 0.006 0.2 0.006
 BACKING =  'EXPOSED'
```

```
 COLOR = 'SILVER' /

&SURF ID = 'WALL_UP'
 MATL_ID(1,1) = 'GYPSUM_BOARD'
 THICKNESS = 0.006
 BACKING =  'INSULATED'
 COLOR = 'BEIGE'
 LEAK_PATH =  1,0 /

 Floors and ceiling are made of chip board

&MATL ID = 'GYPSUM_BOARD'
 DENSITY = 940
 EMISSIVITY = 0.9
 CONDUCTIVITY = 0.17
 SPECIFIC_HEAT = 0.9 /

&RAMP ID =  'k_ramp' T = 20 F = 0.166 /
&RAMP ID =  'k_ramp' T = 360 F = 0.216 /

&RAMP ID =  'c_ramp' T = 20 F = 1.208 /
&RAMP ID =  'c_ramp' T = 600 F = 4.05 /

&MATL ID = 'GLASS'
 DENSITY = 2500
 EMISSIVITY = 0.92
 CONDUCTIVITY = 1
 SPECIFIC_HEAT = 0.84 /

&MATL ID = 'ROCK_WOOL'
 DENSITY = 160
 EMISSIVITY = 1
 CONDUCTIVITY = 0.04
 SPECIFIC_HEAT = 1 /

&MATL ID = 'EPS'
 DENSITY = 20
 EMISSIVITY = 1
 CONDUCTIVITY = 0.03
 SPECIFIC_HEAT = 1.13 /

 Fire in the room
&VENT XB = 0 2.74 0 5.5 0 0 SURF_ID = 'FIRE' IOR =   3 / floor
&VENT XB = 0 0 0 5.5 0 0.6 SURF_ID = 'FIRE' IOR =   1 / wall of the window
&VENT XB = 2.74 2.74 0 5.5 0 1.6 SURF_ID = 'FIRE' IOR =   -1 / wall opposite to window
&VENT XB = 0 2.74 0 0 0 1.6 SURF_ID = 'FIRE' IOR =   2 / side walls
&VENT XB = 0 2.74 5.5 5.5 0 1.6 SURF_ID = 'FIRE' IOR =   -2 / side walls


&SURF ID = 'FIRE' COLOR =  'ORANGE RED' HRRPUA = 257.974212585699 RAMP_Q =  'fire_ramp' / A =  35.67 m2
&RAMP  ID =  'fire_ramp' T =  0 F =  0 / A =  36.3857931034483 m2
&RAMP  ID =  'fire_ramp' T =  1772.21663303347 F =  1 / Q =  808.201870603351 MJ/m2
&RAMP  ID =  'fire_ramp' T =  2672.21663303347 F =  0 /

 Breaking window
&DEVC XB = -0.2 0.2 1.43 3.88 0.8 2.08 STATISTICS =  'MAX' QUANTITY =  'WALL TEMPERATURE'
 SETPOINT =  500 ID =  'T_window' / devc 1

&CTRL ID =  'Time_delay' INPUT_ID = 'T_window' FUNCTION_TYPE =  'TIME_DELAY'
 INITIAL_STATE =  .FALSE. DELAY =  135.17008233555 /

&CTRL ID =  'EPS_CTRL_1' INITIAL_STATE =  .FALSE. INPUT_ID =  'EPS_start_1' 'EPS_stop_1' FUNCTION_TYPE =  'ALL' LATCH =  .FALSE. /
&CTRL ID =  'EPS_CTRL_2' INITIAL_STATE =  .FALSE. INPUT_ID =  'EPS_start_2' 'EPS_stop_2' FUNCTION_TYPE =  'ALL' LATCH =  .FALSE. /

&CTRL ID =  'EPS_start_1' INITIAL_STATE =  .FALSE. INPUT_ID =  'EPS_hf_1' 'EPS_start_delay_1' FUNCTION_TYPE =  'ALL' LATCH =  .TRUE. /
&CTRL ID =  'EPS_start_2' INITIAL_STATE =  .FALSE. INPUT_ID =  'EPS_hf_2' 'EPS_start_delay_2' FUNCTION_TYPE =  'ALL' LATCH =  .TRUE. /

&CTRL ID =  'EPS_hf_1' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_1' FUNCTION_TYPE =  'ALL' LATCH =  .FALSE. /
&CTRL ID =  'EPS_hf_2' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_2' FUNCTION_TYPE =  'ALL' LATCH =  .FALSE. /

&CTRL ID =  'EPS_start_delay_1' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_1' FUNCTION_TYPE = 'TIME_DELAY' DELAY =  180 LATCH =
.TRUE. /
&CTRL ID =  'EPS_start_delay_2' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_2' FUNCTION_TYPE = 'TIME_DELAY' DELAY =  180 LATCH =
.TRUE. /

&CTRL ID =  'EPS_stop_delay_1' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_1' FUNCTION_TYPE = 'TIME_DELAY' DELAY =  1080 LATCH =
.TRUE. /
```

```
&CTRL ID =  'EPS_stop_delay_2' INITIAL_STATE =  .FALSE. INPUT_ID =  'hf_max_w_2' FUNCTION_TYPE = 'TIME_DELAY' DELAY =  1080 LATCH =
.TRUE. /

&CTRL ID =  'EPS_stop_1' INITIAL_STATE =  .TRUE. INPUT_ID =  'EPS_stop_delay_1' FUNCTION_TYPE =  'ALL' LATCH =  .TRUE. /
&CTRL ID =  'EPS_stop_2' INITIAL_STATE =  .TRUE. INPUT_ID =  'EPS_stop_delay_2' FUNCTION_TYPE =  'ALL' LATCH =  .TRUE. /

 Gas temperatures outside the window
&DEVC ID =  'T_gas_outside_m_1' XYZ =  -0.4 2.75 0.2 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 2 T_gas_outside_m_ 1 '
&DEVC ID =  'T_gas_outside_m_2' XYZ =  -0.4 2.75 1.2 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 3 T_gas_outside_m_ 2 '
&DEVC ID =  'T_gas_outside_m_3' XYZ =  -0.4 2.75 2.2 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 4 T_gas_outside_m_ 3 '
&DEVC ID =  'T_gas_outside_m_4' XYZ =  -0.4 2.75 3.6 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 5 T_gas_outside_m_ 4 '
&DEVC ID =  'T_gas_outside_m_5' XYZ =  -0.4 2.75 4.6 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 6 T_gas_outside_m_ 5 '
&DEVC ID =  'T_gas_outside_m_6' XYZ =  -0.4 2.75 5.6 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 7 T_gas_outside_m_ 6 '
&DEVC ID =  'T_gas_outside_m_7' XYZ =  -0.4 2.75 6.4 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 8 T_gas_outside_m_ 7 '
&DEVC ID =  'T_gas_outside_m_8' XYZ =  -0.4 2.75 7.9 IOR =  1 QUANTITY =  'TEMPERATURE' / devc 9 T_gas_outside_m_ 8 '


&SLCF QUANTITY =  'TEMPERATURE' PBX =  -1.9 /
&SLCF QUANTITY =  'TEMPERATURE' PBX =  -0.4 /
&SLCF QUANTITY =  'TEMPERATURE' PBX =  0.2 /
&SLCF QUANTITY =  'TEMPERATURE' PBX =  2.54 /
&SLCF QUANTITY =  'TEMPERATURE' PBY =  2.75 /
&SLCF QUANTITY =  'TEMPERATURE' PBZ =  0.2 /
&SLCF QUANTITY =  'TEMPERATURE' PBZ =  1 /
&SLCF QUANTITY =  'TEMPERATURE' PBZ =  2 /
&SLCF QUANTITY =  'TEMPERATURE' PBZ =  4.3 /
&SLCF QUANTITY =  'TEMPERATURE' PBZ =  7.1 /


 Oxygen content in the room
&SLCF QUANTITY =  'MASS FRACTION' PBX =  -1.9 SPEC_ID =  'OXYGEN' /
&SLCF QUANTITY =  'MASS FRACTION' PBY=  -0.4 SPEC_ID =  'OXYGEN' /
&SLCF QUANTITY =  'MASS FRACTION' PBZ =  0.5 SPEC_ID =  'OXYGEN' /
&SLCF QUANTITY =  'MASS FRACTION' PBZ =  2.54 SPEC_ID =  'OXYGEN' /
&SLCF QUANTITY =  'MASS FRACTION' PBZ =  0.2 SPEC_ID =  'OXYGEN' /

&SLCF QUANTITY =  'PRESSURE' PBX =  -1.9 /
&SLCF QUANTITY =  'PRESSURE' PBY =  -0.4 /
&SLCF QUANTITY =  'PRESSURE' PBZ =  1 /

 Fire detectors
&DEVC ID =  'heat_1' XYZ =  1.37 2.75 2.3 PROP_ID =  'heat' / ' devc 10 heat_ 1
&DEVC ID =  'heat_2' XYZ =  2.54 2.75 2.3 PROP_ID =  'heat' / ' devc 11 heat_ 2
&DEVC ID =  'heat_3' XYZ =  1.37 5.3 2.3 PROP_ID =  'heat' / ' devc 12 heat_ 3
&DEVC ID =  'heat_4' XYZ =  1.37 0.2 2.3 PROP_ID =  'heat' / ' devc 13 heat_ 4

&DEVC ID =  'smoke_1' XYZ =  1.37 2.75 2.3 PROP_ID =  'smoke' / ' devc 14 smoke_ 1
&DEVC ID =  'smoke_2' XYZ =  2.54 2.75 2.3 PROP_ID =  'smoke' / ' devc 15 smoke_ 2
&DEVC ID =  'smoke_3' XYZ =  1.37 5.3 2.3 PROP_ID =  'smoke' / ' devc 16 smoke_ 3
&DEVC ID =  'smoke_4' XYZ =  1.37 0.2 2.3 PROP_ID =  'smoke' / ' devc 17 smoke_ 4

&PROP ID =  'heat' QUANTITY =  'LINK TEMPERATURE' RTI =  150 ACTIVATION_TEMPERATURE =  74 /

&PROP ID =  'smoke' QUANTITY =  'CHAMBER OBSCURATION' LENGTH =  1.8 ACTIVATION_OBSCURATION =  3.24 /

 Heat flux -----------------------------
&BNDF QUANTITY =  'NET HEAT FLUX'  /
 Middle
&DEVC ID =  'hf_m_w_1' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 2.475 / ' hf_m_w_ 1 devc 18
&DEVC ID =  'hf_m_w_2' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 2.85 / ' hf_m_w_ 2 19
&DEVC ID =  'hf_m_w_3' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 3.225 / ' hf_m_w_ 3 20
&DEVC ID =  'hf_m_w_4' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 5.35 / ' hf_m_w_ 4 21
&DEVC ID =  'hf_m_w_5' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 5.7 / ' hf_m_w_ 5 22
&DEVC ID =  'hf_m_w_6' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 6.05 / ' hf_m_w_ 6 23
&DEVC ID =  'hf_m_w_7' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 7.9 / ' hf_m_w_ 7 24

 Middle glass
&DEVC ID =  'hf_m_g_1' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 3.95 / ' hf_m_g_ 1 devc 25
&DEVC ID =  'hf_m_g_2' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 4.3 / ' hf_m_g_ 2 26
&DEVC ID =  'hf_m_g_3' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 4.65 / ' hf_m_g_ 3 27
&DEVC ID =  'hf_m_g_4' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 6.75 / ' hf_m_g_ 4 28
&DEVC ID =  'hf_m_g_5' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 7.1 / ' hf_m_g_ 5 29
&DEVC ID =  'hf_m_g_6' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 2.75 7.45 / ' hf_m_g_ 6 30
 Sides
&DEVC ID =  'hf_l_1' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 5.4 1.45 / ' hf_l_ 1 31
&DEVC ID =  'hf_l_2' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 5.4 4.3 / ' hf_l_ 2 32
&DEVC ID =  'hf_l_3' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 5.4 7.1 / ' hf_l_ 3 33
&DEVC ID =  'hf_r_1' QUANTITY =  'NET HEAT FLUX'  IOR =  -1 XYZ =  -0.2 0.1 1.45 / ' hf_r_ 1 34
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&DEVC ID = 'hf_r_2' QUANTITY = 'NET HEAT FLUX'  IOR = -1 XYZ = -0.2 0.1 4.3 / ' hf_r_ 2 35
&DEVC ID = 'hf_r_3' QUANTITY = 'NET HEAT FLUX'  IOR = -1 XYZ = -0.2 0.1 7.1 / ' hf_r_ 3 36

&DEVC ID = 'hf_max_w_1' QUANTITY = 'NET HEAT FLUX'  STATISTICS = 'MAX' IOR = -1 INITIAL_STATE = .FALSE.
 XB = -0.3 -0.1 1.43 3.88 2.08 3.6 SETPOINT = 35 LATCH= .FALSE. / devc 37
&DEVC ID = 'hf_max_w_2' QUANTITY = 'NET HEAT FLUX'  STATISTICS = 'MAX' IOR = -1 INITIAL_STATE = .FALSE.
 XB = -0.3 -0.1 1.43 3.88 5 6.4 SETPOINT = 35 LATCH= .FALSE. / devc 38
&DEVC ID = 'hf_max_w_3' QUANTITY = 'NET HEAT FLUX'  STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 7.8 8 / devc 39

&DEVC ID = 'hf_max_g_1' QUANTITY = 'NET HEAT FLUX'  STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 3.6 5 / devc 40
&DEVC ID = 'hf_max_g_2' QUANTITY = 'NET HEAT FLUX'  STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 6.4 7.8 / devc 41

 Wall Temperature
&BNDF QUANTITY = 'WALL TEMPERATURE' /

 Middle
&DEVC ID = 'T_wall_m_w_1' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 2.475 / ' T_wall_m_w_ 1 devc 42
&DEVC ID = 'T_wall_m_w_2' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 2.85 / ' T_wall_m_w_ 2 43
&DEVC ID = 'T_wall_m_w_3' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 3.225 / ' T_wall_m_w_ 3 44
&DEVC ID = 'T_wall_m_w_4' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 5.35 / ' T_wall_m_w_ 4 45
&DEVC ID = 'T_wall_m_w_5' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 5.7 / ' T_wall_m_w_ 5 46
&DEVC ID = 'T_wall_m_w_6' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 6.05 / ' T_wall_m_w_ 6 47
&DEVC ID = 'T_wall_m_w_7' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 7.9 / ' T_wall_m_w_ 7 48

 Middle glass
&DEVC ID = 'T_wall_m_g_1' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 3.95 / ' T_wall_m_g_ 1 devc 49
&DEVC ID = 'T_wall_m_g_2' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 4.3 / ' T_wall_m_g_ 2 50
&DEVC ID = 'T_wall_m_g_3' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 4.65 / ' T_wall_m_g_ 3 51
&DEVC ID = 'T_wall_m_g_4' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 6.75 / ' T_wall_m_g_ 4 52
&DEVC ID = 'T_wall_m_g_5' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 7.1 / ' T_wall_m_g_ 5 53
&DEVC ID = 'T_wall_m_g_6' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 2.75 7.45 / ' T_wall_m_g_ 6 54

 Sides
&DEVC ID = 'T_w_l_1' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 5.4 1.45 / ' T_w_l_ 1 55
&DEVC ID = 'T_w_l_2' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 5.4 4.3 / ' T_w_l_ 2 56
&DEVC ID = 'T_w_l_3' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 5.4 7.1 / ' T_w_l_ 3 57
&DEVC ID = 'T_w_r_1' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 0.1 1.45 / ' T_w_r_ 1 58
&DEVC ID = 'T_w_r_2' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 0.1 4.3 / ' T_w_r_ 2 59
&DEVC ID = 'T_w_r_3' QUANTITY = 'WALL TEMPERATURE' IOR = -1 XYZ = -0.2 0.1 7.1 / ' T_w_r_ 3 60

&DEVC ID = 'T_w_max_w_1' QUANTITY = 'WALL TEMPERATURE' STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 2.08 3.6 / devc 61
&DEVC ID = 'T_w_max_w_2' QUANTITY = 'WALL TEMPERATURE' STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 5 6.4 / devc 62
&DEVC ID = 'T_w_max_w_3' QUANTITY = 'WALL TEMPERATURE' STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 7.8 8 / devc 63

&DEVC ID = 'T_w_max_g_1' QUANTITY = 'WALL TEMPERATURE' STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 3.6 5 / devc 64
&DEVC ID = 'T_w_max_g_2' QUANTITY = 'WALL TEMPERATURE' STATISTICS = 'MAX' IOR = -1
 XB = -0.3 -0.1 1.43 3.88 6.4 7.8 / devc 65

 hrr -------------------------------------------
&SLCF PBX = -0.3 QUANTITY = 'HRRPUV'  /
&SLCF PBX = -1.3 QUANTITY = 'HRRPUV'  /
&SLCF PBX = -2.3 QUANTITY = 'HRRPUV'  /
&SLCF PBY = 2.75 QUANTITY = 'HRRPUV'  /

&DEVC XB = -0.6 -0.2 1.43 3.88 0.8 2.08 QUANTITY = 'HRR' ID = 'HRR_window' / devc 66 window area
&DEVC XB = -0.6 -0.2 0 5.5 0 2.5 QUANTITY = 'HRR' ID = 'HRR_mesh_1' / devc 67 whole wall of mesh 1
&DEVC XB = -3 -0.2 0 5.5 0 8 QUANTITY = 'HRR' ID = 'HRR_all_outside' / devc 68

&TAIL /
```