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Indoor climate of single-family house constructed by use of glued solid wood elements

In-situ measurements and calculations

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Wood Technology – Træteknik

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Preface

Solid wood elements are a relatively novel type of products on the market for building construction materials. Hence, there has been a need on behalf of the whole chain in the building material industry to develop, research in and provide documentation for the properties of the products. This need is formulated as a quest for development, research and subsequent documentation with regard to marketing on behalf of the producers, a desire for accredited documentation on behalf of the counselling engineers with regard to the physical and mechanical design, a wish for product standards on behalf of the technical laboratories involved in the certification process and a general quest for documentation and answers to basic questions from the end consumers. In sum, this documentation targets the six essential requirements of the European Construction Products Directive.

This report contributes to the documentation for the requirement relating to hygiene, health and the environment. The report contains results from in-situ measurements of emissions in a single-family house constructed with large, exposed inner surfaces of glued solid elements. The in-situ measurements are supplemented with laboratory determination of the emissions from the used construction products. The in-situ measured emissions and the theoretical emission based on the laboratory measurements are compared. These results enter the package of documentation that shall be used for establishing product standards for solid wood elements.

The work has been carried out at Danish Technological Institute, Wood Technology, in the period August 2001 to May 2002. The work is part of a Nordic research and development project for solid wood elements in building constructions “Massivträelement”. This project is co-funded by the Nordic Industrial Fund through the Nordic Wood Programme (Project P00023), the national Danish activities have been co-funded by the Danish Ministry of the Enviromment, through the sector support given by “Produktudviklingsordningen for Skov- og Træindustri”.

Summary

An evaluation of the emissions of volatile organic compounds and formaldehyde in the indoor climate of a single-family house constructed with large exposed glued solid wood elements inner surfaces has been carried out. The emissions are both determined by in-situ measurement and based by calculation based on laboratory measurements, the latter performed in accordance with the requirements in (EN 717-1,1998).

The main findings are that the concentration of formaldehyde is well below the WHO guideline value of 100µg/m^3 given in (World Health Organisation, 2000).

The concentration of the measured remaining aldehydes and the measured terpenes is well below the threshold values suggested by Nordic Committee on Building Regulations, given in (Nielsen et al., 1996).

An acceptable correspondence was observed between in-situ measurement and calculated values for formaldehyde emissions. This supports the requirements for formaldehyde emission which in the product standards (prEN 14080 (DRAFT), 2000) and (EN 13986, 2001) is formulated by use of (EN 717-1,1998).

The results serve generally to enhance the knowledge of the in-situ effect of emissions from wood-based products used in building constructions with very large free inner surfaces. This result will be used as background material with respect to transferring the current requirements for formaldehyde emissions from wood panel products and glued laminated timber, given in Annex B of (prEN 14080 (DRAFT), 2000) and (EN 13986, 2001) to a proposal for product standard for glued solid wood elements, (Clorius & Adelhøj, 2002).

Resumé

Der er foretaget en bestemmelse af emissionen af formaldehyd og flygtige organiske forbindelser (VOC'er) i det indendørs klima i et enfamiliehus, som er konstrueret med limede massive elementer, og som i den færdige konstruktion har store indre overflader med frit eksponerede limede massive træelementer. Emissionerene er bestemt såvel ved målinger in-situ som ved beregninger baseret på laboratorie-målinger af emissioner fra de anvendte byggematerialer. Laboratoiremålingerne af formaldehydemissionen er foretaget i overensstemmelse med kravene i (EN 717-1,1998). De laboratoriemålte formaldehydemissionshastigheder er rapporteret i (Funch, 2002) og er i nærværende rapport blevet anvendt til at bestemme den teoretiske emission i huset.

Hovedresultatet er, at koncentrationen af formaldehyd er et stykke under WHO vejledningen, der angiver en værdi på 100 µg/m³ (WHO Health Organisation, 2000).

Koncentrationen af de resterende målte aldehyder og de målte terpener er et stykke under tærskelværdierne foreslået af "Den Nordiske Kommission vedrørende Byggeregulativer" anført i (Nielsen et al., 1996).

Der blev observeret en acceptabel overensstemmelse mellem in-situ målingerne og de beregnede værdier for formaldehydemissionen. Dette understøtter kravene for formaldehydemissioner, som i produktstandarderne (prEN 14080 (DRAFT), 2000) og (EN 13986, 2001) er formulerede med henvisning til (EN 717-1,1998).

Resultatet tjener både til at øge den generelle viden om emissionerne fra træbaserede produkter, anvendt med meget store frie overflader i boligers indre, herudover vil resultatet indgå i det baggrundsmateriale, der kan bruges til at validere brugen af formaldehydemissionskravene for træbaserede produkter og limtræ, som de fremgår af Annex B til (prEN 14080 (DRAFT), 2000), i et forslag til en produktstandard for limede massive træelementer (Clorius & Adelhøj, 2002).

1. Background and scope

Wood is known to contain and emit Volatile Organic Compounds (VOCs) which can be demonstrated by the fact that wood smells. Wood products for the building- and furniture industry are often a combination of wood and the materials added e.g. adhesive.

Emissions from solid wood are mostly terpenes and aldehydes. When glue are added to the wood material, other compounds as formaldehyde and aromatic hydrocarbons may be emitted from the wood-based material.

Where formaldehyde-containing materials, particularly aminoplastic resins, have been added to wood-based materials as a part of the production process, the product shall be tested and classified into one of the two emission classes: E1 or E2 according to (EN 13986, 2001) for wood-based panels and (prEN 14080 (DRAFT), 2000) for glued laminated timber. These classes are part of the normative requirements stated in Annex B of both standards. When tested in accordance with (EN 717-1,1998), the limit value for class E1 is $\leq$ 0,124 mg/m^3 air, and the limit value for class E2 is $\geq$ 0,124 mg/m^3 air according to (EN 13986, 2001) and (prEN 14080 (DRAFT), 2000).

In the latest version of the harmonised standard for glued laminated timber (prEN 14080, 2002) deviations from (EN 717-1,1998) regarding test criteria are required. These deviations correspond to a lower material load. To maintain consistency with the body of standards the testing has been made corresponding to the requirement of (prEN 14080 (DRAFT), 2000).

The Danish building regulation (Bygningsregelement, 1995) states general performance requirement with respect to emissions: Building materials must not emit vapours and gasses, which can give an unsatisfactory indoor environment. For formaldehyde emissions quantified requirements similar to those in (prEN 14080 (DRAFT), 2000) and (EN 13986, 2001) are given.

The use of glued solid wood elements in constructions entails that the volume of wood present in the construction is larger compared to traditional post and beam timber constructions. Where the solid wood elements have free exposed surfaces, these can contribute considerably with emissions to the indoor air in both offices and dwellings. Therefore, the overall purpose of the project is to document the influence of large volumes and/or large exposed areas of solid wood elements on the indoor environment.

This report give the results of the in-situ measurements and a theoretical calculation of the expected indoor concentrations based on laboratory results (Funch, 2002).

The present report and the results in (Funch, 2002) establishes the background for the recommendations with regard to emission classes for glued solid wood elements that are given in the proposal for a product standard (Clorius & Adelhøj, 2002).

2. Scope of testing

The scope of the testing is to evaluate the calculated and measured emission of formaldehyde and volatile organic compounds in a single family house constructed by and having large free exposed inner surfaces of glued solid wood elements in the final design.

The results shall be used in a general context of assessing new product types with respect to the six essential requirements of the CPD (BEK nr 118 af 16/02/1998). In a more specific context the scope is to assess the validity of transferring the requirements for emission for glued laminated timber of Annex B in (prEN 14080 (DRAFT), 2000) to the proposed product standard for glued solid wood elements (Clorius & Adelhøj, 2002).

The calculation of the expected indoor air concentrations is based on the quantitative chemical analysis of the emissions from Melamine-Urea-Formaldehyde glued solid wood elements, tested in climate chamber according to (EN 717-1,1998) reported in (Funch, 2002). To obtain additional information regarding emissions from the construction, samples of the concrete floor and an expansion joint for windows and doors were tested likewise

The calculation of the theoretical concentrations in the indoor environment is carried out by use of the actual data for free exposed glued solid wood element surface area and the volume of the house. The calculation is carried out at two conditions of air change rate with values of 0.5 and 1.0 air change per hour.

3. Test object and test material

3.1 Test object – single-family house

3.1.1 Construction principle

The house is a two-storey dwelling with approximate principal dimensions of 7x12 m the first floor has cathedral ceiling directly to the 22,5° sloping roof. The static design uses three primary load-carrying glulam portal frames c-c 6 m and a secondary load carrying system of 400 mm wide glued solid wood elements of varying thickness. For the roof 120 mm elements is used carrying between the frames. For the deck a 120 mm element in composite action with a 80 mm concrete layer carrier from facade to facade is used. For the facades and gables a 95 mm element is used with stabilising and inner cladding functions. All inner surfaces in the house have freely exposed glued solid wood elements in direct contact with indoor air, Figure 1 and Figure 2, except the floors, which are concrete surfaces.

Figure 1: View of ground floor in staircase area.

Figure 2: View of first floor living room.

3.1.2 Materials

The materials, which form the largest freely exposed surfaces in the house are solid wood elements glued with Melamine Urea Formaldehyde and concrete.

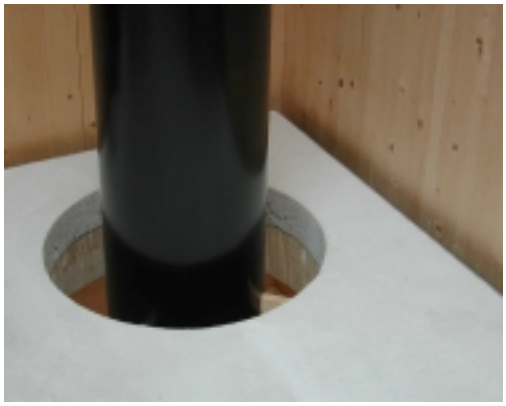

Figure 3: View of deck from first floor the composite construction is visible.

Figure 4: Cross-sectional view of glued solid wood elements with the used tongue groove connection.

3.1.3 Surfaces and volumes

The main geometrical data for the dwelling are summarised in Table 1 and Table 2.

Table 1: Area summary for inside freely exposed MUF glued solid wood surfaces and concrete decking.

Outer walls incl. gables inside surface	101,0 m^2
Roof - ceiling surface 1st floor	74,0 m^2
Deck - ceiling surface ground floor (same area for concrete deck)	76,3 m^2
Partition walls (double sided surface)	131,3 m^2
sleeping platform deck (double sided surface)	33,0 m^2
Total inside exposed MUF glued surface solid wood surface	415,6 m^2

Table 2: Volume summary for inside volume of house.

Volume 1st floor	290 m^3
Volume ground floor	195 m^3
Total inside volume	485 m^3

3.2 Test material for laboratory tests

Laboratory tests by the chamber method in accordance with (EN 717-1,1998) were carried out on the following samples:

- Two test pieces of melamine urea formaldehyde glued solid wood elements, one delivered from the building site, and one additionally delivered directly from the producer, Lilleheden - Limtræ Danmark A/S. The chamber test on the first sample was carried out in July 2001 and on the latter tests were made in May 2002.

- A test piece of the floor concrete used both on ground floor and 1st floor was poured at the building site in June 2001. The chamber test on this sample was carried out in August 2001.

- Additionally, a chamber test of the expansion joint used around windows and doors was carried out in February 2002.

4. Test methods

4.1 In-situ measurements

The first measurement in the house was planned to take place immediately after construction when the house was ready for occupation but before actual moving in. In this way, it was ensured that the measured volatile chemical substances originated from the construction only. The construction was, however, delayed and the family had moved in before the construction was finished. The outer walls and the skylight was not mounted, Figure 5 and Figure 6. This gave a high air change rate at the time of first measurement. Furthermore, the deck of the sleeping platform and none of the partition walls were installed. The first measurement was carried out in August 2001.

Figure 5: External view of the house at time of first measurement.

Figure 6: Internal view of the house at time of first measurement.

The second measurement took place in January 2002. The construction of the house was finalised and outer walls, skylight, partition walls and sleeping platform were mounted. Air samples were taken in duplicate in the kitchen on the ground floor and in the living room on 1st floor.

Samples were taken for analysis of formaldehyde, aldehydes and VOCs. Formaldehyde was sampled in distilled water and determined fluoremetrically by the acetylacetone method according to (EN 717-1,1998) which is the same standard used for the laboratory chamber measurements on the materials, reported in (Funch, 2002).

Other aldehydes were sampled on Sep-pack-tubes (C_{18} polymers, coated with 2.4-dinitrophenylhydrazin), and after elution with acetonitrile analysed by HPLC (high-pressure-liquid-chromatography) with UV-detection.

VOCs were sampled on Tenax, thermally desorbed and analysed by GC-MS (gas-chromatography with mass-spectrometric detection) after addition of internal standards.

4.2 Laboratory tests

The chamber tests were performed according to (EN 717-1,1998). A description of the test method and the results of the laboratory analysis of the Melamine-Urea-Formaldehyde glued samples are given in (Funch, 2002).

4.3 Theoretically determined emission

The concentration of chemical compounds measured in the test chamber is converted to a concentration in the indoor environment by use of the surface and volume data. The expected concentration in the indoor air is calculated according to the expression given in (1). In the expression it is assumed that the emission rates in the test chamber and in the house are comparative, and the method (1) does not consider the influence of air temperature and relative humidity.

$$C_h = C_c \frac{n_c}{n_h} \frac{L_h}{L_c}, \quad (1)$$

where:

C_h is the concentration in the house, µg/m^3
C_c is the concentration measured in the test chamber, µg/m^3
n_c is the air change rate in the chamber, h^{-1}
n_h is the air change rate in the house, h^{-1}
L_h is the material loading in the house, m^2/ m^3
L_c is the material loading in the test chamber, m^2/ m^3

5. Results

5.1 Results of in-situ measurements

The results from the first and second on-site measuring are given in Table 3 with the following comments:

- On the day of first sampling the air temperature was 18°C, and the relative humidity 65 %. Due to the exceptional high air exchange rate, air samples were taken only in the kitchen on the ground floor.

- On the day of the second sampling the temperature was 20°C and the relative humidity 51 %. Two days before the second measurement a failure in the chimney outlet from the wood stove caused black smoke in the house from wood combustion.

Table 3: Results of in-situ measurements

	First measuring	Second measuring		
Chemical compound	Kitchen 2001.08.07 [µg/m^3]	Kitchen 2002.01.17 [µg/m^3]	Living room 2002.01.17 [µg/m^3]	Threshold value for odour [µg/m^3]
Aldehydes				
Formaldehyde	25	61	64	150#
Acetaldehyde	18	68	70	340
Propanal	6	9	9	14
Butanal	1	3	2	28
Pentanal	12	14	16	22
Hexanal	35	40	41	58
Octanal	<1	8	8	7
Furaldehyde	<1	3	3	
Benzaldehyde	4	3	4	186
Sum of aldehydes	101	209	217	
Ketones				
Acetone	38	78	83	14000
Alcohols				
Butanol	<1	11	12	90
Pentanol	5	3	3	20
Sum of alcohols	5	14	15	
Alifatic Hydrocarb.				
C10-C16	9	580	600	7760 (C11)
Aromatic hydrocarb.				
Toluene	8	12	13	644
Xylene/ethylbenzene	<1	18	18	2140
Sum of aromatic hydrocabons	8	30	31	
Monoterpenes				
α-Pinene	110	216	218	3890
β-Pinene	9	23	25	36000
3-Carene	39	105	105	2450
Limonene	8	31	32	2450
β-Myrcene	<1	9	10	140
Sum of monoterpenes	166	384	390	
Siloxane *(others)*	<1	18	18	-

5.2 Result of laboratory tests

The emission determinations from the glued solid wood elements, the concrete and the expansion joint from laboratory tests are given in Table 4, Table 5 and Table 6.

Table 4: Solid wood element glued with Melamine-Urea-Formaldehyde, chamber method determined emissions. The results are given as the mean values for the two specimens tested in (Funch, 2002), in case where the two tests show large difference the two values are given, i.e. "Direct factory delivery" and "Building site delivery". All threshold values are from the VOCBase (Jensen & Wolkoff, 1996); # = threshold value for irritation according to the VOCBase. At the given test conditions the concentration in µg/m^3 equals the emission rate in µg/m²h.

Chemical compound	3 days [µg/m^3]	10 days [µg/m^3]	28 days [µg/m^3]	Threshold value for odour [µg/m^3]
Aldehydes				
Formaldehyde	102	66	63	150# (E1=124)
Acetaldehyde	71	39	20	340
Propanal	8	6	3	14
Butanal	5	2	1	28
Pentanal	23	16	11	22
Hexanal	46	33	25	58
Benzaldehyde	5	3	3	186
Sum of aldehydes	260	165	126	
Ketones				
MIBK/Hexanone	-	5	5	-
Acetone	55	39	29	14000
Sum of ketones	55	44	34	
Alifatic Hydrocarb.				
C10-C16	34	17	8	7760 (C11)
AromaticHydrocarb				
Toluene Building site deliv. Direct factory deliv.	 Failing 6	 44 2	 39	644
Xylene/ethylbenzen Building site deliv. Direct factory deliv.	 Failing 5	 26 <1	 20	2140
Monoterpenes				
α-Pinene	245	84	42	3890
β-Pinene	27	14	10	36000
3-Carene	7	6	6	2450
Limonene	17	17	14	2450
Sum monoterpenes	296	121	72	
Others				
Butyl acetate only building site deliv.	Failing	6	5	47
Propanoic acid only building site deliv.	Failing	5	3	110

Table 5: Expansion joint, chamber method determined emissions. All threshold values are from the VOCBase (Jensen & Wolkoff, 1996); # = threshold value for irritation according to the VOCBase. At the given test conditions the concentration in µg/m³ equals the emission rate in µg/m²h.

Chemical compound	3 days [µg/m³]	10 days [µg/m³]	Threshold value for odour [µg/m³]
Formaldehyde	<10	Not analysed	150#
Propanal	6	Not analysed	14
Acetone	23	Not analysed	14000
Xylene/ethylbenzene	12	58	2140
2-Ethyl-1-hexanol	75	121	500

Table 6: Floor concrete used for the floor slabs, chamber method determined emissions. All threshold values are from the VOCBase (Jensen & Wolkoff, 1996); # = threshold value for irritation according to the VOCBase. At the given test conditions the concentration in µg/m³ equals the emission rate in µg/m²h.

Chemical compound	3 days [µg/m³]	10 days [µg/m³]	Threshold value for odour [µg/m³]
Formaldehyde	<10	<10	150#
Acetaldehyde	5	6	340
Hexanal	2	1	58
Acetone	3	5	14000
Heptane	2	2	95500
Toluene	8	6	644
Xylene/ethylbenzene	3	3	2140
2-ethylhexanone	2	3	-

5.3 Results of theoretically determined concentrations

5.3.1 Volumes and surfaces of the house

The volumes and surfaces of the house are given in Table 1 and Table 2. The total inside exposed area of melamine urea formaldehyde glued solid wood elements is 416 m^2, and the indoor air volume is 485 m^3.

5.3.2 Theoretically determined concentrations

The emission of chemical compounds from the concrete and the expansion joint is omitted, as the contribution is low regarding both area and emission. The concentration used in the calculation is the mean value (where possible) for the two melamine urea formaldehyde glued solid wood element samples tested. The concentrations used in the theoretical determination of indoor concentration are those determined at 28 days, Table 3. The formula *(1)* is used to obtain the concentration results given in Table 7.

Table 7: Theoretically determined concentrations calculated by: $C_h = C_c \times n_c/n_h \times L_h/L_c$. All threshold values are from the VOCBase (Jensen & Wolkoff, 1996); # = threshold value for irritation according to the VOCBase. n.d.= not detected.

Chemical compound	Theoretical concentration determined for:		In-situ measuring	Threshold value for odour
	1 h^{-1} air change [$\mu g/m^3$]	0.5 h^{-1} air change [$\mu g/m^3$]	Average all 2002.01.17 [$\mu g/m^3$]	[$\mu g/m^3$]
Aldehydes				
Formaldehyde	54	108	63	150# (E1=124)
Acetaldehyde	17	34	69	340
Propanal	3	5	9	14
Butanal	1	2	3	28
Pentanal	9	19	15	22
Hexanal	22	43	41	58
Octanal	n.d		8	7
Furaldehyde	n.d		3	-
Benzaldehyde	3	5	4	186
Sum of aldehydes	108	217	213	
Ketones				
MIBK/Hexanone	4	9	n.d	-
Acetone	25	50	81	14000
Sum of ketones	47	95	81	
Alcohols				
Butanol	n.d	n.d	12	90
Pentanol	n.d	n.d	3	20
Sum of alcohols			15	
Alifatic Hydrocarb.				
C10-C16	7	14	590	7760 (C11)
Aromatic Hydrocarb.				
Toluene From building site	34	67	13	644
Xylene/ethylbenzene From Building site	17	34	18	2140
Sum Aromatic Hydrocarb.			31	
Monoterpenes				
α-Pinene	36	72	217	3890
β-Pinene	9	17	24	36000
3-Carene	5	10	105	2450
Limonene	12	24	32	2450
β-Myrcene	n.d		10	
Sum of monoterpenes	62	124	388	
Others				
Butyl acetate/ from Building site	4	9	n.d	47
Propanoic acid/ from Building site	3	5	n.d	110
Siloxane	n.d		18	-

6. Interpretation and discussion

From the wood itself emissions of aldehydes and terpenes are expected. Any measured emissions of aromatic hydrocarbons and alcohols cannot originate from the wood. Formaldehyde in concentrations above approximately 10 µg/m^3 cannot be expected to originate from the wood. Nailed wood elements without any glue and produced by use of the same wood as for the tested glued elements are seen to have this low emission rate, (Funch, 2002).

As expected, the concentrations found during the first in situ measurement were very low, due to the high ventilation rate caused by missing skylight windows and the outer walls uncompleted. Hence, the results from the second in situ measurement show a higher concentration of all the detected chemical compounds - except for the alcohols.

Regarding formaldehyde emissions the following observations are made:

- The measured in-situ concentration of formaldehyde is below the WHO (World Health Organisation, 2000) recommendation of 100 µg/m^3, Table 3.

- The concentration of formaldehyde determined theoretically based on the laboratory measurements of the material emissions is in the range 54 -108 µg/m^3, Table 7.

- Assuming that the air change in the house is in the range 0,5 – 1 h^{-1}, the measured concentration of formaldehyde can be explained by the emissions originating from the glued elements, Table 7, and must thus be due to the glue.

Regarding other aldehydes the following observations are made:

- The in-situ measurements correspond to the theoretical determination.

- Aldehydes are known to emit both from the wood itself and the glue. This is verified in, (Funch, 2002), where the emission from MUF-glued samples is found to be twice the value of the sample without glue.

- The measured aldehyde emission is, however, far below the proposed health based indoor air exposure limit proposed by Nordic Committee on Building Regulations in (Nielsen et al., 1996), for the individual substances. The in-situ measurements are approximately 2 orders of magnitude lower than these limits, see Table 8.

Regarding terpenes the following observations are made:

- The sum of terpene emission from the in-situ measurements is 3 – 6 times higher than the corresponding theoretical determination. This variation in terpene emission was also seen in the chamber test on different elements (Funch, 2002). According to (Miljøprojekt Nr. 501, 1999) the variation is considered normal for softwood, because the emission of terpenes is dependent on factors like growth conditions and origin.

- The measured terpene emission is, however, also approximately 30 times lower than the proposed health limits, see Table 8.

Table 8: Toxicological based air quality guidelines for substances in indoor air, suggested health based indoor air exposure limit for aldehydes and terpenes. (Nielsen et al., 1996).

Aldehydes	
Propanal	1000 µg/m³
Butanal	1000 µg/m³
Hexanal	800 µg/m³
Octanal	350 µg/m³
Benzaldehyde	800 µg/m³
Terpenes	
α-Pinene and β-pinene	7000 µg/m³

Regarding the concentration of alifatic hydrocarbons the in-situ measured value is approximately 60 times higher than expected from the laboratory test. This could be due to the mentioned wood stove outlet of black smoke.

7. Concluding remarks

In-situ measurements of formaldehyde and other volatile organic compounds have been carried out in a single-family house constructed of glued solid wood elements. The amount of freely exposed wood surfaces in the investigated dwelling occupies 2/3 of the total inner surfaces of the construction including floors, and the following conclusions are drawn with regard to known health limits for emitted substances:

- Though, the glued wood elements covering the inner surfaces are glued with a melamine urea formaldehyde emitting formaldehyde, the measured concentrations of formaldehyde in the dwelling is well below the recommended value given in (World Health Organisation, 2000).

- Though, wood is known to emit large amounts of terpenes and aldehydes, the measured emissions of terpenes and aldehydes other than formaldehyde are well below the health based indoor air exposure limit for aldehydes and terpenes suggested by Nordic Committee on Building Regulations in (Nielsen et al., 1996).

The in-situ measured concentrations have been correlated with calculated concentrations based on laboratory chamber measurements on the relevant materials according to the chamber method in (EN 717-1,1998). Results for chamber tests are reported in the present report and in (Funch, 2002). With regard to the current product requirements the following conclusion is drawn:

- An acceptable correspondence was observed for formaldehyde emissions. This supports the requirements for formaldehyde emission which in the product standards (prEN 14080 (DRAFT), 2000) (EN 13986, 2001) is formulated by use of (EN 717-1,1998).

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