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EVALUATION OF CONSUMER RISK RESULTING FROM EXPOSURE AGAINST DIPHENYLMETHANE-4,4'-DIISOCYANATE (MDI) FROM POLYURETHANE FOAM

Hans-Dieter Hoffmann[1], Thomas Schupp[2]*

[1] formerly: BASF SE, Experimental Toxicology and Ecology, Carl-Bosch-Str. 38, D-67056 Ludwigshafen, Germany
[2] Elastogran GmbH, Product Safety, Ecology and Toxicology, Elastogranstrasse 60, D-49448 Lemfoerde.
* Corresponding author (e-mail address: thomas.schupp@elastogran.de, phone: +49-5443 122135)

ABSTRACT

Flexible polyurethane foam made from diphenylmethane-4,4'-diisocyanate (MDI) may contain a few ppm of residual monomer. As this foam is used in consumer articles like upholstered furniture and bed mattresses, the question arises if the residual monomer can result in consumer exposure and risk to consumer health. Integral skin polyurethane foam used for steering wheels and armrests and flexible polyurethane foam were analyzed for extractable MDI. The latter was also investigated with respect to migration and evaporation of MDI. There was no migration or evaporation of MDI detected. Against the experimental design and the corresponding detection limits less than 5.4 ng MDI per m^3 air in the test chamber and a migration rate below 9 ng/cm^2 per day was found under simulated worst-case conditions (up to 10 ppm MDI in the flexible foam). For exposure by inhalation, these findings were compared to the German MAK value for MDI in air, the US EPA Reference Concentration and the NOAEC for respiratory tract irritation. For dermal exposure, the findings were compared against a derived No Expected Sensitization Induction Level (NESIL) for allergic contact dermatitis in man. As a result, polyurethanes containing up to 24 ppm extractable MDI do not pose a critical toxicological risk to consumers. Whether higher contents are acceptable depends on the result of migration and evaporation tests.

Keywords: Diphenylmethane diisocyanate, polyurethane, emission, migration, consumer risk

INTRODUCTION

Flexible polyurethane foam may be produced by the reaction of diphenylmethane-diisocyanate (MDI, CAS-No. 101-68-8) with polyetherols and/or polyesterols. For the reaction different additives are required, e. g. tertiary amines as catalysts, silicones-surfactants and water as blowing agent. Flexible foams are used in bed mattresses and upholstered furniture, integral skin foam is used for example for steering wheels of cars and armrests of office chairs.

The isocyanate reacts with OH-groups from alcohols, NH-groups, water, urethane-groups and urea-groups to form urethanes, ureas, allophanates and biurets (Saunders and Frisch, 1967). The reaction of isocyanate with water liberates a primary, aromatic amine as an intermediate, which will instantaneously react further with another isocyanate-group. Amines are much more reactive to isocyanates than are alcohols and water (Mormann et al., 2006).

With respect to consumer risk the question is whether residual monomeric MDI in the polyurethane results in exposure. This is of interest as MDI is a known respiratory sensitizer, and occasional cases of skin sensitization have been reportet (European Communities, 2005).

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Several investigators have already looked for residual NCO groups or residual monomeric diisocyanate in polyurethanes using different analytical methods. FTIR has been used for the detection of NCO-groups in polyurethanes (Cole and Gheluwe, 1987). A distinction between NCO-groups belonging to free, unreacted MDI and those belonging to the polymer-chain is not possible by FTIR-spectroscopy. Conte and Cossi (1981) and Jedrzejczak and Gaind (1993) investigated residual toluene diisocyanate (TDI) in a flexible foam via gas chromatography (GC). Using GC, it has to borne in mind that above 200 °C polyurethanes start thermolytic cleavage releasing the isocyanate (Dick et al., 2001). Duff and Maciel (1991) followed the reaction of NCO-groups in an MDI-based polyurethane by ^{15}N- and ^{13}C- CP/MAS NMR.

In our experiments the content of c MDI in polyurethanes was investigated in combination with potential release via direct migration and evaporation. With respect to the purpose of this investigation, cold-cure moulded flexible foam can be regarded as a worst-case for the following reasons: 1) Other types of MDI-based foams are processed at higher temperatures a more complete reaction of MDI, and 2) In comparison to integral foam with a skin-like surface (e. g. steering wheels), flexible foam has an open-cell-structure facilitating evaporation of any residual MDI, which should be detectable in the surrounding air.

MATERIALS AND METHODS

The tests were run with a five days old MDI-based cold-cure flexible foam with a foam-index of 100 (molar ratio NCO-groups : NCO-reactive groups = 1). For the extraction, toluene (for UV/VIS-spectroscopy, Riedel de Haen) and, as an alternative, ethyl acetate (for UV-spectroscopy, Riedel de Haen) were used. The MDI was derivatized with 1-(2-pyridyl)piperazine (PP), which was added to the toluene (1.17 g/L) and the ethyl acetate (0.80 g/L, fresh solution!) respectively. The foam cushions investigated were produced from the raw materials (MDI and polyol with additives) either by hand mixing (stirring for 10 sec., samples “H”) or with a high-pressure mixing-head machine (Puromat 80, pressure 130-160 bar; samples “M”).

Solvent extraction of the foam

About 5 g foam (10 cm x 10 cm x 1 cm) was cut from the surface and from the middle of the cushion (size of cushion: 40 cm x 40 cm x 10 cm, density 30 g/L) and weighed (accuracy ± 0.5 mg). The foam samples were cut into four pieces, put into a 600 mL beaker and after adding 200 mL of the derivatizing solvent, squeezed and expanded 30 times (duration approx. 2-3 min), using a clean 400 mL beaker as a plunger. The derivatizing solution was decanted; the process was repeated two times with 140 mL derivatization solution. The combined extracts were evaporated to dryness, the residue was taken up in 2 mL solvent (acetonitrile: dimethylformamide = 9 : 1). 20 µL of this solution were injected into the injection-port of the high performance liquid chromatograph (HPLC) MDI-derivatives were detected with an UV/VIS-detector (254 nm). Due to extractable UV-active impurities causing a background noise, the detection limit was 1 µg MDI per g foam.

Detection of MDI in air

For the measurement of air extractable MDI, the foam cushion was placed in a dynamic fatigue test chamber (volume of chamber 400 L, volume of foam about 16 L, T = 40 °C, 50 % rel. humidity) together with two MDI-sampling-devices consisting of an PP-coated glass-fibre filter fixed in a cassette, connected to a suction-pump with a flow of 120 L/h. The design is shown in Figure 1. The advantage of the selected kind of chamber is the perfect simulation of normal use, where polyurethane foam is iteratively compressed and released, thus creating an air-exchange in the foam which may increase the release of volatile compounds. The chamber was

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closed for 135 minutes while pumping air through the coated filters.

Figure 1: MDI-based polyurethane foam in the dynamic fatigue test chamber with air sampling pumps (white arrows) and sampling filters (orange arrows)

The cushion was periodically compressed with 1.2 Hz. The compression-force varied between 150 and 750 N. Although there was no external air-exchange, the air was "purified" from MDI by passing the coated glass-fibre filters placed inside the chamber. By this way, 240 L air per hour were extracted from MDI. The MDI analysis was performed according to OSHA 47 (United States Occupational Safety and Health Administration, 1989), with some modifications. For analysis the filters were extracted with 2 mL solvent (acetonitrile : dimethylformamide = 9 : 1). The extract was concentrated to 1 mL, and 10 µL of the extract were injected into the HPLC. The detection limit was 2.9 ng MDI absolute which is equivalent to 5.4 ng/m³ air. Earlier experiments have shown that, during sampling, no breakthrough of MDI is expected at an air-flow of 2 L/min and a sampling time of 2 h.

Migration of MDI

One foam sample was used to check MDI can be extracted by direct contact. Three glassfibre filters, coated with 1-(2-pyridyl)piperazine (PP) with a diameter of were placed in contact with flexible foam pieces on both sides for 5 days. This sandwich–construction was compressed to 75 % of the original height. The residual MDI in the foam was analyzed by extraction with ethyl acetate and derivatization with PP as described above. In addition, the filters were extracted and analyzed as described above. In this case the detection limit was 1 µg MDI per filter due to the background noise (i. e. detection limit 1 µg/22.68 cm²).

HPLC analysis

MDI-PP derivatives from foam extracts or the coated glass-fibre filter extracts were quantified by HPLC-UV. Instrument: Spectra-Physics 8800. Column: Nucleosil 7 C-18, ET 250/8/4 (Macherey Nagel). Eluent: acetonitrile/water (50/50) with 2.5 g triethylamine and 0.77 g ammonium-acetate per litre, pH = 6.3 (adjusted with acetic acid). Flow: 1.5 mL / min. Detector: UV-VIS 254 nm fixed.

RESULTS

The results of the foam extraction tests are summarized in Table 1. No detectable amounts of MDI could be found in the air-samples, with a detection-limit of 5.4 ng/m³. All chromatograms showed peaks of residual, unreacted derivatizing reagent.

The foam used for the contact migration-tests contained 3.15 ppm extractable MDI in the centre of the sample (arithmetic mean from 4 measurements: 3.1, 3.1, 3.2 and 3.2 ppm, extraction with ethyl acetate). There was no MDI-derivative detectable in the filter extracts which had been in contact with both sides of the foam for 5 days at 22 °C. Therefore, the migration of MDI over 5 days is less than 1 µg/22.68 cm² = 44 ng/cm² or, continuous migration over time assumed, less than 9 ng/m³ per day.

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Table 1: Extractable amounts of MDI; "H": hand-mix flexible foam; "M": machine flexible foam; I: integral skin foam

Sample	Solvent	MDI extracted (ppm)
H-surface-01	toluene	1
H-surface-02	ethyl acetate	8
H-surface-03	ethyl acetate	7
H-center-01	toluene	2
H-center-02	ethyl acetate	6
H-center-03	ethyl acetate	3
M-surface-01	toluene	3
M-surface-02	ethyl acetate	14
M-center-01	toluene	2
M-center-02	ethyl acetate	5
I-01	ethyl acetate	< 1
I-02	ethyl acetate	< 1

DISCUSSION

Analytical findings

The available data suggest that during the manufacturing of MDI based flexible foam trace amounts of MDI can remain in the polymer matrix. Using organic solvents it is possible to mobilize and extract residual MDI. By using ethyl acetate as solvent, slightly higher amounts were detected than using toluene, although the differences are neither consistent nor very large. MDI is known to react rapidly with water (Yakabe et al., 1999). The data generated in this project suggest that this reaction does not occur as long as MDI is physically bound and protected in hydrophobic regions of the polymer matrix. This can be taken as evidence that diffusion of water into the hydrophobic regions of the foam matrix is very limited. In addition, these results demonstrate that diffusion of such physically bound MDI out of the polymer matrix does also not occur in practice. Integral skin foam shows lower amounts of residual, extractable MDI. Although the difference in MDI concentration between the surface and the centre of the foam is not high, there is an explanation for that finding. During curing the centre of the cushion has a higher temperature (about 120 °C) than the surface (about 60 °C), ensuring a more complete reaction of the MDI. However, as the data generated are around the detection limit of the method, the differences observed may be attributable to statistical noise. Therefore, any differences observable between foam types, solvent and location of the sample should be regarded with caution.

In the dynamic fatigue test, the foam was periodically compressed. This, as well as a temperature of 40 °C is a worst-case approach when compared to real life situations. However, an air-exchange rate of 0.6 h^{-1} and a loading of 0.016 m^3 foam per 0.4 m^3 space are not unlikely to be found in real life. The model room has a volume of 17.4 m^3, an air exchange rate of 0.5 h^{-1} and a temperature of 23 °C (ENV 13419-1:1999, annex B).

The non-detectability of MDI in the chamber air triggers the question whether the experimental set-up was appropriate at all. First, although not completely congruent to the climate chamber defined by the EN 13419 standards, it seems unlikely that in normal sleeping rooms MDI emitted from polyurethane foam would reach concentrations that were not achievable in our test chamber. Second, our findings are congruent to the findings of Hugo et al. (2000); they demonstrated that toluene diisocyanate (TDI) based flexible foam not only did not emit detectable amounts of TDI, but even filtered TDI out of contaminated air. TDI has a 100 times higher vapour pressure than MDI.

Respiratory risk

In the European Union, MDI is – between others – classified as harmful by inhalation, risk of irreversible damage by repeated inhalation, a respiratory irritant, respiratory sensitizer and as carcinogen category 3 (European Communities, 2008). In the following, literature is cited where either diphenylmethane-4,4'-diisocyanate (MDI, CAS-no. 101-68-8) or polymeric diphenylmethane diisocyanate (pMDI, CAS-no. 9016-87-9) were used. pMDI contains approximately 50 % MDI, and the two grades of "MDI" are regarded as being

equivalent in terms of toxicity (Feron et al., 2001; European Communities, 2005).

In chronic inhalation studies, highly respirable MDI aerosols caused lung tumors in rats (Feron et al., 2001). However, these findings were regarded to be of low relevance for man as MDI is most likely a non-genotoxic carcinogen, acting primarily via a threshold mechanism (European Communities, 2005). Tumor formation was observed only at concentrations that were irritating to the respiratory tract (Feron et al., 2001). The same line of argumentation is presented by the MAK commission of the Deutsche Forschungsgemeinschaft, who has allocated MDI to the cancer category 4 (Deutsche Forschungsgemeinschaft, 2008a). This category names substances where a non-genotoxic mechanism predominates, and tumour-induction is not expected if the MAK-value is followed throughout (Deutsche Forschungsgemeinschaft, 2008b). Based on these judgements, it is justified to assume that a sufficient protection of consumers against airway irritation is a sufficient protection against cancer induction due to potential MDI-exposure.

The irritation threshold of MDI is about 0.5 mg/m³ in rats (Pauluhn, 2002) and 0.05 – 0.1 mg/m³ in man (Deutsche Forschungsgemeinschaft, 1992). MDI- induced respiratory tract irritation in Brown Norway rats follows Haber's rule (C x t = constant) when concentrations of 3.4, 6.2, 12.7, 25.1 or 58.1 mg/m³ were applied for 6 h, 3 h, 1.5 h, 45 min or 23 min (Pauluhn, 2000, 2002). In the scope of these experiments, about 180 mg/m³ x min was reported to be the acute irritant threshold of MDI in Brown Norway rats. A workplace exposure limit of 0.05 mg/m³ is regarded as protective against airway irritation (Deutsche Forschungsgemeinschaft, 1992).

MDI is a respiratory sensitizer. Currently, there is no international accepted test-guideline for the quantitative evaluation of the respiratory tract sensitization hazard available, and the derivation of "safe" levels is difficult and open to challenging discussions (European Chemicals Agency, 2008a). Pauluhn proposed to use the Brown Norway rat as model for MDI-induced occupational asthma (Pauluhn, 2005). With this animal model, he demonstrated an elicitation threshold of 81 mg MDI/m³ x min in repeatedly challenged, "asthmatic" rats (Pauluhn, 2008). Based on this result, he derived a threshold concentration of 0.006 mg MDI/m³ for 8 h for asthmatic human beings. For nonsensitized subjects, an 8 h time weighted average threshold of 0.13 mg/m³ was derived (Pauluhn, 2008). This is in reasonable agreement with the MAK evaluation, where it is said that for the induction of respiratory hyperresponsiveness in workers, concentrations above 0.2 mg MDI/m³ or intensive skin contact seem to be important, but 0.05 mg MDI/m³ seem to be protective (Deutsche Forschungsgemeinschaft, 1992). In summary, 0.05 mg/m³ are deemed to be protective with respect to airway irritation and sensitization at the workplace. To derive a safe level for the general population, we propose a factor of three to extent the results to 24 h exposure and a factor of 7 d/5 d for permanent exposure; together, this is approximately a factor of 5. If a threshold value from animal experiments is derived, a further factor of 10 is the default assumption for intra-human variability for the general population, whereas 5 is the default factor for workforces. (European Chemicals Agency, 2008b). That means, the default factor for workforce to general population extrapolation is 2. Based on the German MAK value, a threshold of 50 µg/m³ : ~5 : 2 = 5 µg/m³ would result for the general population. However, as some users of polyurethane foam are likely to be asthmatics, the according threshold of 8 µg/m³ for the workplace derived by Pauluhn (2008), based on studies in Brown Norway rats, seems to be a more appropriate starting point. If the time factor of 5 (workplace to continuous exposure) and the worker-to-consumer factor of 2 are applied, a threshold of 800 ng/m³ results, slightly higher than the value of the US EPA Reference Concentration, which is 600 ng/m³ (United

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States Environmental Protection Agency, 1998). Therefore, we regard the Reference Concentration of 600 ng/m³ as being a sufficient conservative threshold for the general population with respect to respiratory tract irritation, sensitization and cancer. The RfC is more than 100 times higher than the derived maximum chamber concentration in our test (5.4 ng/m³).

Dermal risk

The induction of dermal sensitization is regarded to be the most critical endpoint with respect to dermal exposure to MDI. In the local lymph node assay (LLNA), the EC3-value for MDI was established as 0.08 % MDI in acetone-olive oil (Selgrade et al, 2006). For risk evaluation, a procedure proposed by Safford (2008) is used. Safford proposes to calculate the human No Expected Sensitization Induction Level (NESIL) based on the EC3 (in µg/cm²) value first:

$\log_{10}(\text{NESIL}) = \log_{10}(\text{EC3}) * 1.16 - 0.64$

and then to devide the result by a safety factor (SAF) to derive the Acceptable daily Exposure Level (AEL). For the total SAF, Safford proposes a factor of 10 for human variability, a factor of 3 for matrix effects and a factor of 3 to 10 for use variability. The matrix factor pays tribute to a potential adverse impact of the matrix (further irritants, enhanced penetration due to carriers); the use of the variability factor pays attention to the fact that breached skin due to – for example – shaving or occlusion is exposed. For the PU foam matrix, the matrix variability factor and the use variability factor can be set = 1; this is justified as the normally moisture sensitive MDI seems to be protected by the foam matrix, which indicates a kind of encapsulation. Therefore, SAF = 10 is used. Following the algorithms proposed by Safford (2008), the result is

EC3(MDI) = 0.08 % = 20 µg/cm², =>

NESIL(MDI) = 7.4 µg/cm²,

and, with SAF = 10,

AEL(MDI) = 740 ng/cm² per day.

This level is much higher than the maximum migration of MDI out of the flexible foam (containing about 3 ppm extractable MDI), which was calculated to be below 44 ng/cm² over five days or – continuous migration assumed – 9 ng/cm² per day. The approach chosen still is conservative as it is developed to be used for cosmetics with intended repeated skin contact (Safford, 2008); the foam contains only accidentially residual, extractable MDI with a non-measurable migration. Additionally, flexible foam is usually covered by textiles that should also represent some barrier for migration.

CONCLUSION

As the open cell structured flexible polyurethane foam should be most critical concerning emission and migration of MDI, conclusions drawn from our test results can be extrapolated to other kinds of polyurethanes. A foam containing about 5 ppm extractable MDI gave reason to less than 5.4 ng/m³ MDI in the test chamber air. This is well below the RfC of 600 ng/m³.

Polyurethane containing about 3 ppm extractable MDI gave reason to a migration of less than 9 ng/cm² per day, which is well below the AEL of 740 ng/cm².

Higher amounts of extractable MDI in polyurethanes might be acceptable with respect to consumer risk. Although it is not clear whether or not migration and evaporation follow Fick's law of diffusion – as it is unclear where the MDI is located inside the foam matrix and how it is bound – a content of 24 ppm seems to be acceptable. In case of linear dependence on the extractable amount, the expected exposure against MDI is at least ten times below the RfC and the AEL.

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