The Current MDI Industrial Hygiene Data on Spray Foam

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ABSTRACT

Spray application of polyurethane foam for thermal insulation of buildings represents the polyurethane application with the highest potential worker exposure to MDI. This paper reviews the existing work done to characterize the MDI exposures of the sprayed polyurethane foam workers as well as identifying several elements of an effective industrial hygiene program suggested by the existing work. In addition, areas for additional possible work are suggested.

The existing work shows clearly that MDI exposures for both the sprayed foam applicator and helper can exceed both task and shift occupational exposure limits. Additional feasible engineering controls are not obvious, so control schemes based on administrative controls (work practices, establishment of “work zones” and re-entry clearance times) and personal protective equipment (respirators, gloves, and protective clothing) are necessary. Suggestions for more work in the areas of establishing re-entry clearance times and work zones as well as characterizing amine catalyst exposures are made.

INTRODUCTION

The use of sprayed polyurethane foam based on 4,4’-methylene diphenyl diisocyanate (methyl diphenylene isocyanate, or MDI) for thermal insulation in residential and commercial buildings has been growing steadily over the last two decades. With the current emphasis on energy conservation, this trend in sprayed polyurethane thermal insulation use is likely to continue. Sprayed polyurethane foam offers advantages of high thermal insulation value, good sealing and water-resistance characteristics, and avoidance of indoor air quality problems introduced by some other insulation choices. From an industrial hygiene perspective, sprayed polyurethane foam application is the operation presenting the highest airborne MDI exposure potential for workers of all MDI uses [1], and is second only to vehicle spray painting in presenting the highest airborne exposure potential for diisocyanates of all types [2]. For these reasons, an effective industrial hygiene program based on a good understanding of the details of the MDI exposure patterns is important for protecting workers involved in applying sprayed polyurethane foam. This paper is intended to review the MDI worker exposure data that exists for sprayed polyurethane foam, summarize practical conclusions that can be drawn from it, and suggest areas where further investigation could be considered.

BACKGROUND

MDI in Sprayed Foam Formulations

Sprayed polyurethane foam systems consist of two liquid parts which when mixed, react to form a polyurethane polymer: a diisocyanate (referred to commonly as the “A side”), and a polyhydroxy alcohol (polyol; referred to commonly as the “B side”). The B side also contains a blowing agent for foam cell formation (typically a low-boiling hydro-flourocarbon) and small amounts of amine catalysts and other additives. During application, the A and B sides are heated and fed separately to the spray gun, mixing in the spray gun just prior to application. The resulting spray consists of droplets of the warm, rapidly-reacting mixture, as well as vapor from the more volatile components of the system (the blowing agent, and, to some extent, the diisocyanate and the amine catalyst).

The properties of the foam produced are governed primarily by the composition of the B side of the formulation; systems differ in the polyol, catalysts and blowing agents used as well as the relative amounts of each. The A side used in sprayed polyurethane foam insulation is almost always “polymeric MDI” (PMDI) -- an undistilled mixture of MDI and higher molecular weight MDI oligomers. Like MDI, MDI oligomers have active isocyanate functional groups (-N=C=O) that react to form polyurethane polymers. In spray foam formulations, the PMDI used consists of 45-55% of each component (MDI and MDI oligomers) [3].
MDI is a skin, eye and respiratory tract irritant [4]. Exposure to excessive airborne concentrations of MDI can lead to respiratory sensitization, which may result in occupational asthma. MDI may cause skin sensitization in rare cases [4]. There is limited data in animals suggesting that dermal exposure to diisocyanates may also contribute to respiratory sensitization, but this has not been confirmed in humans [5].

**Application of Sprayed Foam Insulation**

Sprayed polyurethane foam insulation may be applied to residential and commercial buildings during initial construction or as a retrofit insulation improvement. It may be applied to the building exterior (roof tops and walls before sheathing is added), or to interior building spaces (walls, attics, crawl spaces). Because of the need for customized application, sprayed polyurethane foam insulation is usually applied by hand rather than by automated equipment. Application crews typically consist of an applicator, who operates the spray gun, and one or more helpers who work in close proximity to the applicator conducting support activities (guiding hoses, holding windscreens, etc.). Individual workers may switch between the applicator and helper role throughout the workday [3].

**EXPOSURE MONITORING CONSIDERATIONS**

The complex nature of the exposure environment in sprayed polyurethane foam application (i.e., the presence of both aerosol and vapor forms of air contaminants and the multiple isocyanate-containing species in PMDI) presents several complicating factors in conducting and interpreting MDI exposure monitoring.

**Sampler Type**

Since isocyanates are reactive species, exposure monitoring methods used for them employ a derivatizing agent, usually a primary amine which serves to stabilize the reactive isocyanate group by forming a urea derivative with them. In addition, the derivatizing agents often contain molecular features which enhance the analytical sensitivity of the resulting derivative [6]. The MDI exposure monitoring done during sprayed foam application reviewed for this paper employed a variety of derivatizing agents, but only two methods of sampling were used: (1) air was drawn through a glass fiber filter which was coated with the derivatizing agent or (2) air was drawn through a glass impinger or bubbler containing an organic solvent solution of the derivatizing agent. In one case [10], a combination of the two techniques was used: the sample train consisted of an impinger followed by an inline coated glass fiber filter.

The coated filter sampling technique has the clear practical advantage of ease of use in the field since the apparatus is less bulky and prone to breakage, and liquid organic solvents, which may evaporate or spill while an impinger is worn by a worker are not used. However, when sampling reactive aerosols such as those present during sprayed foam application, the impinger sampler offers a more accurate assessment of the MDI level present since the reacting droplets that enter the impinger are dissolved in solution with the derivatizing agent, facilitating rapid and complete reaction. In the case of coated filters, the aerosol droplet which is trapped on the filter must spread out and wet the filter in order to come into complete contact with the derivatizing agent. Lesage [7] compared the results of MDI monitoring in sprayed foam environments using both coated filter and impinger-based sampling methodologies, finding that filter sampling results were 6-40% lower than side-by-side samples obtained using impingers. In light of this finding, a practical solution to the dilemma of sampler type versus ease of use for the field industrial hygienist might be to use filter sampling and multiply results by an appropriate compensating factor (e.g., two).

**Exposure Guidelines**

Exposure monitoring methods are generally designed to yield results that can be compared to established occupational exposure guidelines for interpretation. Such exposure guidelines are set by governmental or professional bodies based on a review of the toxicological, medical and human experience data. One of the most widely-recognized set of occupational exposure guidelines are the Threshold Limit Values (TLVs®), set by the American Conference of Governmental Hygienists (ACGIH®). The ACGIH TLV for MDI is 0.005 ppm (5 ppb or 51 μg/m³) as an 8-hour time weighted average. The Permissible Exposure Limit (PEL) set by the United States Occupational Safety and Health Administration (OSHA) for MDI is 0.020 ppm (20 ppb or 200 μg/m³) as a ceiling (never to be exceeded) value.

These exposure limits are representative of the majority of those followed globally. A notable exception is the United Kingdom Health and Safety Executive, which has set an occupational exposure limit based on the determination of “total reactive isocyanate group” (TRIG). The HSE TRIG exposure guideline is 70 μg/m³ as a ceiling (never to be exceeded) value, and 20 μg/m³ as an 8-hour time weighted average [2]. While the TRIG method has the advantage of accounting for exposure to the isocyanate groups present in the MDI oligomers in addition to those in MDI alone, commentators in the U.S.
and elsewhere have noted that neither it nor any other current analytical method is capable of accurately quantitating all reactive isocyanate groups [7].

Chemical Species Monitored

Exposure monitoring methods designed to produce data for comparison with the TRIG exposure guideline quantitate both the levels of MDI and the MDI oligomers. As such, they require a PMDI calibration standard, which is often difficult to obtain. The mass of MDI found in the sample is added to the mass of MDI oligomers found and the total is converted to a TRIG number based on the ratio of the monomer molecular mass to the isocyanate group mass; for MDI, this ratio is (250/89) = 0.34 [5].

For exposure monitoring methods whose data is designed to be compared with MDI-based values, only MDI monomer need be determined. In actual practice, a number of investigators determine MDI oligomers as well although comparison with occupational exposure limits is not clear [3,7,10].

The results from studies where both MDI and MDI oligomer data was obtained in sprayed polyurethane foam environments was examined for trends. A total of 53 personal breathing zone results where both MDI and oligomers were detected from four studies [3,5,7,10] were compared. The results of the comparison showed that the mean ratio of total PMDI found to MDI was 1.82 (SD = 0.67). Since the composition of the PMDI is 45-55% MDI, this ratio in the bulk PMDI would be 1.8 – 2.2. This result indicates that the most typical situation found is that the spray sample retained a composition similar to the bulk PMDI material being sprayed. However, there was variation in this relationship: in ten of the samples (20%), the MDI oligomer concentration was higher than that of MDI (i.e., PMDI / MDI ratio greater than 2.0) while in 28 cases, the PMDI / MDI ratio was less than 1.7 (i.e., MDI made up more than 60% of the total PMDI found).

Since analysis of samples for MDI oligomers is considerably more difficult (and therefore more expensive) than analyzing for MDI alone, a practical application of this observation for the practicing field industrial hygienist taking samples in sprayed polyurethane foam environments might be to determine MDI and multiply the results by an appropriate adjustment factor (e.g., two).

SPRAYED FOAM WORKER EXPOSURES

Worker exposure data during sprayed polyurethane foam application from several studies conducted over the last 30 years [2,3,5,7,10-15] were examined. The data represented over 240 task and shift personal breathing zone samples taken on applicators and helpers during foam application.

The MDI exposure concentrations of spray foam applicators in the studies ranged from 5-2100 µg/m³. Where 8-hour time weighted averages were calculated, they ranged from 10-460 µg/m³. (The 8-hour time-weighted average takes into account the portion of the 8-hour workday for which the measured concentration applies. For instance, if an applicator’s exposure concentration during spraying was 100 µg/m³ and they sprayed four hours out of a workday and had no exposure for the rest of the day, their 8-hour time-weighted average exposure would be (100*4/8 =) 50 µg/m³.) The MDI exposure concentrations of workers in the spray foam helper role in the studies ranged from 0.1-408 µg/m³. Where 8-hour time weighted averages were calculated, they ranged from 1-308 µg/m³.

Both the spray applicator and helpers clearly have the potential for exposures over both the 8-hour TLV and the OSHA PEL (51 µg/m³ and 200 µg/m³ ceiling, respectively). The exposures for the spray applicator were consistently 2-4 times higher than those of the helper, but a high degree of variability was noted for both job roles. The high variability in MDI exposures for both the spray applicator and helper was affected by several factors. Indoor spraying resulted in higher exposures [11] while outdoor spraying resulting in more variability in exposure since keeping upwind of the point of application became more important [12]. Natural ventilation, atmospheric and seasonal conditions, building characteristics, surface area and thickness of foam sprayed, applicator’s experience level, were also noted as factors affecting exposure levels [3,11].

Two studies [7,10] also measured spray foam workers’ exposures to the foam blowing agent and one [10] measured exposures to the amine catalyst. In both studies, the exposure of both the applicator and helper to the blowing agent were below the relevant exposure guideline. In the one case where amine catalyst exposure levels were measured, concentrations ranging from less than detection limit to over 900 ppb were found. No exposure guideline for the amine catalyst was given, so evaluating the significance of these results is difficult.

EXPOSURE CONTROL

Given the clear potential for over-exposure to MDI during spray application of polyurethane foam, it is clear that exposure controls are important for workers involved. Ideally, engineering controls are the first tool to be used in exposure reduction efforts. Exploring the use of air curtains, reactive mist barriers, and remote control spraying have been suggested [14], but
their application seems difficult given the variability of the construction environment. Since additional engineering controls appear to be impractical, consistent, disciplined use of administrative controls and personal protective equipment must be relied upon.

**Administrative Controls**

**WORK PRACTICES**

One of the fundamental actions that workers can take to reduce exposures to MDI during spraying is positioning themselves upwind of the spray stream as much as possible. This concept should be included in spray applicator and helper training, and rigorously used in the preparation for each spraying session. While attention to upwind positioning has more importance for outside applications because of the variations in wind speed and direction that must be noted and adjusted to, even for indoor applications, there is usually a natural air flow direction that should be noted and taken into consideration.

**THE “WORK ZONE” CONCEPT**

Several authors [3, 7, 10, 12, 13, 15] report data on the reduction of MDI concentration with distance from the point of spray application. Some refer to the concept of a “work zone” – a distance around the spray gun where MDI concentrations are highest and outside of which significant exposure is not likely. For indoor application, work zone recommendations in the literature range from 6 m (20 ft) [10] to 8 m (25 ft) [12, 15]. For outdoor application, work zone recommendations range from 2m (7 ft) [13] to 3 m (10 ft) [12, 15]. One publication [16] suggests that, since outside spray application is highly influenced by wind speed, an “exclusion zone” be established for 6m (20 ft) on either side of the applicator in still air conditions, or 3 m (10ft) upwind and 8m (25 ft) downwind of the applicator.

Setting a work zone outside of which overexposure to MDI or other components of spray foam system is unlikely to occur is useful as a simple, practical workplace exposure management technique. It establishes a discipline for allowing other construction trades to complete their work safely in areas of the structure reasonably remote from the area to which foam is being applied. Additional data measuring the concentrations of MDI and other spray foam components in areas of the structure other than those being sprayed support this concept. While migration of MDI and other spray foam components to floors other than the one on which foam was being applied was noted, levels found were consistently well below exposure guidelines [3, 10].

**CLEARANCE TIME**

Another aspect of exposure management is consideration of when to allow re-entry of unprotected workers to the sprayed area. Several of the papers reviewed reported pertinent data.

Lesage et al. [7] report MDI levels in the room where sprayed foam was applied as high as 19 μg/m³ in the first 15 minutes after spraying ceased. However, by the time 60 minutes had passed, all samples taken were below the analytical detection limit (0.036 μg).

Karlović [10] studied the variation with time of concentrations of MDI, blowing agent, and amine catalyst following spray application in the interior of five residential structures. Of 64 samples taken to measure MDI concentrations up to 2 hours post-application, 62 were below the detection limits while two detected MDI at a level of 5 μg/m³. All 64 samples were below detection limits for MDI oligomers. Area levels of blowing agent were determined for one of the structures over the period of 40-140 minutes post-application. These levels were well below applicable exposure guidelines and were reduced by a factor of approximately six in the period from 40 to 140 minutes after spraying. Similarly, amine catalyst post-spraying levels were followed in one of the structures. The amine catalyst levels were detectable throughout the period measured and were reduced by a factor of approximately two in the period from 40 to 140 minutes after spraying. Since exposure guidelines for the amine catalysts were not given, interpretation of the exposure significance of the levels found is difficult.

Other authors [3,5] report MDI and MDI oligomer measurements 2 hours after spraying. In all cases, MDI results were below detection limits or detected at levels of 0.03 μg/m³ or lower. It is interesting to note that in one case [3] where MDI levels were measured 30 minutes, 60 minutes and 120 minutes post-spraying, on both the level sprayed and another level of the structure to which spray foam had not been applied, MDI levels were observed to peak at 60 minutes post-spraying on the level which was not sprayed while they decayed steadily with time on the level sprayed. This is probably an indication of the time it took suspended aerosol spray droplets to disperse through the structure as a result of diffusion and natural air currents. Achuan et al. [3] report collecting two samples 2 hours after application of sprayed foam on a rooftop in which detectable levels of MDI oligomers were found but MDI was below detection limits. The authors conclude that this was a reflection of the higher reactivity of the isocyanate groups on MDI compared to those on MDI oligomers.
The MDI and blowing agent clearance results point out the importance of ventilating the structure after spraying, and restricting entry for an appropriate period after spraying ceases. It is unclear what clearance time is sufficient to reduce exposure to the amine catalysts to safe levels as exposure evaluation criteria for the amine catalysts were not given. Since there are many factors that could affect this clearance time at a specific job, more work to develop a simple procedure for establishing reentry clearance would be useful.

**Personal Protective Equipment**

In situations where feasible engineering controls and administrative controls do not adequately lower the potential for overexposure, personal protective equipment is appropriate as a last line of defense. Spray polyurethane foam workers require protection from MDI exposure through both the inhalation and dermal route.

**Respiratory Protection**

The studies reviewed for this paper are unanimous in their opinion that respirators need to be used by spray applicators and helpers, although the type of respirators observed in use and the observed effectiveness of the employer respiratory protection programs and worker attention to appropriate respirator use procedures varies widely.

Supplied-air respirators (SARs) offer the highest levels of protection, supplying clean compressed breathing air from tanks worn by the worker (self-contained breathing apparatus, or SCBA) or through a hose (airline respirators). While offering the highest levels of protection, this type of respirator has the disadvantages of being relatively expensive and requiring ongoing attention to the maintenance of the equipment and breathing air source.

Air purifying respirators (APRs) offer protection by passing workplace air through cartridges which contain filters and / or adsorbents that remove contaminants from the air. APRs are generally less expensive and simpler to maintain, but since they are “negative-pressure respirators”, relying on the wearer’s breathing to draw air through the cartridges, APRs are heavily dependent on the wearer’s ability to put the face piece on and tighten it correctly to prevent leakage around the face-to-face piece seal. APRs typically use elastomeric half- or full-face pieces; the full-face pieces include an integrated polycarbonate lens providing face and eye protection.

One type of APR minimizes the problem of face seal leakage by using a battery-powered air mover to draw air through the cartridges; these are referred to as powered APRs (PAPRs). PAPRs are available in hood or helmet styles that have an integrated face shield.

If APRs are selected for use by polyurethane foam spraying workers, APR cartridges that are NIOSH approved for both organic vapor protection and particulate (preferably P100 rated) are appropriate. Half-face APR face pieces are not preferred, both because the full-face piece provides a higher level of protection and because eye exposure to many of the amine catalysts used can produce a “halo vision” effect [10].

Whatever types of respirators are selected for use by sprayed foam workers, their use in the workplace should be governed by a respiratory protection program established by the employer (in the United States, this is an OSHA requirement). A respiratory protection program addresses such topics as medical approval, fit testing and training of respirator users; approved respirators and their maintenance; and responsibilities for program oversight. Assistance in establishing such a respiratory protection program that is designed for employers using MDI and PMDI is available [17].

**Protective Clothing**

Spray foam workers may experience dermal exposure both by direct contact with the fresh foam surface as well as from spray drift or overspray; both gloves and body protective clothing are required. Lesage et al [7] monitored the foam surface with isocyanate-indicating colorimetric wipes at various times after application. Their results showed the presence of reactive isocyanate groups on the foam surface immediately after spraying, but in all cases (20 samples) no reactive isocyanate was detectable on the foam surface 15 minutes after application. However, some tasks (e.g., trimming excess foam) may result in dermal contact with the interior of the foam before final cure has occurred, so for these tasks wearing chemical resistant gloves will help avoid dermal contact with uncured foam.

Information is available on the resistance of many glove and protective clothing materials to MDI and PMDI [18]. Nearly any gloves designed and constructed to be liquid proof will keep the MDI from sprayed foam material from penetrating to the skin. The most highly permeation-resistant materials are needed only when workers are using solvents (as when cleaning spray guns and equipment); in these cases, the gloves should be selected based on permeation resistance to the solvent being used. Likewise, protective clothing used should be designed to keep the sprayed foam material off street clothes and shoes and be readily disposable. Many of the limited-use coverall and boot cover materials available today (e.g., Tyvek™ and Kleenguard™) do an excellent job of this.

Disposable or limited-use clothing and gloves offer the added advantage of reducing dermal contamination from contact with outside surfaces during storage or re-use.
CONCLUSIONS AND SUGGESTIONS

The literature reviewed in this paper suggest that many aspects of worker exposure and its control during sprayed polyurethane foam application have been well studied and the elements of an effective industrial hygiene program for this important energy conservation product can be reliably described.

Exposure Monitoring

An impinger-based sampling method with an analysis that quantitates MDI oligomers as well as MDI will produce the most accurate characterization of PMDI exposures in sprayed polyurethane foam environments. If a filter-based sampling technique is used, an appropriate multiplier (e.g., four) can help correct for filter under-sampling of reactive spray aerosols and MDI oligomer concentrations.

Exposure Control

Both the spray foam applicators and helpers can be exposed to MDI concentrations in excess of the relevant task and shift occupational exposure guidelines. Administrative controls such as keeping upwind of the spray drift, establishing a work zone around the point of spray application inside of which respiratory and dermal protection is required, and establishing a clearance time before which unprotected re-entry to the sprayed area is prevented are useful tools in controlling exposure. A set work zone distance in all directions from the point of spray application can be effective. Setting an appropriate re-entry clearance time after spraying is also advisable, although it should be noted that the types and levels of amine catalysts in the sprayed foam formulation could make the set distances and times variable. The work zone distance or re-entry clearance time could potentially be shortened or lengthened by considering conditions on a case-by-case basis.

Respiratory protection to prevent over-exposure to MDI is needed for both sprayed foam applicators and helpers while working in the work zone. Either supplied-air respirators or air purifying respirators with cartridges having both an organic vapor sorbent and a particulate filter can provide adequate protection. Where face and eye protection is needed, respirator styles with full-face pieces, hoods, or helmets with an integral face shield are appropriate for use. No matter which respirator is chosen, a respiratory protection program must be established and diligently adhered to if the expected respiratory protection is to be realized.

Protective clothing and gloves are essential to reduce MDI exposure by the dermal route. Clothing items (coveralls, boot covers, etc.) should be selected to keep the sprayed foam material off street clothes and any exposed skin surfaces. Except for the times when solvents are used, any liquid-proof glove should provide adequate protection. Disposal of contaminated gloves and clothing whenever they are removed is an important practice to reduce dermal exposure to MDI.

Further Work for Consideration

This review has suggested several areas where further work would be of benefit in clarifying the understanding or reduction of sprayed foam worker exposures.

ESTABLISHMENT OF RE-ENTRY CLEARANCE TIMES

The indication that some sprayed foam components (i.e., MDI oligomers, blowing agents, and amine catalysts) may remain present in the air following sprayed foam application for longer periods than indicated by MDI concentrations warrants further study in order to help provide additional guidance in setting clearance times for re-entry.

ESTABLISHMENT OF WORK ZONE LIMITS

The author suggests that an appropriate work zone be established around the point of application. Developing some sort of procedure based on reliable field measurements of MDI concentrations, as well as a better understanding of blowing agent and amine catalyst exposures, would help provide the information needed to understand the site conditions and variables that affect the size of the work zone.

EXPOSURES TO BLOWING AGENTS AND AMINE CATALYSTS

The data on exposure to blowing agents and amine catalysts during sprayed foam application is limited. While measures taken to protect workers from MDI exposure during foam spraying would likely provide protection from blowing agent and amine catalyst exposure, having a more complete database would support this assertion.
REFERENCES


BIOGRAPHY

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Mark Spence is currently a consultant specializing in health & safety programs for manufacturing operations and products in the chemical & plastics industry following a 30-year career with the Dow Chemical Company. Following assignments as industrial hygiene chemist and then Laboratory Director of Dow’s AIHA-accredited Industrial Hygiene Laboratory, Mark served as a Senior Industrial Hygienist...
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