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Applicability of Spray Polyurethane Foam Ventilation Guideline for Do-It-Yourself Application Events

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Abstract

Small two-component spray polyurethane foam (SPF) application kits are often applied by Do-It-Yourself (DIY) consumers. The United States Environmental Protection Agency (EPA) publishes a guideline for ventilating a space where SPF is being applied to minimize exposure to mists, vapors, particles and dust. This study sought to assess the applicability of the EPA ventilation guideline in protecting non-application areas of a house from exposure to SPF-associated emissions during a DIY application. Specifically, the research sought to determine if the flame retardant in SPF, Tris(1-chloro-2-propyl)-phosphate (TCPP), migrates outside a temporarily-constructed isolation area during and after a SPF application in the basement of a test home. Tracer decay tests were used to characterize the enhanced ventilation during application. The tracer gas results highlighted the importance of setting up the house internal and external openings to achieve effective isolation and ventilation of the spray area. The DIY spray led to a statistically significant increase in the airborne TCPP concentration in the basement during the first eight hours after application. However, the basement TCPP concentrations during and immediately after the SPF application were not statistically different from the TCPP concentrations in the basement (associated with the application of SPF during construction) measured four years prior to this application. The data indicate that, for the case tested in this study, following the EPA SPF ventilation guideline protected the rest of the house from elevated TCPP concentrations. However, these results may not hold for higher loading rates, lower airflow rates, leakier isolation enclosures or non-analyzed chemicals.

Keywords

Exposure; Tris(1-chloro-2-propyl) phosphate (TCPP); Spray Polyurethane Foam (SPF)

1. Introduction

Spray polyurethane foam (SPF) is a spray-applied insulation that can reduce air infiltration through cracks, seams and joints [1]. The desire to create more energy efficient buildings in

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6. Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

the United States has increased the application of SPF insulation [2, 3]. Two-component SPF application kits can be purchased at home improvement stores or online. Despite some of these products being labelled “For Professional Use Only”, these products are used by Do-It-Yourself (DIY) consumers. Applying the two-component SPF may expose the applicator and residents to a range of chemicals [4, 5].

1.1. Chemicals

Two-component SPF consists of two sets of chemicals, referred to as A-side and B-side. The A-side components are primarily made up of highly reactive isocyanates. These chemicals react with B-side chemicals that include polyols (alcohols) to form the polyurethane polymers that make up the foam. The B-side chemicals also include catalysts to enhance the reactions, flame retardants, and blowing agents. The exact B-side components typically vary for each foam. Once applied, chemicals may emit from SPF since they are not chemically bound to the SPF matrix. Several studies have quantified chemical emissions from SPF using micro-chambers, including Tris(1-chloro-2-propyl) phosphate (TCPP) [6–9]. Exposure to chemicals emitted from SPF may lead to adverse health impacts including asthma, coughing, irritation of eyes and throat, and headaches [10, 11].

Most SPFs use TCPP as the flame retardant at concentrations of 8 % to 13 % by mass [9, 12]. The large initial mass, minimal reactivity and relative low volatility of TCPP (reported boiling points range from 235 °C to greater than 270 °C) [6] allow it to be used as an indicator for the spread of chemicals during a spray event. In contrast, the isocyanates can react prior to or during sampling [10], and therefore are not good indicators of the possible presence of other chemical constituents. The components and concentrations of the catalysts are proprietary and unknown prior to application, and as such are not practical to be used as a surrogate for the presence of other chemicals. Finally, sampling the blowing agent may be difficult depending on the agent used.

1.2. Test house

The tests described in this paper were conducted in the Net-Zero Energy Residential Test Facility (NZERTF), which was constructed on the campus of the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland to support the development and adoption of cost-effective net-zero energy designs, technologies, and construction methods. The two-story house shown in Figure 1 has a basement and attic. The NZERTF is similar in size and aesthetics to homes in the surrounding communities. The house is unoccupied and not furnished other than permanently installed cabinetry. More details about the NZERTF and its performance can be found in Fanney, et al. [13] and Poppendieck, et al. [14].

SPF was applied at the rim joists in the basement and between the first and second floors during construction of the NZERTF in 2012. Previous research identified the SPF as the sole source of TCPP in the NZERTF [15]. To upgrade the data collection systems and to allow the installation of new heating and cooling equipment for future testing, part of the existing SPF insulation was removed from three basement rim joist locations in 2018. A DIY SPF application kit was purchased online to replace the removed SPF.

1.3. Ventilation for SPF application

Few field studies have been conducted for field measurement of chemical concentrations during and after a spray event [16–19]. In the existing studies, airborne chemical concentrations (including TCPP and MDI), during spray event were much higher than the concentrations in post spray samples [16, 20]. Hence, it's important to isolate the spray area and exhaust chemicals outdoors to avoid contaminating the rest of the building during spraying [21]. The effectiveness of the isolation can be influenced by the ventilation strategy during and after spraying.

The United States Environmental Protection Agency (EPA) published a guideline for ventilating a SPF work space to minimize exposure to mists, vapors, particles and dust [22]. The primary goal of the EPA guideline are to protect applicators, their assistants and others at adjacent work locations. The EPA guidance does not directly address re-occupancy decisions, nor does it specifically target DIY application events. The guidelines assume the applicator and assistants will wear appropriate personal protective equipment and clothing, as designated in United States Department of Labor Occupational Safety and Health Administration (OSHA) training materials [23]. The guidelines also assume that no other workers are in the building.

The EPA SPF ventilation guidance is based on four major principles: 1) establish enclosures to isolate the spray area, 2) use fans to direct airflow across the spray area, 3) direct filtered exhaust from the enclosed area to a safe location outside of the building, and 4) continue the exhaust ventilation after the application [22]. From these principles, EPA recommends that a) a temporary local exhaust system be used to immediately remove vapors, mists, dust and particles, b) the established enclosure be kept at a negative pressure relative to the rest of the building, c) the airflow and enclosure be setup to avoid short circuiting (of the spray area by the airflow) and to direct airflow to the exhaust, d) the building HVAC system (if there is one) be turned off and any larger paths connecting the enclosure with other parts of the house (i.e., return grilles, transfer ducts, etc.) be sealed, and e) the spray starts near the exhaust and progress away from the exhaust.

The EPA SPF ventilation guideline does not specify an exhaust ventilation rate, a target negative pressure value for the enclosure, and how long to ventilate after application. These omissions are presumably due to the lack of sufficient published data upon which to make such recommendations. In addition, no field studies have been conducted to evaluate the applicability of the guidance.

2. Objective

The hypothesis of this work is that the EPA ventilation guideline is applicable to a DIY SPF application event. Specifically, the research sought to determine if the flame retardant TCPP was transported outside of the isolation area during and/or after a DIY SPF application in the basement of the NZERTF.

3. Methods

As per the EPA's Ventilation Guidance for Spray Polyurethane Foam Application, an isolation enclosure was installed in the NZERTF basement that was partitioned into two sections, with one containing all three of the insulation cavities and the other section having no spray areas. The goal of the partition was to isolate the work area, to help establish the desired airflow path and to increase the effectiveness of the enhanced ventilation. As described below, the effectiveness of the partition and ventilation arrangement was tested using tracer gas tests prior to the spray event. The SPF was applied by NIST personnel. To determine if airborne TCPP migrated outside the isolation area, airborne TCPP was sampled with Tenax sorption tubes outside of the isolation area. In addition, TCPP masses sorbed onto surfaces were measured with pieces of aluminum foil placed throughout the NZERTF. Most of the foil pieces were placed on both sides of the partitioned basement floor. The foil samples were collected before, during and after the SPF application. Each sample was analyzed in a laboratory separated from the NZERTF within a few hours after collection.

3.1. Isolation Enclosure

The EPA SPF guideline calls for physical isolation of the spray area. In accordance with the guideline, a polyethylene sheet was hung along the main support beam in the unfinished ceiling of the basement to isolate the part of the basement where SPF was to be applied (Figure 2). The volume of the isolation enclosure was approximately 140 m^3. The volume of the entire NZERTF basement is 411 m^3, and the volume of the entire NZERTF is 1300 m^3.

At the end of the support beam that is opposite the lone basement window, the polyethylene sheet was angled in the direction of the spray area, thus creating a short tunnel (Figure 3). For this short tunnel, the high edge of the polyethylene sheet was anchored to one of the open floor trusses. The long edge of the polyethylene sheet was mechanically connected to wood furring strips, laid end-to-end and attached to the basement beam and truss. Duct masking tape was used to cover openings that remained at the truss level. While the enhanced ventilation system was operational, smoke generating sticks were used to verify minimal airflow from the isolation area to rest of the basement above or below the polyethylene partition, which could allow ventilation air to bypass some of the spray locations.

3.2. Ventilation

The EPA SPF guideline recommend that the isolation enclosure be kept at a negative pressure relative to the rest of the building using a temporary local exhaust system. A blower door fan (rated at 8 700 $m^3\ h^{-1}$ or 5 100 cfm) was installed in the basement window to generate a negative pressure and to exhaust the enclosed isolation area outdoors via the basement window well. The pressure difference between the isolation area and the rest of the house was measured using a digital micromanometer. The blower door fan has a manufacturer-calibrated manometer that converts the pressure across the fan to a volumetric flow rate. A small "directing" fan was also placed at the entry to the spray area to promote air movement towards the two application areas located directly in front of it (Figure 2). As noted above, three transfer grilles that allowed air to flow between the basement and first floor under normal building operation were sealed for the spray event.

Tracer gas decay tests were used to examine the effectiveness of two different configurations to ventilate the isolation enclosure. They also allowed an independent measurement of the blower door fan airflow rate. Sulfur hexafluoride (SF_6) was injected into the isolation enclosure between locations 2 and 3 and sampled near location 2. The SF_6 was injected while the directing fan was on and the exhaust fan was off. The directing fan mixed the SF_6 throughout the isolation enclosure for 15 minutes. After this mixing, an initial concentration higher than the upper limit of the photoacoustic infrared detector (36.5 mg m^{-3}, 6 ppm) of SF_6 was reached. The SF_6 concentration decayed once the exhaust fan was turned on (the directing fan remained on). Within the decay period, only the SF_6 concentrations between the upper and lower (3.0 mg m^{-3}, 0.5 ppm) calibration limits of the detector were used to calculate the decay rate. The reported repeatability and accuracy of the detector are 1% and 5%, respectively. By assuming that the SF_6 was well mixed in the enclosure during the decay period, the decay rate was calculated according to the procedure in ASTM E741–11[24].

3.3. Spray Foam Event

A low pressure, closed cell SPF application system capable of covering 0.25 m^3 was applied to three locations in the basement rim joists (total volume filled 0.12 m^3), where new conduit intrusions had been installed, as shown in Figure 2. In addition, a mock 0.4 m by 2.4 m wall cavity constructed from lumber was sprayed to allow more foam to be sprayed as part of this experiment. The SPF was applied in three lifts in the rim joists, rotating between each application location during each lift. Next, a single application was done on the mock wall cavity followed by one final lift to the two largest cavities, which were those located in the corner nearest the directing fan. A comparatively small amount of foam was also dispensed into a lined trash. The trash can was positioned between the window with the exhaust fan and the rim joist cavity located along that same wall. The trash can spray helped the applicator to become familiar with the system and provided a place to clear the spray head between rim joist applications. In total, 6.2 kg of SPF was applied over 25 min.

Immediately prior to the application of SPF, the temperature at the airborne sampling location (at an elevation of 1.3 m) was 22.4 °C and the relative humidity was 54 %. During the spray event, the house's heating and air conditioning system and heat recovery ventilator (HRV) were turned off. Outside air was drawn into the building by the temporary exhaust system as described below. The spray event took place in summer (July 2018) with the air conditioning system off. At the end of the eight hours of the enhanced ventilation, the temperature at the airborne sample location rose to 26.0 °C and the relative humidity decreased to 47 %. The average temperature and relative humidity were 21.8 °C (standard deviation = 1.2 °C) and 48.4 % (5.8 %) at this location over the next seven days during which TCPP samples were taken.

3.4. Airborne TCPP sampling

Airborne TCPP was sampled in the basement and the first and second floors of the NZERTF prior to the SPF spraying. Two Tenax sorption tubes (6.35 mm ID and 88.9 mm long) were connected in series for each sampling event, with the second tube used to ensure no TCPP breakthrough from the first tube. Sampling in this manner does not separate gaseous, particulate and aerosol phase of the sampled chemical. Therefore, total airborne concentrations (all phases) were measured. Duplicate or triplicate pairs were collected during each sampling event. Flow rates through the tubes were controlled with mass flow controllers at 100 mL min^{-1} for 1.4 h to 3.4 h and confirmed with a calibrated bubble flow meter. All basement samples were collected just outside of the polyethylene sheet used to isolate the spray area (Figure 2).

Once sampling was over, the tubes were disconnected and analyzed using a thermal-desorption, gas chromatograph mass spectrometer (TD-GC-MS). The thermal desorption started at 30 °C for 0.5 min^{-1}, ramped 1 °C s^{-1} to 300 °C and held for 8 min. The transfer temperature to the gas chromatograph was 350 °C. The gas chromatograph used a 30 m, 0.25 mm ID, and 0.25 μm film thickness column with a flow of 1 mL min^{-1} of helium. The column oven temperature started at 100 °C for 1 min, ramped at 15 °C min^{-1} to 310 °C and held for 3 min. The mass spectrometer was operated in full scan mode. The mass-to-charge ratios for quantification of the three TCPP isomers and Triamyl Phosphate (TAP, used as internal standard) were m/z = 125, 99, 99, and 99, respectively.

Standards curves were made by spiking 0.2 μL to 2 μL of 45 ng mL^{-1} of TCPP in methanol and 1 μL of 50 ng mL^{-1} TAP directly onto the bottom of the Tenax bed in the sorption tube. Five-point standard curves were used, typically evenly spaced from 10 ng to 50 ng TCPP per injection. Instrument detection limits for TCPP were determined by multiplying three times the standard deviation of seven replicates at a concentration that was less than five times the determined method detection limit [25]. The instrument TCPP detection limit was 6 ng per injection and the method detection limit for the TCPP air concentration was 0.21 μg m^{-3} to 0.70 μg m^{-3}, depending on the sample volume. Only values above the method detection limit for the corresponding sampling volume are shown below. The average relative standard deviation of 23 triplicate samples in the basement prior to the spray event was 7.9 %.

3.5. Sorbed TCPP

To determine the masses of TCPP sorbed onto surfaces throughout the house during the spray, aluminum foil disks with a diameter of 65 mm were placed on the floor throughout the house. In these tests, the sorbed mass on each disk includes both TCPP adsorbed to the surface from the gas phase and TCPP mass deposited on the surface via particles. Prior to the spray event, disks were placed throughout the house for ten days to check for background adsorption of TCPP. Immediately prior to the spray event, three sets of disks were placed within the enclosed spray area, while three additional sets of disks were placed in other areas of the basement outside of the polyethylene sheet used to isolate the spray area (Figure 2).

Disks at locations 2 and 3 (Figure 2) were sampled six times in duplicate over the course of 30 hours (0.25 h, 1 h, 3 h, 6 h, 24 h, 30 h). The disks at the other basement locations were sampled at a subset of three of the same times, with one disk sampled each time. The disks at nine other locations in the first and second floors of the house were sampled after 24 hours, with one disk sampled in each location.

After the end of the designated time, each disk was placed into a 40 mL glass vial with a polytetrafluoroethylene (PTFE) cap. The vials were then transported to the lab. Each disk was taken out from the vial and cut into small pieces with a scissors. The scissors was cleaned with methanol between each sample. The pieces were then put back into the 40 mL vial and 10 mL of methanol was added to each vial. The vials were then sonicated for 45 min at 25 °C. The extracts were stored at 4 °C until analysis.

Before analysis 10 μL Triamyl Phosphate (TAP, 4.5ng/μL) was added into 100 μL of each extract as an internal standard. All samples were then analyzed by GC-MS. The chromatographic column was Rtx-5MS (30m x 0.25 mm (i.d.) x 0.25 μm thickness). The carrier gas was high purity helium (> 99.99 %). Samples (1 μL) were injected into an injector at 30 °C, which was then ramped up to 280 °C at a rate of 720 °C min^{-1} with a splitless time of 2 min. The column oven temperature was held for 1 min at 40 °C, and then ramped up to 300 °C at a rate of 15 °C min^{-1} and then held for 2 min. The mass spectrometer was operated in full scan mode. The mass-to-charge ratios for quantification of the three TCPP isomers and TAP were m/z = 125, 99, 99, and 99, respectively. The total TCPP concentration for standard curves ranged from 0.1 ng/μL to 4.5 ng/μL. The instrument detection limit for each of the three TCPP isomers was 0.05 ng [25]. The method detection limit was 7.6 ng per aluminum disk. TCPP was not detected in the triplicate field blanks collected with the spray event samples. The average absolute relative difference of the 4 duplicate samples in the basement, in which both samples were above the detection limit, after the spray event was 33 %.

4. Results and Discussion

To determine if the flame retardant TCPP migrated outside the isolated area during and after the SPF application in the basement of the NZERTF, the airborne TCPP concentrations outside the isolated area and the TCPP masses on the surface of aluminum foil pieces were measured. Before the TCPP migration measurements, the effectiveness of the ventilation was evaluated via the tracer gas decay tests as described earlier.

4.1. Ventilation

The isolation enclosure in combination with the temporary local exhaust system were used to limit the migration of the chemicals and aerosols emitted during the spray event to the rest of the house. The EPA ventilation guideline for such enclosures do not address two important issues: the exhaust airflow rate, and the airflow and pressure relationships of the insolation enclosure to other building volumes.

There are only limited data on ventilation rates during spray events. Typically, ducted fans designed to operate at roughly 1 000 m^3 h^{-1} to 5 000 m^3 h^{-1} (600 cfm to 3 000 cfm) are used to exhaust the spray location [16]. Regardless of the fan's designed airflow rate, the actual flow through the fan depends on the pressure that the fan must overcome, which in turn depends on the connection of the exhausted volume to the rest of the building and the outdoors. The fan used to exhaust the basement in these tests was rated at 8 700 m^3 h^{-1} (5 100 cfm), but the measured flow once installed was 5 000 m^3 h^{-1} (3 100 cfm) based on the manufacturer's calibration.

The physical isolation barrier in the basement was not expected to fully achieve a negative pressure relative to the rest of the basement, as there was a 1 m wide gap near the directional fan to allow access to the isolation enclosure (Figure 3). In practice, the actual volume under negative pressure is dependent upon the airflow connections to the rest of the house, specifically the airflow resistance along the path that the makeup air takes to exhaust fan. Two house configurations were employed in the pre-spray tracer gas tests to assess the impact of those configurations on the airflow through the isolation enclosure: #1) the basement door to the first floor open and all exterior windows and doors on the floors above closed and #2) the basement door closed and two windows on the first floor open. In Configuration #1, the airflow resistance to the isolation enclosure exhaust was dominated by the small amount of leakage in the exterior building envelope of the NZERTF. For Configuration #2, the airflow path to the exhaust included only the (much leakier than the exterior walls) basement ceiling and basement door undercut.

Tracer decay tests were conducted for both configurations, and the measured decay rates are shown in Table 1 along with the 95 % confidence interval. Values were calculated per the procedure in ASTM E741–11. The tracer gas decay rate for Configuration #2 was about four times higher than the rate for Configuration #1, which reflects the lower airflow resistance to the exhaust fan when the house windows were open. As a result, Configuration #2 was used for the spray event with the expectation that it would result in SPF aerosols and chemicals being removed from the isolation enclosure more effectively.

Under Configuration #2, the upstairs was at essentially the outdoor pressure. The basement pressure was −117 Pa relative to the outdoors and rest of the NZERTF. In this configuration, the tracer gas decay rate can be multiplied by the basement volume to estimate the airflow rate through the fan. Using the average values for tests 2 and 3 in Table 1, and the basement volume of 410 m^3, results in an exhaust flow rate of 5 060 m^3 h^{-1} (2 980 cfm). This is similar to the value from the manufacturer's calibrations of 5 000 m^3 h^{-1} (3 100 cfm).

The tracer gas decay rate was not measured after the enhanced ventilation period ended (spanning the spray event and eight hours afterwards), when the house was configured and operated normally (no exhaust fan, forced-air system and HRV operating, and windows and basement door closed). The HRV operated at the minimum airflow specified in ASHRAE 62.2–2010. The total (HRV plus envelope infiltration) outdoor air change rate of the house measured during monthly tests in 2013 and 2014 ranged from 0.14 h^{-1} to 0.23 h^{-1}, which corresponds to 182 m^3 h^{-1} to 300 m^3 h^{-1}(107 cfm to 176 cfm) [14].

4.2. Airborne TCPP Concentrations

All airborne TCPP concentrations were measured outside of the isolation enclosure, opposite from the spray locations (triangle in Figure 2). The average airborne TCPP concentration (Figure 4) at two to four weeks prior to the spray event was 1.36 μg m^{-3} (number of samples = 19, standard deviation = 0.19 μg m^{-3}). A single data point was analyzed during the spray event, resulting in a concentration of 2.18 μg m^{-3}. The average TCPP concentration during the 8-h enhanced ventilation period after the spray event was 2.48 μg m^{-3} (number of samples = 4, standard deviation = 0.37 μg m^{-3}). This 1.12μg m^{-3} increase in TCPP concentration (after spray event relative to before) is statistically significant (Student t test, P= 0.0001). This increase indicates that some TCPP has been transported outside of the isolation enclosure to the rest of the basement. However, after the initial peak, the TCPP concentrations decayed within 26 hours.

For the basement samples taken at 26 hours to 7 days after the spray event (all basement post spray samples were between 0.5 μg m^{-3} and 2.0 μg m^{-3}, the average TCPP concentration was 1.26 μg m^{-3} (number of samples = 12, standard deviation = 0.23 μg m^{-3}), which is not statistically different from the TCPP concentration prior to the spray event (Student t test, P= 0.1736). An increase in TCPP concentration five days after the spray (dashed vertical line in Figure 4) coincided with the polyethylene sheet being removed from the basement. There was also no significant difference in the TCPP concentration measured on the first and second floors before and after the SPF application (Student t test, P= 0.5198; number of samples before = 4, average before = 0.36 μg m^{-3}, standard deviation 0.08 μg m^{-3}; number of samples after = 5, average after = 0.33 μg m^{-3}, standard deviation 0.08 μg m^{-3}).

The TCPP concentrations in this study are an order of magnitude lower than those measured in other SPF field studies. The measured TCPP concentrations in an attic 12 h to 168 h after a closed-cell SPF application ranged from 19 μg m^{-3} to 119 μg m^{-3}. The much higher concentrations are consistent with the fact that more SPF were sprayed by Ecoff, et al. [1] (567.5 kg) compared to current study (6.2 kg). Tian, et al. [2] measured TCPP concentrations in several locations throughout a retrofitted house from 5 h to 100 h after closed-cell SPF application, ranging from 10 μg m^{-3} to 100 μg m^{-3}. The much higher concentrations are consistent with the fact that more SPF were sprayed by Tian, et al. [2] (most of the exterior of a three-story, single family house) compared to current study (part of basement rim joists). Besides the type and amount of SPF applied, the ventilation conditions would also influence the concentrations. A portable fan was used to exhaust air during SPF event in Ecoff, et al. [1] and the air change rates reached 10 h^{-1} within the spray space. The house measured by Tian, et al. [2] had average air change rates after application of 3.05 h^{-1}, while it is unknown if any enhanced ventilation was used during spray.

To put the TCPP concentrations into perspective, it is also useful to compare them with historical TCPP concentrations in the basement of the NZERTF. A total of 30 m^2 of rim joists in the basement and between the first and second floors were insulated with SPF during the construction of the NZERTF in 2012. TCPP concentrations in the basement have been quantified since the 2012 installation. Basement TCPP concentrations were analyzed from 2014 through 2018 (Figure 5) in the same manner as outlined above. The TCPP concentrations during the 2018 DIY spray event and enhanced ventilation period (2.2 μg m

$^{-3}$ to 3.0 μg m^{-3}) were not statistically different (Student T Test, p = 0.0415) from the TCPP concentrations (2.2 μg m^{-3} to 3.4 μg m^{-3}) measured in the basement roughly two years after the SPF application during NZERTF construction (2014 measurements.

The data in Figure 4 and Figure 5 demonstrate, for the tests in this study, following EPA ventilation and isolation guidelines was sufficient to prevent significantly elevated airborne TCPP concentrations in the non-application areas of the NZERTF basement 26 hours after a DIY application event. The relatively minimal change in airborne TCPP concentrations is likely due to a combination of the high ventilation rate (5 000 m^3 h^{-1}), short spray time (25 min) and small application mass (6.2 kg). However, these trends may not hold for higher loading rates, lower ventilation rates, leakier enclosures or other non-analyzed chemicals.

4.3. Sorbed TCPP Mass

Aluminum foil disks with a diameter of 65 mm were placed throughout the house to determine the mass of TCPP sorbed to the aluminum disks before, during and after the spray event. No TCPP was detected on disks exposed for ten days prior to the spray event.

The measured TCPP masses varied at different locations within the enclosed area. TCPP was detected on a total of 13 of the 15 samples at location 1 in Figure 2 (referred to as "exhaust airstream") and location 2 (located between the spray locations). These locations were both within the isolation enclosure. The "exhaust airstream" samples at location 1, which were directly in the exhaust airflow path, averaged 36 ng TCPP per sample. In contrast, the samples at location 2, with presumably lower airflow, averaged 10 ng per sample. Location 4 was also within the isolation enclosure but in an area that was likely out of the primary exhaust airstream. There was no TCPP detected at location 4, indicating that such areas can have lower TCPP exposure during a spray event.

TCPP was above the detection limit for 5 of the 15 samples in the basement outside of the isolation enclosure (average detected TCPP concentration 9.6 ng). TCPP was also detected in 2 of the 9 samples on the first and second floors (average detected concentration 8.4 ng).

Figure 6 shows the sorbed mass of TCPP over time, with time zero being the conclusion of the SPF application. Note that the enhanced ventilation was stopped eight hours after the SPF application. The sorbed TCPP mass at the "exhaust airstream" location increased with time up to 24 h. This indicates that TCPP was emitted from the primary spray locations after the enhanced ventilation ended. The fact that the adsorbed mass at this location increased by over 10 ng after the spray event ended and again after the enhanced ventilation was turned off, suggests that the sorbed TCPP is not solely a function of the aerosol deposition during the spray event but also adsorption from the TCPP remaining in the air, as most aerosols of 5 μm or greater in diameter would have deposited within the first 24 h time frame.

The TCPP mass in all other detected samples, including the two locations on the first and second floor, were consistently near 10 ng. The detection of the TCPP at NZERTF locations outside of the isolation enclosure, but not prior to the spray, indicates that some TCPP from the spray was transported throughout the house. This is consistent with that higher airborne TCPP concentration was detected with 26 hours after spray.

To the best of our knowledge, there is no existing data for direct comparison of TCPP adsorption onto aluminum foil. In a study by Tian, et al. [2], carpet and drywall samples were placed throughout the retrofitted home immediately after a spray event completed and the TCPP concentrations on these two materials were quantified. The surface concentrations after 26 h of exposure ranged from 1 470 μg m^{-2} to 1 770 μg m^{-2} by Tian, et al. [2], while the maximum surface concertation on aluminum foil in current study after 24 h exposure was 15 μg m^{-2} (50 ng in the exhaust airstream Figure 6). As discussed above, the house in the Tian, et al. [2] study used more SPF per volume of the room resulting much higher airborne TCPP concentrations than the concentrations in current study. Furthermore, the carpet and drywall may have higher adsorption ability than aluminum foil due to their porous structures.

To put the spray in perspective, 6.2 kg of SPF was applied. Assuming that 10 % of the SPF mass was TCPP [26], approximately 600 g of TCPP were sprayed in the basement. The average mass in the NZERTF that was not in the “exhaust airstream” sampling location was 6.5 ng (non-detect samples assumed to have concentrations that are half the detection limit) or a surface concentration of 2.0 μg m^{-2}. Assuming a uniform concentration throughout the basement, this surface concentration corresponds to 0.3 mg of TCPP on the basement floor (or roughly 0.05 % of the applied TCPP mass). This estimate does not account for TCPP adsorption onto other surfaces (HVAC ducts, plumbing, walls, etc.).

5. Conclusion

A DIY SPF kit was used in the NIST NZERTF to re-insulate portions of the exterior wall. Installation followed EPA SPF ventilation guideline by using a fan to direct airflow across the work spray area, isolating the spray area, directing exhaust outside of the building, and ventilating after the application. Although the EPA SPF ventilation guideline calls for ventilation, negative pressure in the isolation area, and ventilation after application, no values are recommended for these parameters. More research is warranted to establish recommendations for ventilation flow rates, enclosure pressures relative to the remainder of the building and ventilation time after application. The EPA SPF ventilation guideline was followed in this study for a spray event at the NZERTF by installing a blower door fan in the basement window, which was in the isolation enclosure. The basement was negatively pressurized to −117 Pa, compared to the outdoors and rest of the NZERTF, with the 5 000 $m^3 h^{-1}$ blower door fan operating during the spray event and eight hours afterwards. This study demonstrates that the isolation enclosure, created by a polyethylene sheet, may not be totally effective in isolating the spray area from the surrounding volume. It also demonstrates that the house configuration that defines the makeup airflow path to the exhaust fan is important for increasing the impact of the enhanced ventilation.

The DIY spray increased the airborne TCPP concentration in a statistically significant manner in the basement (outside the isolation enclosure) only during the first eight hours after application. The TCPP concentrations during and immediately after the SPF application were not statistically different than TCPP concentrations in the basement four years prior and two years after SPF was sprayed during initial construction. The sorbed TCPP masses on the aluminum discs detected in samples taken at locations between the primary application areas and the exhaust fan were higher than the masses at other measured locations. No TCPP mass was detected in zones outside the primary airflow path within the isolation enclosure. Together, the data indicate that, for the tested case in this study, following the EPA SPF ventilation and isolation guideline protected the rest of the NZERTF from significant TCPP contamination.

The relatively minimal change in the airborne TCPP concentrations and sorbed TCPP mass was likely due to a combination of the high ventilation rate (5 000 $m^3 h^{-1}$), short spray time (25 minutes) and small application mass (6.2 kg).

However, these results may not hold for higher loading rates, lower ventilation rates, other isolation enclosure designs and for non-analyzed chemicals. This small investigation was limited by the fact that the pressure was not monitored throughout the structure. Additional studies to support ventilation guidance for SPF applications should target pressure relationships between the isolation enclosure and the remainder of the building and the outdoors. In addition, future guidance should provide exhaust airflow rates that are normalized by the enclosure floor area or volume.

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Highlights

- Polyethylene sheet enclosures may not completely isolate the SPF application area.
- EPA ventilation guideline protected the rest of building from TCPP contamination.
- Following the guideline may not be sufficient for all SPF application scenarios.

Figure 1.
NZERTF located on the NIST campus in Gaithersburg, Maryland, USA.

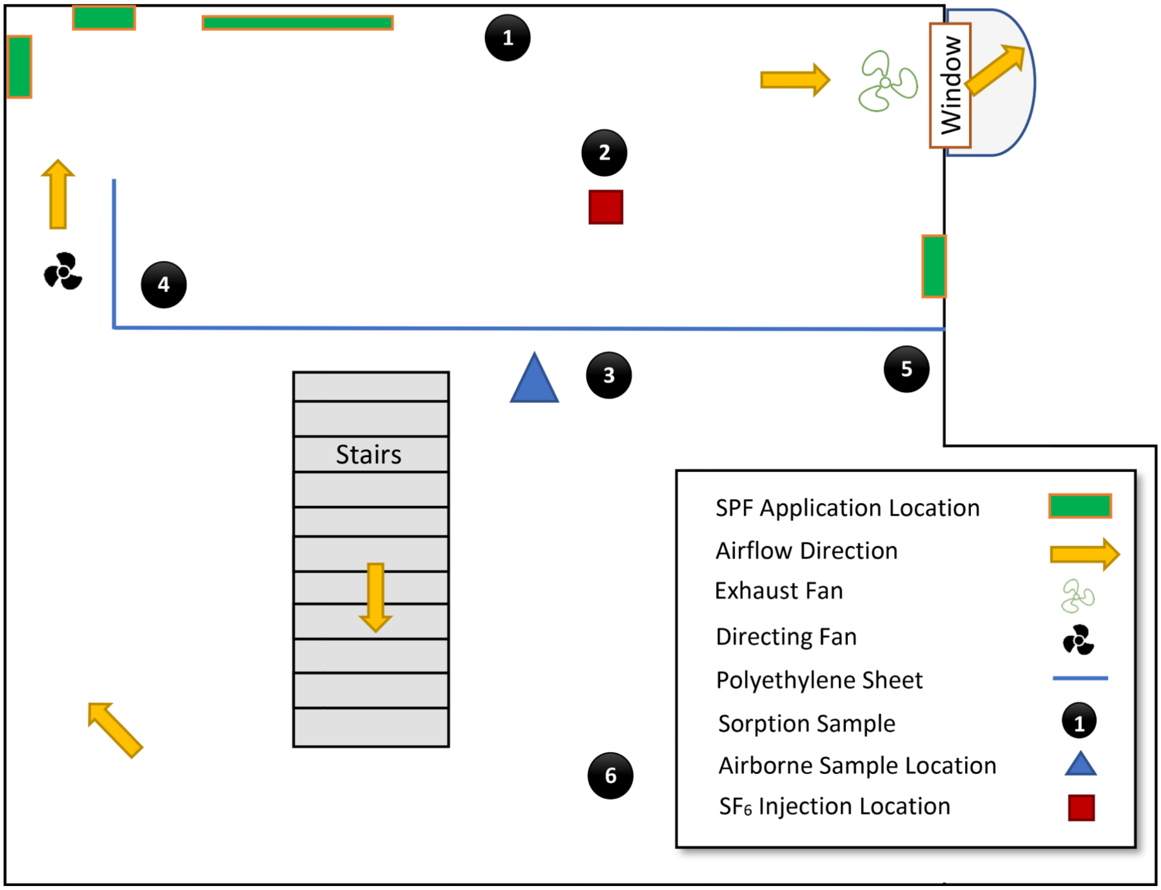

Figure 2.
Diagram of NZERTF Basement during SPF application event. Intended airflow path was down the stairs and out the the window.

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Figure 3.

Photograph of the isolation area formed with poly polyethylene sheet and blower door fan in the window well (Left). Photograph of the directing fan and access area to the isolation area (Right).

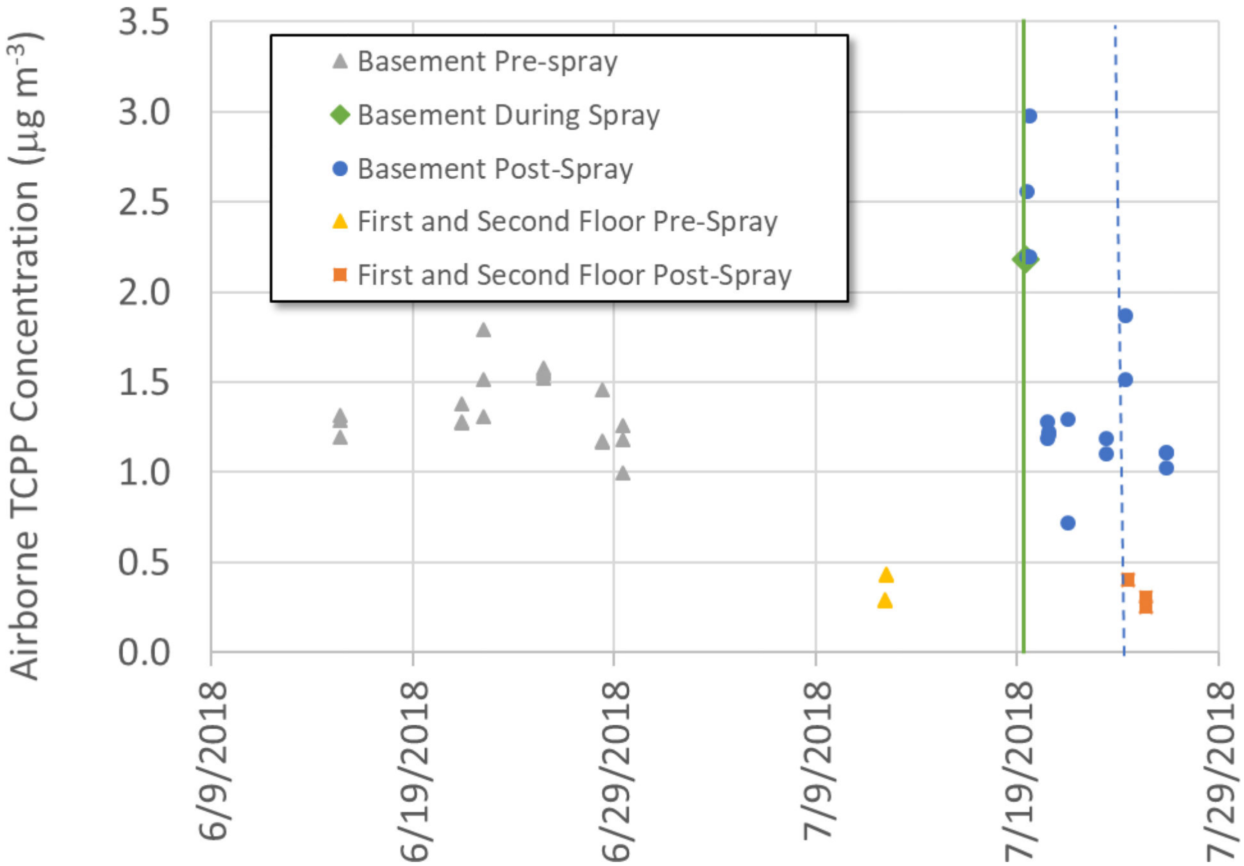

Figure 4.

Airborne TCPP concentrations before, during and after spray event. The solid vertical line indicates the timing of the spray event. The dashed vertical line indicates the timing of removing the polyethyelen sheet.

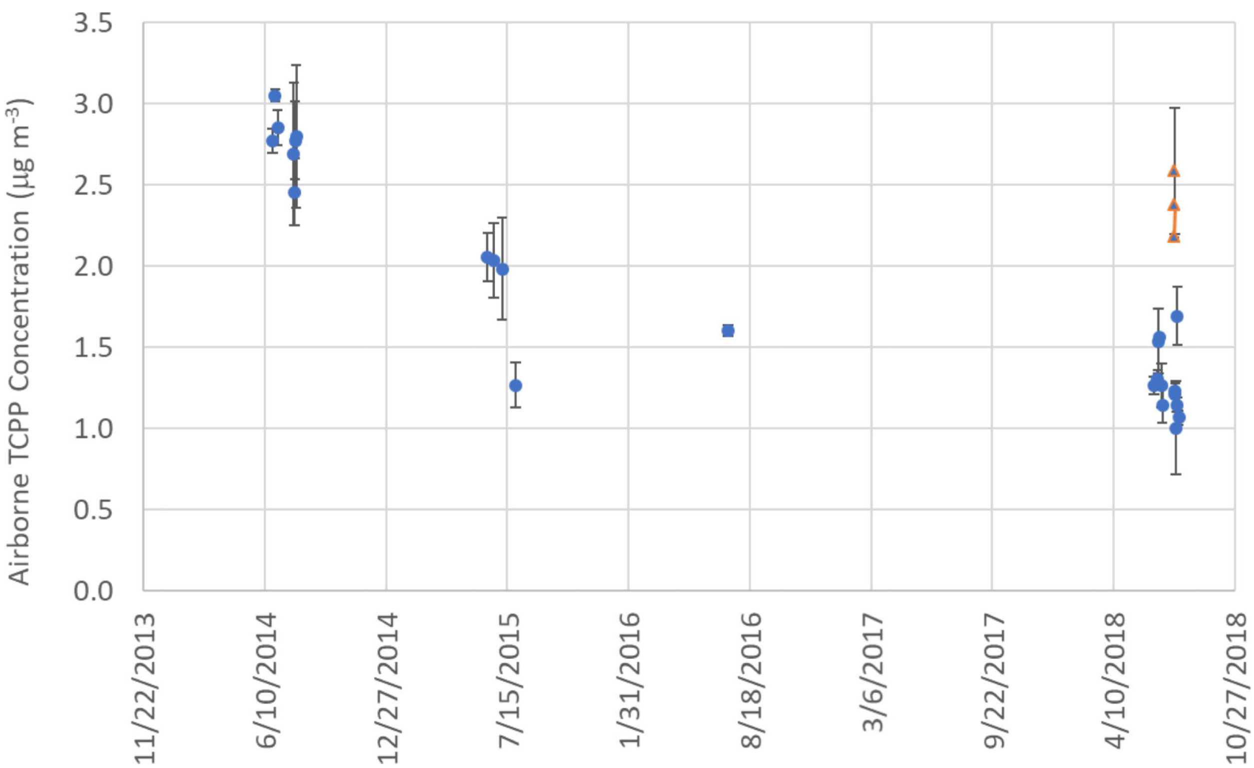

Figure 5.
Airborne TCPP concentrations in summer months in the years prior to the DIY SPF application event. Only one set of measurements was performed in 2016. Error bars show one standard deviation of triplicate data collection. Triangle data points are from during the spray event.

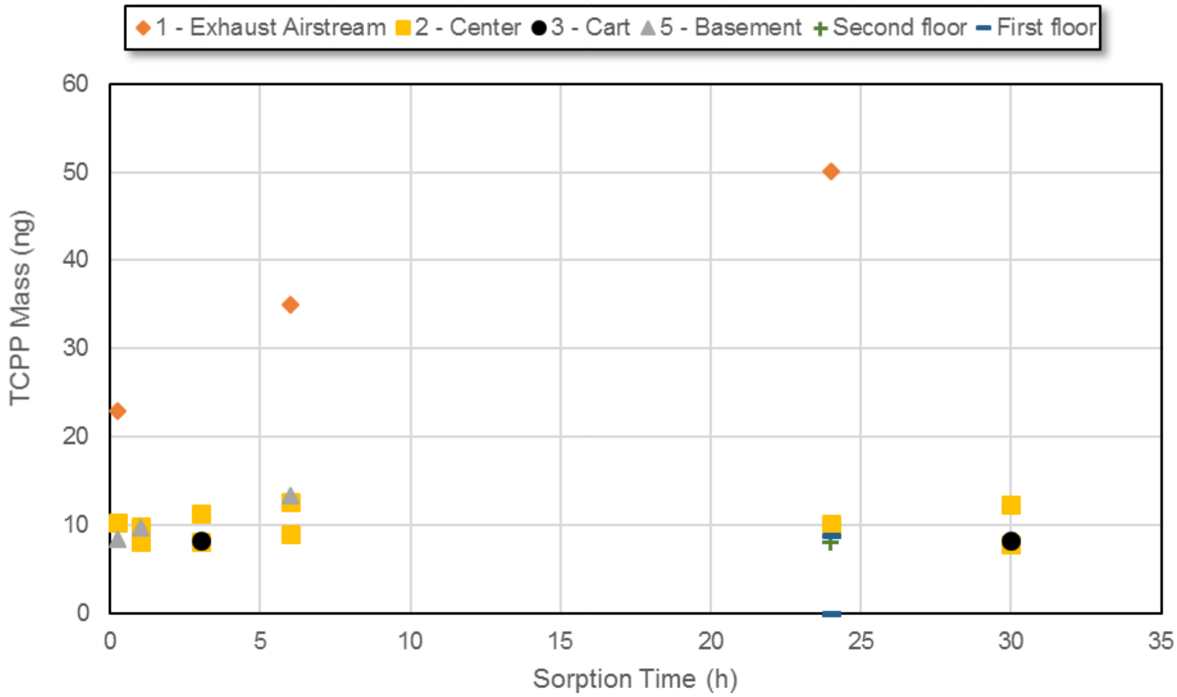

Figure 6.

Sorbed TCPP mass on aluminum foil disks at different times and different locations after spary event Numbers in the legend correspond to locations identified in Figure 2. Diamond and sqaure (orange and yellow) samples were taken within the isolation area, while circle and triangle (grey and black) samples were taken in the basement outside the isolation area. (There was no TCPP detected at locations 4 and 6.)

Table 1.

Measured tracer gas decay rate during enhanced ventilation.

Injection Number	Configuration	Dominant Airflow Path to Basement	Tracer Gas Decay Rate (h^{-1})	95 % Confidence Interval (h^{-1})
1	1[a]	Building Envelope	2.9	±0.2
2	2[b]	Basement Ceiling	13.8	±2.2
3	2[b]	Basement Ceiling	11.1	±1.9

[a] the basement door to the first floor open and all exterior windows and doors on the floors above closed

[b] the basement door closed and two windows on the first floor open.