

**Flame retardants in building insulation:  
a case for re-evaluating building codes**

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## **ABSTRACT**

US building codes balance the consideration of hazards to public safety, health and general welfare. Current codes require foam plastic insulation materials to have both protection by a thermal barrier and compliance with Steiner Tunnel test requirements. The Steiner Tunnel test is met by adding flame retardant chemicals to the foam. Studies demonstrate that the Steiner Tunnel test does not give reliable fire safety results for foam plastic insulations. Foams that meet the Steiner Tunnel test still pose a fire hazard if used without a code-mandated thermal barrier. Insulations protected by a thermal barrier are fire safe and the use of flame retardants does not provide any additional benefit. Evidence is examined of the health and ecological impacts from the added flame retardant chemicals. Changing the building codes could prevent health and environmental harm from the toxicity of these substances without a reduction in fire safety. Plastic foam insulations that are protected by a thermal barrier should be exempted from the Steiner Tunnel test and the need to use flame retardants. This change would align US codes with code regulations in Sweden and Norway and ensure the fire safety as well as improve health and environmental impacts.

## **KEYWORDS**

building codes, fire safety, flame retardants, flammability, insulation, public health, Steiner Tunnel, thermal barrier, toxicity

Word count: 8,788

## **INTRODUCTION**

For improved energy efficiency and to reduce global climate change, the use of plastic insulation materials with high R-values such as polystyrene, polyisocyanurate, and polyurethane is increasing in buildings and especially in “green” buildings. In the U.S., the International Code Council (ICC), ASTM International (formerly known as the American Society for Testing and Materials, ASTM), and the National Fire Protection Association (NFPA) set flammability requirements for plastic foam insulations and other building materials. These requirements are found in building codes, insurance requirements, and other fire regulations for building materials. To meet these performance requirements for plastic insulation materials, flame retardant chemicals-- usually halogenated organic compounds with chlorine or bromine bonded to carbon-- are added at percent levels to the insulation. Flame retardants whose primary use is in building insulation are found at increasing levels in household dust, human body fluids, and in the environment, and have been associated with neurological and developmental toxicity, endocrine disruption, and potential carcinogenicity (Covaci et al., 2006; Marvin et al., 2011; Van der Veen & de Boer, 2012). Thus highly energy efficient buildings are likely to contain potentially harmful flame retardant chemicals in their insulation.

Given the additional cost of adding flame retardants to foam building insulation and their potential adverse health and ecological impacts, an important question is whether their use leads to an improvement in fire safety. In this paper we evaluate the provisions in building codes leading to requirements for both a thermal barrier and a flame spread rating for foam insulation, as well as evidence that the thermal barrier alone is equally effective in providing fire safety. Though the goals of fire safety and long-term human and ecological health might appear to be competing, we will discuss how, in this case, it may be possible to eliminate the use of flame retardants in plastic foam building insulation without a reduction in overall building fire safety.

## **HISTORY**

Until 2000, the U.S. had three separate building code bodies and three separate “model” building codes. “Model” means that the codes are published by private organizations, and only acquire a regulatory status when states, counties, or municipalities enact them into regulation. The three organizations merged to form the International Code Council (ICC) which issued the International Building Code (IBC) and International Residential Code (IRC) in 2000. The ICC re-issues their codes every three years, and most U.S. jurisdictions use some version of the IBC and the IRC, occasionally supplemented by local provisions. The current ICC provisions governing foam plastic insulation in buildings are essentially unchanged from the predecessor building codes that had been in place for over five decades.

Code provisions regulating plastic insulations in buildings were first introduced in the early 1960s (ICBO, 1961). These included a requirement for ASTM E 84 testing, known as the Steiner Tunnel test (ASTM, 2012). Though the goal of these provisions was to ensure that insulations did not show rapid flame spread over their surface, Steiner Tunnel testing did not result in foams with acceptable flame spread behavior. In the 1970s, serious fires occurred when exposed foam plastic insulation was installed in unfinished basement rooms, garages and other habitable spaces.

To address this issue, the 1976 Uniform Building Code (UBC) introduced Section 1717, regulating foam plastics with some new provisions (ICBO, 1976) as described by Williamson and Mowrer (Williamson & Mowrer, 2004). According to this section, foam plastics are required to be separated from the interior of a room by a “thermal barrier,” usually ½ inch (12.7 mm) thick gypsum wallboard, which protects the foam underneath from the heat of a fire. The UBC did allow foams to be used uncovered if they met certain large-scale (corner, or room fire test) test requirements, but such foams are expensive and will not be found in exposed-use in general purpose buildings. When the thermal barrier requirement was introduced in 1976, the UBC code maintained the 1960s requirement for Steiner Tunnel testing of the foam (ICBO, 1976). The dual set of requirements for both a thermal barrier and Steiner Tunnel test were incorporated into other model building codes and every subsequent edition of the IBC and IRC (ICC, 2000a, 2000b, 2003a, 2003b, 2006a, 2006b, 2009a, 2009b, 2012a, 2012b) The current wording in the 2012 IBC is “foam plastic insulation and foam plastic cores of manufactured assemblies shall have a flame spread index of not more than 75 and a smoke-developed index of not more than 450 when tested in the maximum thickness intended for use in accordance with the ASTM E 84 or UL 723 (ICC, 2012a).” (2012 IRC R316.3, 2012 IBC section 2603.3). It is important to note that the codes do not specify that chemicals be added to foam plastic insulation, but in practice organohalogen flame retardant compounds are added to meet the Steiner Tunnel test requirements. Also, U.S. building codes do not regulate materials usage during construction or demolition, and all requirements refer only to the condition as found after completion of construction. Thus, since 1976 in the U.S., foam plastic insulations have both met the Steiner Tunnel requirements and been protected from fire by a thermal barrier. The code provisions in other countries are not discussed in detail here, but the same principles will apply to codes which mandate both flame-spread ratings and thermal barriers for foam plastic insulations.

In 2003 and 2009, respectively, the intent statements of the IBC and the IRC were expanded: "The purpose of this code is to establish minimum requirements to safeguard public safety, health and general welfare...from fire and other hazards attributed to the built environment and to provide

safety to fire fighters and emergency responders during emergency operations (ICC, 2003a, 2009a) (2012 IRC R101.3; 2012 IBC 101.3)." This expanded scope covers firefighters and emergency responders and recognizes a larger range of hazards, suggesting a reconsideration of code provisions in order to reduce the use of materials with negative health or ecological impacts.

## **EVALUATING BUILDING CODES FOR FOAM INSULATION**

Are both the thermal barrier and Steiner Tunnel requirements necessary? A number of factors need to be examined to assess this:

1. Adequacy of the thermal barrier
2. Validity of the Steiner Tunnel test for plastic foams
3. Fire propagation into a cavity constructed in violation of codes
4. Behaviour of exposed foam insulations installed in violation of codes
5. Potential value of a more accurate test

### *1. Adequacy of the thermal barrier*

During a room fire under pre-flashover conditions, gypsum wallboard can essentially withstand indefinitely long fire exposure. After flashover has occurred, a gypsum board barrier will keep fire, heat, and ignition sources originating in the room from impinging on the foam insulation for at least 15 minutes. The concept of a thermal barrier being able to withstand a post-flashover fire for a certain length of time is termed a 'finish rating'<sup>1</sup> in the building codes. According to the 2012 IBC Section 2603.4 and IRC Section R316.4, after 15 minutes, the temperature at the interface of the thermal barrier and foam (back of thermal barrier/ front of foam) cannot exceed the criteria of NFPA 275: 121°C (250°F) average with 163°C (325°F) at one peak value thermocouple (NFPA, 2009). This is far below the auto-ignition temperature of plastic foams, which are in excess of 400°C for polystyrene and polyurethane (Babrauskas, 2003). Gypsum wallboard of ½-inch or greater thickness is accepted by the codes as a complying thermal barrier. Materials such as concrete and soil are also accepted as compliant thermal barriers. For other materials, the codes require testing according to NFPA 275, with the time and temperature criteria identified above (IRC R316.4, IBC 2603.4).

Research supports this code requirement. On the basis of conducting ASTM E 119 fire tests (which simulate a post-flashover fire), Zicherman et al. showed that ½ inch gypsum wallboard barriers obtained from diverse manufacturers provide 15 – 20 minute finish ratings, meeting the intent of the codes (Zicherman & Eliahu, 1998). At the end of that time period, the gypsum board layers had not cracked or fallen off, and the back face temperature rise values were so low that no combustibles (e.g., foam) behind the barrier would have been capable of igniting. Similarly, Mehaffey et al. documented times of 16 – 24 minutes (Mehaffey, Cuerrier, & Carisse, 1994). D'Souza et al. (1981) ran a full-scale room corner test where a ½ inch gypsum barrier protected expanded polystyrene (EPS) foam insulation for 30 min, as judged by the temperature criterion and absence of fire involvement of foam (D'Souza, Kasem, & Galbreath, 1981).

These times are far longer than an individual could survive if a room fire goes to flashover, and even properly attired fire fighters can only safely endure post-flashover exposure very briefly. This indicates that even if foams behind the barrier were tested and regulated to be, in some sense, fire resistive, such a requirement would be superfluous.

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<sup>1</sup> 'Finish' in this context refers to a wall cladding layer.

## *2. Validity of the Steiner Tunnel test for plastic foams*

The Steiner Tunnel test (ASTM E 84) is a test for measuring the fire propagation over surfaces of materials in the early stages of the fire, when a fire is still small and flashover has not been reached. While it produces useful results for other materials such as wood products, research has shown that the Steiner Tunnel test is unreliable in assessing the hazard of plastic foams (Babrauskas, White, & Urbas, 1997). Factory Mutual, now FM Global, one of the largest organizations in the U.S. engaged in fire safety research and testing, issued an advisory notice that “Flame spread ratings by ASTM E 84 tunnel test should be disregarded for foamed plastics (FM, 1974, 1978).” Additionally, section 1.4 of ASTM E 84 itself states that “testing of materials that melt, drip, or delaminate to such a degree that the continuity of the flame front is destroyed, results in low flame spread indices that do not relate directly to indices obtained by testing materials that remain in place (ASTM, 2012).” The most important reason for the inaccuracy of the Steiner Tunnel test is related to the mounting geometry. The specimen is placed on the ceiling of a long, tunnel-shaped apparatus, with an exposure flame directed from one end (Figure 1).



**Figure 1.** View of the Steiner Tunnel, showing flame being applied to the ceiling (Photo: Intertek Testing Services, Inc.)

Under the test conditions, thermoplastic foams tend to melt and the liquid residue flows onto the floor, out of reach of the burner flame. Since the burner does not apply a flame to the floor, the results are registered as no flame spread having occurred, even though the same product would show extreme fire spread if exposed to a more realistic flame. This problem was recognized long ago in Canada, where a special variant of the Steiner Tunnel, CAN/ULC-S102.2, is used with foams in the floor position (Higginson, 1979; UL-CA, 2010). In other cases the foams produce so much smoke that observation of flame front position becomes impossible (Rose, 1971). Some foams also intumesce so much as to completely change the expected air flow in the tunnel (Rose, 1975). Further research details that support this conclusion are discussed in connection with #4, below.

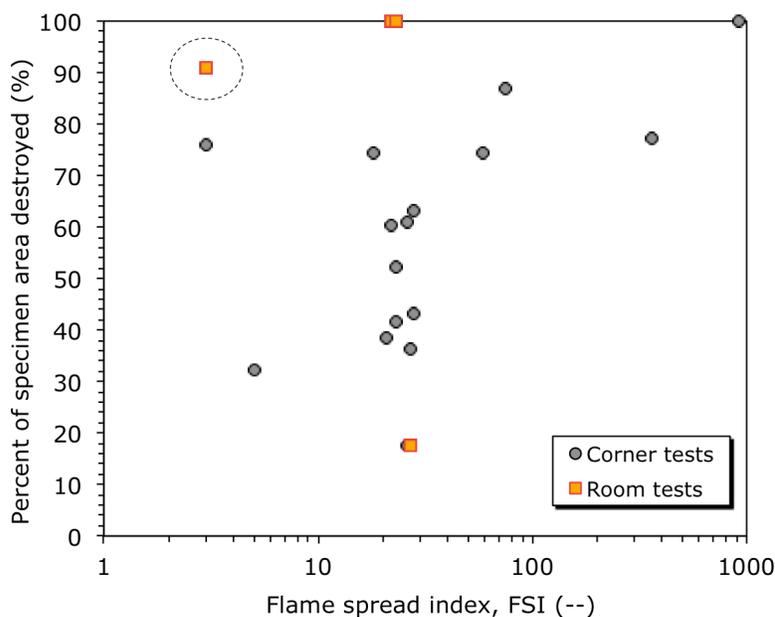
## *3. Propagation into a cavity constructed in violation of codes*

Were the Steiner Tunnel test to produce results which are actually indicative of the flame spread hazard of foams, it would be necessary to examine the question of a potential benefit if fire propagates into a wall or ceiling cavity. However, (a) the Steiner Tunnel test is invalid for foams, (b) U.S. building codes have stringent fire stopping provisions, requiring that openings to or from such cavities be closed and (c) research shows that fire propagation in cavities is not influenced by the Steiner Tunnel rating of the materials, as discussed next.

Researchers have conducted tests to determine under what circumstances insulation materials will allow fire that enters a cavity to sustain continued propagation. Choi and Taylor ran large-scale tests at the National Research Council of Canada (NRCC) and concluded that, in the absence of proper firestopping, fire can spread vertically inside wall cavities (Choi & Taylor, 1984). However, they found that this behaviour was dependent on the thickness of the gap between the insulation and the inner surface of the interior wall finish material (assuming the insulation fails to fully fill the cavity). Gaps of more than 1 inch (25 mm) showed propagation, while smaller ones did not. They demonstrated that the size of the gap was the determining factor that influenced propagation of the fire and that “the flame spread rating of the materials used in the tests was not a significant factor.” Thus, having a lower Steiner Tunnel flame spread test result for the insulation does not improve the fire safety of the cavities.

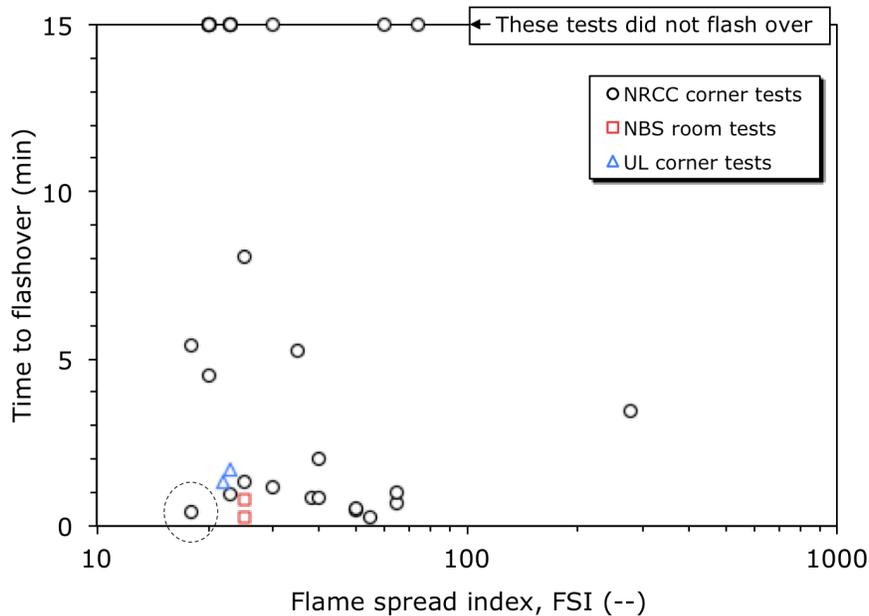
#### 4. Behaviour of exposed foam insulations installed in violation of codes

Finally, there may be a situation when, in violation of the codes, an individual constructs a building with foam plastic insulations exposed to the room interior without a thermal barrier. Would the use of flame retardant-treated foams that meet the Steiner Tunnel requirement (a flame spread index of less than 75) make these constructions fire safe? As discussed above, the fact that prior to 1976 severe fires occurred when foams that met the Steiner Tunnel requirement were used without a thermal barrier suggests the answer is no, and there is extensive scientific research on this topic. Several studies have examined whether it is safe to use foam insulation with flame spread indexes of less than 75 uncovered on room walls and ceiling surfaces. Williamson and Baron demonstrated that rigid polyurethane insulation with flame spread index (FSI) < 25 applied uncovered on the walls and ceiling could undergo extremely rapid, severe fire development within a room (Williamson & Baron, 1973). The most extensive study on this topic was published by Underwriters Laboratories (UL) in 1975 (Castino, Beyreis, & Metes, 1975). UL ran Steiner Tunnel tests and accompanying full-scale room tests, along with open room/corner tests similar to Williamson and Baron’s, and some additional geometry tests. In this series of tests, UL obtained some extremely severe results. Using extruded polystyrene foam (XPS) having a FSI = 3 (*sic*) caused a serious room fire with most (91%) of the walls and ceiling surfaces being burned out. Although some foams in their tests performed much better, there was no correlation between the flame spread index and the room fire hazard (Figure 2).



**Figure 2. Results of the UL study on foams in corner and room test geometries.** A lower flame spread index does not correlate with a smaller percent of area destroyed. The lowest FSI tested (indicated by dotted circle) had one of the highest percent areas destroyed. Source: (Castino et al., 1975)

Additional studies provided very similar results. NRCC conducted corner tests on a variety of exposed foams and concluded that foams with FSI values of 18 – 65 would lead to room flashover (the most extreme kind of room fire) in as little as 0.5 min (Figure 3) (Rose, 1975).



**Figure 3. Relationship of flashover time to Flame Spread Index for several test series.** A lower flame spread index does not reliably increase time to flashover. The lowest FSI tested (indicated by the dotted circle) also had one of the shortest times to flashover. Source: (Castino et al., 1975; Lee, 1985; Rose, 1975)

The National Bureau of Standards (now NIST) similarly showed that uncovered polyisocyanurate and polystyrene foams having FSI < 25 showed very rapid flashover times when tested in full-scale room fire tests (Lee, 1985). Later NIST studies produced very similar findings for uncovered flame retardant-treated foams: XPS foams produced room flashover in 1.5 min, while EPS foams produced flashover in 1.4 and 1.8 min (Dillon, 1998). Thus, these large-scale studies indicate that:

- (a) The Steiner Tunnel (ASTM E 84) test is unreliable in characterizing the fire hazard properties of foam plastics. The evidence presented in section 2. points to the same conclusion.
- (b) Foam plastic insulation that is not protected by a thermal barrier has an unacceptable level of fire hazard, irrespective of the use of flame retardants.
  - a. Foams complying with the building code requirement ( $FSI \leq 75$ ) can produce hazardous fire conditions if used in violation of codes without a thermal barrier.
  - b. Even foams of much lower FSI values than the code criterion cannot be used uncovered without creating a fire hazard.

### 5. Potential value of a more accurate test

If the Steiner Tunnel test gives inaccurate results for foam plastic insulations, is there a test that would be appropriate for assessing flame spread ratings for these materials? There are methods that would be more accurate. For example, ISO 9705 is considered to be a reliable test for assessing the performance of wall/ceiling surfaces, including bare foams (ISO, 1993). Foam plastic insulations treated with flame retardants as typically used in buildings are not able to achieve the desired flame spread ratings in an accurate test such as ISO 9705 (Babrauskas, 1996). As reviewed above, typical foam plastic insulation will exhibit severe fire spread

behaviour if present in the walls or ceiling of a room and not covered by a thermal barrier. Thus, an accurate test would indicate this behaviour and only tests that misrepresent the actual performance are able to provide what appear to be acceptable results. Conversely, there is no known study which would show that foams of types economically viable for use as normal building insulation could perform acceptably in a test such as ISO 9705. Therefore, a method which accurately measured the flame spread index of typical foam plastic insulations would preclude the use of these energy-efficient materials in buildings under the current code requirement for a flame spread test in addition to a thermal barrier.

U.S. fire statistics support the idea that, due to use of thermal barriers, foam insulations very rarely present a fire safety problem. Insulation within a structural area most contributed to flame spread in 2% of U.S. home structure fires, resulting in 0 civilian deaths and 40 injuries (1% of total for the whole U.S.). In contrast, a structural member or framing most contributed to flame spread in 26% of home fires, resulting in 360 civilian deaths and 950 injuries (Ahrens, 2011).

Though building codes often provide safety factors, and sometimes require redundant systems, there is no general rule about redundant requirements in codes. However, the research presented shows that for plastic foam insulations protected by a thermal barrier, there is no added fire safety benefit from flame retardants. Without a demonstrated, significant fire safety benefit in both elements there can be no redundancy.

In summary, the studies discussed above establish that the Steiner Tunnel test is invalid for plastic foams. In the unusual case of a cavity constructed in violation of codes without proper firestopping, the Steiner test rating for insulation materials does not influence fire propagation. If buildings are constructed in violation of code with exposed insulation, meeting the Steiner test requirements still does not provide for acceptable behaviour of these materials. Furthermore, research does not support the view that the change should be to replace the Steiner Tunnel with a more accurate test. If this were done, all economically viable foams would end up being precluded from use. Such a step is not necessary, as the code provisions for thermal barriers alone provide adequate fire safety benefits--that is, the thermal barrier provides a 15 minute finish rating, effectively protecting insulation from fire. This conclusion is supported by fire statistics, which show no fire deaths and very few injuries attributable to fire spread by insulation (Ahrens, 2011).

Indeed, this very approach is already being used in some countries in Europe (Blomqvist, McNamee, & Thureson, 2011; Lassen, Maag, Høiby, Vesterlykke, & Lundegaard, 2011; POPRC, 2011): “Using thermal barriers it is possible to fulfill fire safety requirements in most of the uses in constructions and buildings with EPS and XPS without a flame retardant. The national fire safety requirements are achieved by the building codes specifying the different uses of insulation products in buildings and construction, through the use of thermal barriers. In Scandinavian countries like Norway and Sweden buildings are constructed to prevent the spread of fire and additionally the buildings should not pose any health and/or environmental hazard to residents and the local environment (Posner, Roos, & Olsson, 2010).”

## FLAME RETARDANT CHEMICALS

Given the expanded intent statement of the ICC codes to consider hazards to public safety, health and general welfare, including fire fighters, the impacts of flame retardants as discussed below should be considered when evaluating code provisions.

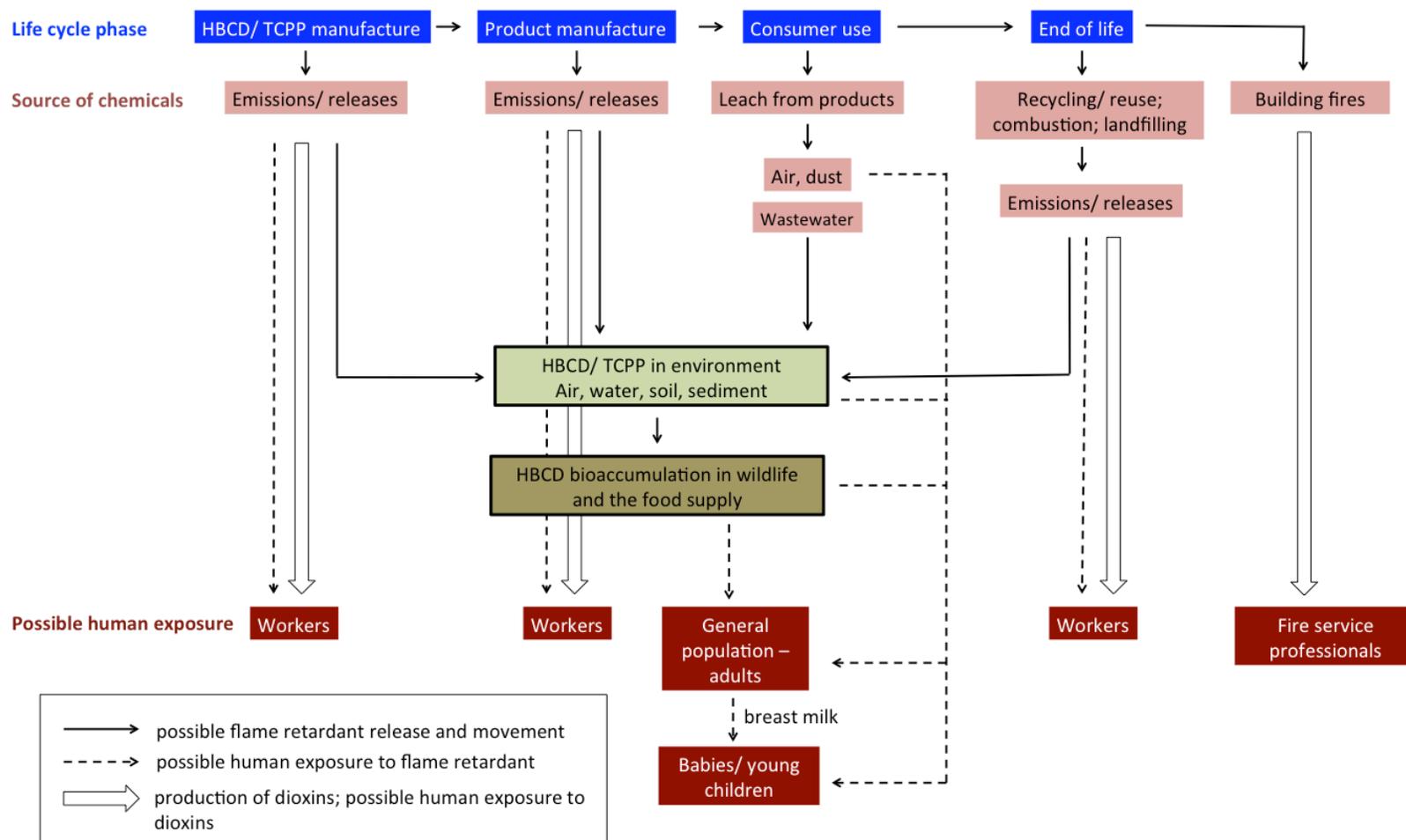
1. The two major flame retardants currently used in building insulation are either known to be harmful or lack adequate health data. The chemicals are released during the product life cycle and move into the environment, humans, and animals.
  - a. Hexabromocyclododecane (HBCD or HBCDD)
  - b. Tris (1-chloro-2-propyl) phosphate (TCPP)
2. The end of life of plastic insulation materials containing flame retardants is problematic.
  - Building fires
    - a. In a fire, the addition of halogenated flame retardants can increase fire toxicity
    - b. Halogenated flame retardants produce toxic halogenated dioxins when burned and throughout the life cycle
  - Managed disposal strategies
    - c. The three main options (recycling/ reuse, combustion, landfilling) have significant disadvantages.
3. Replacements for HBCD may be similarly problematic.

### ***1. Exposure and Toxicology of Major Building Insulation Flame Retardants***

The two main flame retardants used in plastic insulation materials are HBCD and TCPP. Such halogenated flame retardants act by releasing active halogen atoms (called free radicals) which can quench the chemical reactions occurring in the flame. HBCD and TCPP are used additively, which means they are not chemically bonded to foam and have the potential to migrate out. HBCD and TCPP can enter the environment as releases during chemical and product manufacturing, as well as leaching from products during use and disposal. The general public can be exposed by dermal contact with, inhalation or ingestion of contaminated air, water, soil, food, and/ or indoor dust (Figure 4).

Both HBCD and TCPP are found in indoor dust to which the general public may be exposed. However, the source of the chemicals in the dust has not been established, nor what the contribution of migration from building insulation compared to other sources may be. Both air and moisture move through building assemblies, regardless of how tightly they are constructed. Thus, substances within building cavities have the potential to migrate out of those cavities via movement driven by air, liquid and/ or water vapour that occurs due to temperature, air and vapour pressure differentials (Liu & Nazaroff, 2001). Chemicals may be present in dust from abraded materials or could volatilize and then settle in indoor dust to which building occupants could be exposed.

Organohalogen flame retardants are semi-volatile organic chemicals (SVOCs), and for additive uses in furniture foam it is known that they do continuously migrate out, moving from areas of high to low fugacity, and settle in indoor dust (Jones-Otazo et al., 2005; Weschler & Nazaroff, 2008; Zota, Rudel, Morello-Frosch, & Brody, 2008). The main route of human exposure for the SVOC flame retardant PentaBDE has been established as via hand to mouth contact with dust (Lorber, 2008; Watkins et al., 2011). The authors are not aware of any research that has been done into the potential for HBCD or TCPP to migrate from plastic foam insulation into occupied

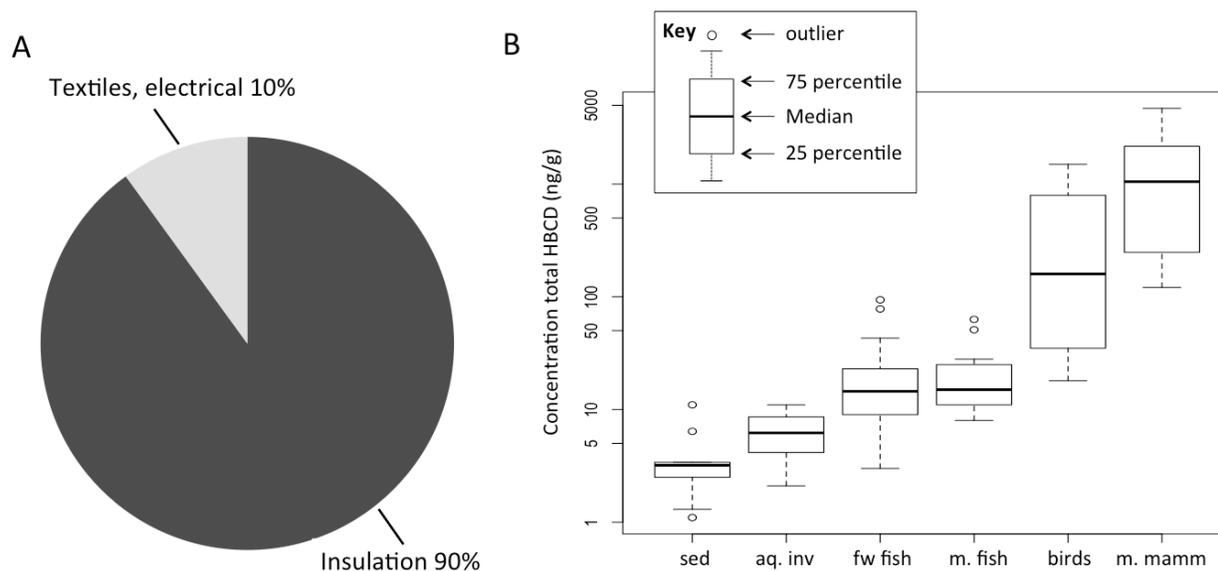


**Figure 4. Sources of HBCD/ TCPP and their by-products in the environment and human exposure.** Flame retardants whose primary use is in building insulation can enter the environment in a number of ways. Solid arrows indicate releases of HBCD/ TCPP and movement in the environment. Dashed arrows indicate possible human exposure to HBCD and TCPP. Block arrows indicate production of and possible human exposure to the HBCD by-products brominated dioxins. Proposed routes of exposure for humans are through dermal contact with, inhalation and ingestion of contaminated dust, food or water. Quantitative information is not available on the relative contribution of HBCD and TCPP used in building insulation to human exposure. Weights of arrows do not represent release amounts- see Supplementary Tables 1 and 2 for quantitative information on releases of HBCD and TCPP in the EU. For HBCD, the dominant source of release is from disposal of insulation. For TCPP, uses for building insulation account for a majority of releases, but it is unclear what phase of the life cycle is the dominant source.

spaces in buildings. Given the concerns about HBCD and TCPP discussed below, this should be a high-priority area for research. Exposure to these chemicals and their by-products also occurs via other pathways. We will now consider the health and ecological effects of these commonly used building insulation flame retardants and what is known about the contribution of building insulation throughout its life cycle to their occurrence in the outdoor environment.

### 1a. HBCD

Polystyrene foam insulation for use in buildings in the U.S. is treated with HBCD, an additive brominated flame retardant. The levels of HBCD commonly used are 0.7% in EPS and 2.5% in XPS. Other uses of HBCD are with upholstery textiles and electrical equipment housing (BSEF, 2009). Current worldwide annual production is estimated at 31,000 tons (POPRC, 2012). The use of HBCD has been increasing in the EU and in the U.S. It is the second highest-volume use brominated flame retardant in Europe and a high production volume chemical in the US (Covaci et al., 2006; Marvin et al., 2011; US-EPA, 2006). Polystyrene insulation is the main use, accounting for 90% of consumption (Figure 5) (EC, 2008a).



**Figure 5. HBCD usage and bioaccumulation.** (A) The primary use of HBCD is in polystyrene building insulation. (B) HBCD in the food chain. Species at the top of the food chain have the highest levels of HBCD. Graph shows concentration of HBCD in sediments (sed, ng/g dry weight) and biological samples (ng/ g lipid weight). aq. inv.= aquatic invertebrates; fw fish = freshwater fish; m. fish = marine fish; m. mamm = dolphins, porpoises. Source: (Covaci et al., 2006)

HBCD is a chemical of concern due to its potential for long-range transport, bioaccumulation, toxicity and human exposure. The source of HBCD found in indoor air and dust is unknown. Outdoors, HBCD is found in landfill leachate, sediment, soil, sewage sludge, and animals up to the Arctic. Mussels, fish, marine mammals, birds, and polar bears contain HBCD. This chemical tends to associate with fat and bioaccumulate, so animals towards the top of the food chain such as falcons and dolphins have higher levels (Figure 5) (Covaci et al., 2006; Marvin et al., 2011).

HBCD is found in fish, poultry, meat and other foods worldwide (Kakimoto et al., 2012; Schechter et al., 2010). In a recent study of 36 foods in a Dallas, Texas supermarket, 42% had detectable levels of HBCD (Schechter et al., 2012).

Several studies of sources of HBCD emissions have concluded that uses for textiles are the primary source of HBCD emissions and releases to the outdoor environment. However these studies did not consider the impact of the disposal of insulation containing HBCD (ECHA, 2009; NICNAS, 2012). In a European Union study, uses for building insulation were estimated to account for 87% of all HBCD releases to the outdoor environment when releases from insulation disposal were included in the calculation (Supplementary Table 1) (ECHA, 2009). This indicates that disposal of insulation should also be evaluated as a primary source of emissions.

While disposal estimates contain considerable uncertainty, these figures suggest that HBCD uses for building insulation are contributing to the global pollution. Disposal releases will continue to grow as an increasing number of buildings containing XPS/ EPS with HBCD are refurbished or demolished (POPRC, 2011).

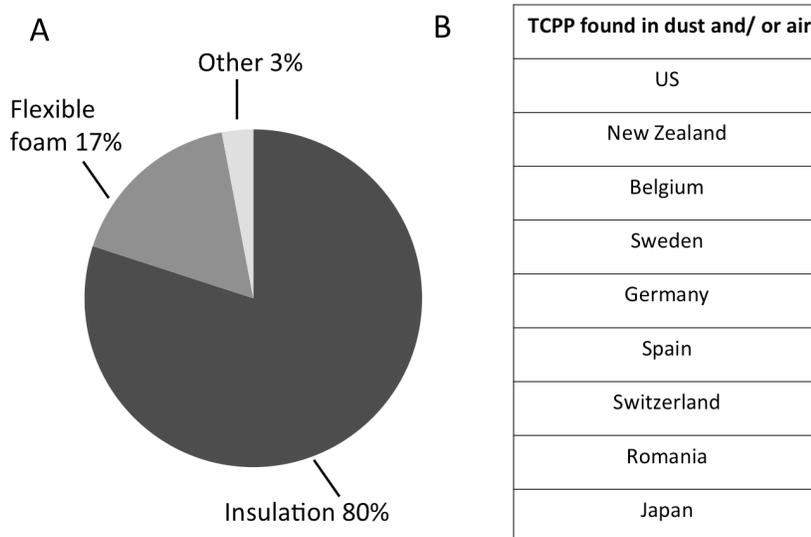
Concerns about HBCD include aquatic toxicity and possible human health effects, as it causes thyroid hormone disruption and adversely affects the developing nervous system in animal studies (Marvin et al., 2011; US EPA, 2008). Human exposure may be through dermal contact with or inhalation/ ingestion, of, air, soil, food, and dust containing HBCD (Figure 4). It is unknown what the relative contributions of each of these pathways is to total human exposure, and thus how much uses for building insulation are contributing compared to other sources. HBCD crosses the placenta and is found globally in human blood, adipose tissue, and breast milk (Covaci et al., 2006; Marvin et al., 2011). Babies and young children are a population of concern because of their sensitive developmental stage and higher exposures to the chemical via dust ingestion and breast milk (Harrad et al., 2010). No limits on HBCD exposure for workers or the general public have yet been set. The lowest observed adverse effect level dose in animal studies showed developmental neurotoxicity in mice at 0.9 milligrams per kilogram of body weight per day (mg/ kg bw/ d) (Eriksson, Fischer, Wallin, Jakobsson, & Fredriksson, 2006). A recent assessment estimates a worst-case scenario as 2-year-old toddlers having an exposure of 0.3 mg/ kg bw/ d from all sources. When comparing the amount of HBCD in dust, breast milk, and food within and between studies, HBCD levels ranged over several orders of magnitude (NICNAS, 2012). There are uncertainties in comparing effects in mice to humans, but these values suggest cause for concern and further study would be warranted.

Due to the above concerns, HBCD is one of the first “Substances of Very High Concern” scheduled to be phased out by 2015 in the EU (EC, 2011). Canada “is proposing to implement regulations to prohibit the manufacture, use, sale, offer for sale, import and export of HBCD and products containing HBCD” by the end of 2016 (Env-Can, 2012). HBCD is also under consideration for listing as a persistent organic pollutant by the 178 member countries belonging to the Stockholm convention in 2013 (POPRC, n.d.). In October 2012, an expert review committee recommended listing HBCD under Annex A (Elimination) with limited exemptions (UNEP, 2012).

### 1b. TCPP

Most polyurethane insulations including flexible-faced laminate, panels, block and injected foams contain TCPP, an additive chlorinated flame retardant. In addition, TCPP is often used in polyisocyanurate (isocyanurate-modified polyurethane) board. TCPP is used at 2-25% in boards and 5% levels in foam (EC, 2008b). TCPP is also used in flexible foam for furniture and bedding (EC, 2008b; Van der Veen & de Boer, 2012).

In 1997, worldwide use was 40,000 tons while in 2000 this same amount was consumed in the EU. In 2006, the manufacture and import of TCPP in the US was estimated at 4,500- 22,600 tons, qualifying it as a high production volume chemical (US-EPA, 2006). 80% of TCPP use is in polyurethane insulations (Figure 6) and 32,000 tons of TCPP were used in this type of insulation in the EU in 2000 (EC, 2008b).



**Figure 6. TCPP uses and presence in dust and air around the world. (A)** The primary use of TCPP is in polyurethane and polyisocyanurate insulations (EC, 2008b). **(B)** TCPP is found in air and dust from homes, offices, and cars around the world. Source: (Covaci et al., 2012)

TCPP is a chemical of concern due to its potential for long-range transport, persistence, toxicity, and human exposure (Van der Veen & de Boer, 2012).

The source of this chemical in indoor air and dust (Figure 6) is unknown (Brommer, Harrad, Van den Eede, & Covaci, 2012; Covaci et al., 2012; Van der Veen & de Boer, 2012). TCPP is found outdoors globally in wastewater, coastal and marine waters, surface water, drinking water, groundwater, sediment, sewage, soil, landfill leachate, mussels, fish, birds, and at the Arctic and Antarctic (Eggen, Moeder, & Arukwe, 2010; Fries & Mihajlović, 2011; Möller et al., 2012; Van der Veen & de Boer, 2012). TCPP does not readily break down into non-biologically available chemicals, which means that it is persistent. For the EU, uses for building insulation account for 76% of all TCPP releases to the environment (Supplementary Table 2) (EC, 2008b). These figures suggest that TCPP uses for building insulation are contributing significantly to the global

pollution.

Human exposure may be through inhalation, ingestion, or dermal contact with air, water, and dust containing TCPP (Figure 4) (Van den Eede, Dirtu, Neels, & Covaci, 2011). It is unknown what the relative contributions of each of these pathways is to total human exposure, and thus how much uses for building insulation are contributing compared to other sources. No limits on TCPP exposure for workers or the general public have yet been set. Little is known about the levels of this chemical in people, though it has been found in breast milk and its breakdown product has been detected in urine, confirming that exposure occurs (Covaci et al., 2012).

This is of concern because TCPP is a potential carcinogen, accumulates in the liver and kidneys, and may affect the developing nervous system based on cellular and animal studies (Crump, Chiu, & Kennedy, 2012; Dishaw et al., 2011; Van der Veen & de Boer, 2012). TCPP is structurally similar to three chemical compounds that have been identified as causing cancer: TCEP (tris (2-chloroethyl) phosphate), TDCPP/ chlorinated tris (Tris (1,3-dichloro-2-propyl) phosphate), and TDBPP/ brominated tris (tris(2,3-dibromopropyl)phosphate) (EC, 2008b; OEHA, 2009; OEHA, 2011). Due to the lack of studies on both human exposure and TCPP carcinogenicity, it is difficult to assess whether the current levels of exposure to TCPP pose a risk to adults and/ or young children. Further study is needed to learn more about the ecotoxicity, routes of exposure, levels in humans and possible adverse health effects of TCPP.

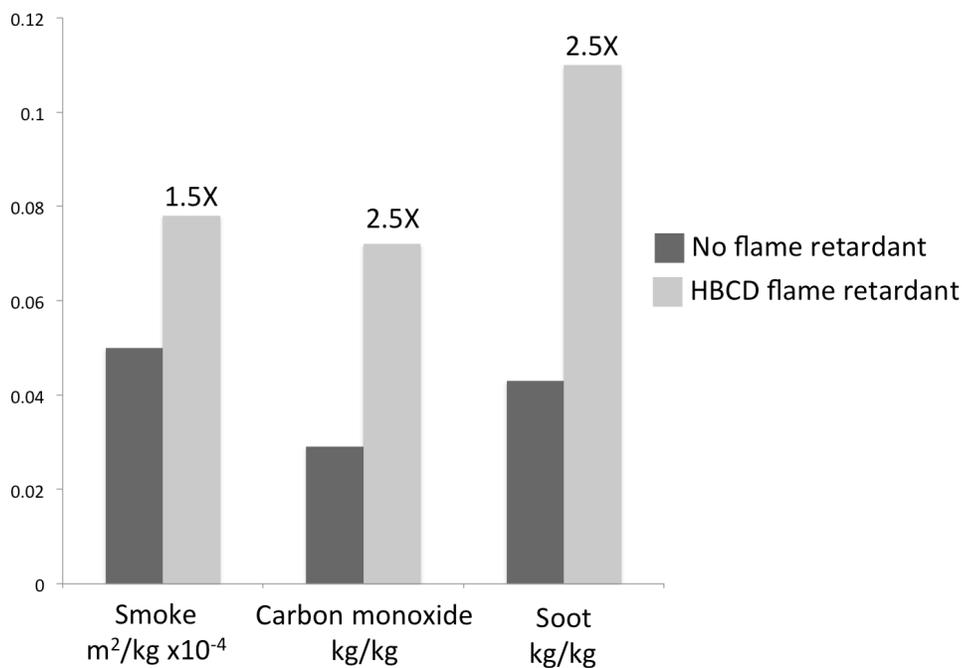
## ***2. End of life***

### ***2a. Building fires and increased fire toxicity***

Most fire deaths and injuries result from the inhalation of carbon monoxide (CO), smoke, soot, and other irritant gases, such as hydrogen cyanide (HCN) (DCLG-UK, 2006, 2011; Hall Jr., 2011). The addition of halogenated flame retardants such as those used in plastic building insulations can increase fire toxicity following ignition (Purser, 2000; Wichman, 2003), unless such a large loading of flame retardant chemical is used that combustion does not occur. Such high levels of flame retardants are not commonly used in commercial foam plastic insulation. Fire effluents from the combustion of materials containing halogenated flame retardants may be more toxic for three reasons (Schnipper, Smith-Hansen, & Thomsen, 1995; Stec & Hull, 2011). The effluents may contain:

1. More carbon monoxide.
2. Irritant acid gases (hydrogen chloride or hydrogen bromide).
3. A mixture of respiratory irritants comprising unburned and partially burned hydrocarbons whose toxicity depends on the combustion conditions.

However, this is a complex issue depending on the fire scenario and products involved, and the overall toxic hazard for fires involving flame retardant treated materials may be lower or higher than for non-flame retardant materials. Under some combustion conditions (as shown in Figure 7), the incorporation of halogenated flame retardants into materials increases the yield of toxic gases and particulate matter during combustion. Increased CO, irritants, soot and smoke hinder escape from a fire.



**Figure 7: HBCD increases fire toxicity.** Polypropylene containing 5% HBCD releases 50% more smoke and 150% more carbon monoxide and soot than material with no flame retardant. (Babrauskas, 1992).

In summary when flame retardants are present, comprehensive evaluation is needed to determine if they provide a fire safety benefit to overcome possible increased hazards from CO, irritant gases, smoke and soot particles. The potential increased toxicity of the combustion products is particularly an issue for first responders who can be exposed to high levels of the harmful combustion products.

### **2b. Formation of dioxins**

Dioxins are a group of toxic halogenated compounds that are persistent environmental pollutants and can be unintentionally formed and released during the production and life cycle of halogenated flame retardants. This can lead to environmental, food, and human contamination (Figure 4) (Hanari et al., 2006; Shaw et al., 2010). After flame retardant incorporation, processing of plastic may occur at sufficiently elevated temperatures to cause formation of dioxins. This is seen when HBCD is incorporated into polystyrene and formation of the by-products can be increased if the material is subjected to repeated extrusion cycles. The by-products can be found in the commercial product and in workplace air (Ebert & Bahadir, 2003). Finally, when halogenated flame retardants burn either in accidental fires or during intentional incineration for disposal, they can produce dioxins (Ebert & Bahadir, 2003; Weber & Kuch, 2003).

Chlorinated dioxins are regulated in many countries, which has led to their decrease in the environment and in humans (Hites, 2011). Human exposure to chlorinated dioxins is associated with adverse health effects such as skin and liver problems, impairment of immune, endocrine, or reproductive function, effects on the developing nervous system, and certain types of cancer (WHO, 1998). The general population is mostly exposed to chlorinated dioxins through diet; dairy, meat, and seafood is monitored for dioxin content by the Food and Drug Administration in the U.S. and the European Food Safety Authority in the EU.

Less is known about the brominated dioxins that are formed during the life cycle of brominated flame retardants such as HBCD. Human exposure guidelines pertain to chlorinated dioxins and no guidelines yet exist for brominated dioxins, though development of these has been identified as high priority by the World Health Organization (WHO) (Van den Berg et al., 2006).

Scientists have found brominated dioxins in the environment, food supply, indoor dust, human milk and tissue (Suzuki et al., 2010; Van den Berg et al., 2006). Brominated dioxins can have similar effects as the related chlorinated compounds and could be contributing to the total dioxin toxicity experienced by humans (Birnbaum, Staskal, & Diliberto, 2003).

Emissions regulations pertain only to the chlorinated dioxins, and are set for processes like municipal waste incineration at 0.1 nanogram/ m<sup>3</sup> (US-EPA, 2003). Polystyrene containing HBCD produces from 400-5,000 nanogram brominated dioxin per kilogram of polystyrene when burned, depending on the conditions (Desmet, Schelfaut, & Sandra, 2005; Ebert & Bahadir, 2003). This is of concern to fire service professionals who are exposed to these substances during and after fires (Ebert & Bahadir, 2003; Weber & Kuch, 2003). Studies show higher rates of cancers associated with exposure to dioxins in this population, including multiple myeloma, non-Hodgkin's lymphoma, prostate, and testicular cancer (Bates, 2007; Hsu, Guo, Wang, Liao, & Liao, 2011; IARC, 2010; LeMasters et al., 2006).

More research is needed to determine levels of human exposure to brominated dioxins and whether halogenated flame retardants used in building insulation are contributing significantly to human dioxin toxicity throughout their life cycle, especially for fire service professionals. The potential for dioxin toxicity should be considered in life cycle assessments and when evaluating the benefits and hazards of including halogenated flame retardants in plastic insulations.

### ***2c. Managed disposal strategies***

The end-of-life management for products treated with HBCD, TCPP, and other halogenated flame retardants requires consideration as it can result in human exposure and environmental contamination (Figure 4). The three main options all have significant disadvantages: recycling/reuse, incineration/ combustion, and landfilling.

#### Recycling and reuse of materials containing halogenated flame retardants

The preferred method for end-of-life treatment of flame retarded materials from both energy efficiency and life cycle toxicity perspectives is mechanical recycling. However, recycling flame retardant-containing materials can lead to the formation of brominated dioxins, exposing workers (Sjödén, Patterson, & Bergman, 2001). Materials containing halogenated flame retardants are often exported to developing and transition countries, resulting in environmental and human contamination (Puckett et al., 2002).

#### Combustion of materials containing halogenated flame retardants

A large proportion of flame retarded materials are eventually burned either on purpose or during accidental fires. Depending on the temperature and quality of combustion, high levels of dioxins and other toxic combustion products can be formed and released. Dioxins are also emitted from open burning of municipal waste (Gullett et al., 2010).

Halogenated flame retardants can be destroyed with high efficiency in high temperature incinerators. But even in this type of incinerator, elevated brominated dioxin levels were found in the bottom ashes, most probably due to particle matter falling through the grate and not subjected to a complete combustion (Wang, Hsi, Wang, Lin, & Chang-Chien, 2010). Further research is needed into the possible destruction of halogenated flame retardant materials at very high temperatures in cement kilns.

#### Landfilling and release of halogenated flame retardants from landfills

A large portion of products treated with halogenated flame retardants end up in landfills. Flame retardants such as the HBCD and TCPP used in building insulation can leach from landfills and contaminate the environment (Danon-Schaffer, 2010; Eggen et al., 2010; Morris et al., 2004). Because of their persistence, halogenated flame retardants will remain in landfills and leach into the environment for decades. Over extended time frames, landfill engineering systems will inevitably degrade and lose their ability to contain the contaminants (Allen, 2001; Buss, Butler, Sollars, Perry, & Johnston, 1995). Therefore, landfilling does not appear to be a sustainable solution for long-term containment of halogenated flame retardants.

All three above options for end-of-life treatments for halogenated flame retardant-containing materials are potentially harmful to human and ecological health and already appear to have contributed to the global environmental contamination by HBCD and TCPP. The waste management of plastic insulation containing flame retardants should be improved.

### ***3. Potential replacements for HBCD***

Even though HBCD will likely be phased out in some countries, flame retardants are still needed in XPS and EPS to meet the Steiner Tunnel requirements in the U.S. and other countries with similar codes. Three replacements for HBCD in polystyrene insulation are:

- Emerald 3000 (Chemtura)
- GreenCrest (Albemarle)
- Pyroguard SR-130 (Dai-Ichi Kogyo Seiyaku Co., Ltd.)

These replacements are brominated organic molecules with the potential to form brominated dioxins during their manufacture, use, and of end of life disposal. Furthermore, they rely on the same chemical mechanism as HBCD to achieve flame retardant properties during combustion, so they are likely to increase fire toxicity. Therefore, many of the same issues with use and end of life management described above will still be present.

Little information is available regarding the toxicology of the proposed HBCD replacements. Emerald 3000 and GreenCrest are synthesized as large polymers to reduce exposure and bioavailability. Pyroguard SR-130 is more similar in size and chemical composition to flame retardants with a tendency to bioaccumulate and cause adverse health effects. While the polymeric nature of the first two flame retardants has the potential to reduce human exposure, it complicates the toxicological analysis. Polymers are by nature a heterogeneous mixture in which different sized particles can exhibit different properties. When evaluating the pre-manufacture notice for Emerald 3000, the EPA predicted potential toxicity from inhalation of some particle

sizes, as well as the potential for smaller polymers to be persistent, bio-accumulative, and toxic (US-EPA, 2011).

## **DISCUSSION**

This paper identifies shortcomings associated with an inappropriate test method within building regulations, against which material performance is to be assessed. Consequently, thousands of tons of chemicals known to be toxic or lacking adequate health information are being used as building insulation flame retardants without a proven fire safety benefit. Regarding the provisions addressing the flammability of building insulation in the current IRC and IBC building codes, we will discuss the following questions:

- (1) What could have been done differently in the past when they were adopted?
- (2) What are the current impacts of the flammability provisions?
- (3) What can be done in the future to mitigate these impacts?

### **1. What could have been done differently when the Steiner Tunnel test was adopted into the model building codes and readopted in the IRC and IBC?**

In the 1960s when requirements for Steiner Tunnel testing of foam plastic insulations were originally introduced into the model building codes, a systematic evaluation into the assumed fire safety benefit of the test for foam plastics could have been carried out. The value of the Steiner Tunnel test for other materials such as wood is not in question here, only its applicability to a new material at the time—foam plastic insulation. A regulatory impact analysis or statement was not required, but might have revealed that it was inappropriate to require that foam plastics be tested using the Steiner Tunnel test.

In 1975, UL published a report, whose authors included Tom Castino, a future president of UL, documenting that the Steiner Tunnel test did not provide reliable results for plastic insulations (Castino et al., 1975). Surprisingly, in developing the original code and subsequent codes, the lack of efficacy and appropriateness of the Steiner Tunnel test for use with foam plastic insulation was apparently not considered by the codes organizations. In addition the health and ecological impacts of the chemical flame retardants added to foams in order to comply with the Steiner test were not considered.

### **2. What are the impacts of the current codes, including the Steiner Tunnel test requirements?**

Flame retardant chemicals, primarily HBCD and TCPP, are currently added to foam plastic insulation to meet the Steiner test requirement. These chemicals make the insulations more expensive and potentially harmful to human health and the global environment. Analysis of releases of HBCD and TCPP during their life cycle indicates that uses in building insulation contribute to environmental pollution.

The growing concern amongst designers, builders, building owners and the public about the toxicity of these flame retardant additives could possibly lessen the use of these insulations, which are valuable for energy efficiency and reducing global climate change. Although HBCD is about to be phased out in some countries due to its persistence, bioaccumulation and toxicity, the three proposed replacements are also brominated, share some similar chemical properties, and lack adequate health information.

The ICC now directs that codes should consider “minimum requirements to safeguard public safety, health and general welfare...from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations (ICC, 2003a, 2009a) (2012 IRC R101.3; 2012 IBC 101.3).”

An overall benefit of adding flame retardant chemicals to the foam has not been established. As discussed above, in the presence of a code-mandated thermal barrier, they do not provide additional benefit in reducing fire hazard. During fires, halogenated flame retardants can add to the acute toxicity of the fire effluents and produce other toxic by-products. Dioxins may be contributing to increased levels of cancers in fire service professionals. The provisions that lead to the use of HBCD and TCPP should be reconsidered, especially in light of the intent statement.

### **3. What alternatives exist to mitigate these problems and provide safe solutions?**

A change in building codes that would provide an exemption from the Steiner Tunnel test for foam plastic insulations which are protected by a code-compliant thermal barrier is suggested. This would eliminate the need to use flame retardant chemicals in these plastic foam insulations, without reducing the current level of fire safety provided by the remaining code requirements. Some foams are used in situations where there is not a fire hazard, such as between layers of concrete or ‘below grade’ between soil and concrete. In these cases the concrete and soil act as thermal barriers. Building codes should also be revised to eliminate flame spread test requirements in these applications.

U.S. fire statistics show that because of the thermal barrier, fire spread due to insulation is a very rare occurrence. Code regulations in Sweden and Norway allow non-flame retarded EPS/XPS when protected by a thermal barrier such as gypsum drywall. A similar strategy to ensure the fire-safety of buildings can be considered in other countries. (Blomqvist et al., 2011; Lassen et al., 2011; POPRC, 2011). Alternatively, less flammable alternative insulation materials such as rockwool and fiberglass can also be used.

Currently, all polystyrene building insulation in the U.S. is treated with HBCD. To provide for situations where flame retardants afford a benefit, having two well-labelled foam varieties, one that is flame retarded and one that is not, would reduce the use of HBCD and its replacements. Foams without flame retardants should cost less, but would require labelling, so that the two sorts of polystyrene would not be confused or used inappropriately.

In cases where chemical flame retardants are useful, safer flame retardants should be developed for plastic insulations. The current flame retardants and proposed substitutes are organohalogens, a chemical class that is often toxic, lipophilic (fat-loving), and/or resistant to degradation, leading to their persistence and bioaccumulation in people and the environment. All 21 chemicals globally banned as Persistent Organic Pollutants under the Stockholm Convention are organohalogens. 'Green' chemistry—the design and use of safer materials and processes with minimal adverse impact on human health and the environment—should be employed to develop a new generation of safer flame retardants based on alternative chemistries.

The process of designing fire standards and building codes would benefit from comprehensive review and revision. For new standards or codes, a regulatory impact analysis or statement that considers both efficacy and larger impacts should be required. For the future, fire scientists, building code officials, and other regulators making decisions about fire and building codes

should consider the efficacy, life cycle, health and ecological impacts of materials that will be used. A more interdisciplinary approach could help, for example collaboration with toxicologists and biologists as well as other scientists who can provide information on implications for human and ecological health before regulations are promulgated.

## **CONCLUSIONS**

Building codes should have reliable scientific and technical bases for their provisions. As knowledge increases, codes should change to reflect the new information. This is the basis for the three-year cycle of code development. The issues surrounding flame retardant chemicals in foam plastic insulation are an example of the need to continually assess code provisions against the results of current research and testing, actual performance, and other relevant health and safety findings. Rigorous review of fire safety benefits of flame retardant chemicals in plastic foam insulation, and their impacts on building occupants as well as fire fighters, is needed.

A range of chemicals such as halons, asbestos, PCBs, and Tris flame retardants in children's pajamas introduced to increase fire safety have been discontinued from use due to their adverse impacts. For building codes that lead to the use of added flame retardant chemicals in plastic foam insulation, a similar question was examined, and evidence was presented that these provisions do not appear to provide fire safety while there is a potential for serious health and ecological harm.

Code changes to exempt thermal barrier protected plastic foam insulations from the Steiner Tunnel test would prevent the use of thousands of tons of flame retardants that are either known to be persistent organic pollutants or in the same chemical family and lacking adequate information. Such a change would align with the expanded intents of the codes to consider hazards to public health and to fire fighters. It would also decrease the cost of foam plastic insulations and encourage the use of insulation materials useful for increasing building energy efficiency and reducing global climate change. The potential for health and ecological harm from the use of flame retardant chemicals would be reduced and the fire safety of buildings would be maintained.

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## **REFERENCES**

- ASTM. (2012). Standard Test Method for Surface Burning Characteristics of Building Materials (ASTM E84 - 12a). West Conshohocken, PA: ASTM International.
- Ahrens, M. (2011). Home structure fires. Quincy, MA: National Fire Protection Association.
- Allen, A. (2001). Containment landfills: the myth of sustainability. *Engineering Geology*, 60(1-4), 3-19.

- BSEF. (2009). HBCD fact sheet. Brussels, Belgium: Bromine science and environmental forum.
- Babrauskas, V. (1992). Plastics, part B, The effect of FR agents on polymer performance. In V. Babrauskas & S. J. Grayson (Eds.), *Heat release in fires* (pp. 423–46). London: Elsevier Applied Science Publishers.
- Babrauskas, V. (1996). Wall insulation products: Full-scale tests versus evaluation from bench-scale toxic potency data. *Interflam 1996* (pp. 257–274). London: Interscience Communications Ltd.
- Babrauskas, V. (2003). *Ignition Handbook*. Issaquah, WA: Fire Science Publishers and Society of Fire Protection Engineers.
- Babrauskas, V., White, J. A. J., & Urbas, J. (1997). Testing for Surface Spread of Flame: New Tests to Come Into Use. *Building Standards*, 66(2), 13–18.
- Bates, M. N. (2007). Registry-Based Case – Control Study of Cancer in California Firefighters. *American Journal of Industrial Medicine*, 344, 339–344. doi:10.1002/ajim.20446.
- Birnbaum, L. S., Staskal, D. F., & Diliberto, J. J. (2003). Health effects of polybrominated dibenzo-p-dioxins (PBDDs) and dibenzofurans (PBDFs). *Environment international*, 29(6), 855–60. doi:10.1016/S0160-4120(03)00106-5
- Blomqvist, P., McNamee, M. S., & Thureson, P. (2011). Compilation of International Building Regulations (Fire) Relevant for EPS/XPS: SP Technical Note 2010:10, revised 2011-11-30. Borås, Sweden: SP Technical Insitute.
- Brommer, S., Harrad, S., Van den Eede, N., & Covaci, A. (2012). Concentrations of organophosphate esters and brominated flame retardants in German indoor dust samples. *Journal of environmental monitoring : JEM*, 14(9), 2482–7.
- Buss, S. E., Butler, A. P., Sollars, C. J., Perry, R., & Johnston, P. M. (1995). Mechanisms of Leakage through Synthetic Landfill Liner Materials. *Water and Environment Journal*, 9(4), 353–359.
- Castino, T. G., Beyreis, J. R., & Metes, W. S. (1975). Flammability studies of cellular plastics and other building materials used for interior finishes, subject 723. Northbrook, IL: Underwriters Laboratories.
- Choi, K. K., & Taylor, W. (1984). Combustibility of Insulation in Cavity Walls. *Journal of Fire Sciences*, 2(3), 179–188.
- Covaci, A., Geens, T., Roosens, L., Ali, N., Van den Eede, N., Ionas, A. C., Malarvannan, G., et al. (2012). Emerging Organic Contaminants and Human Health. In D. Barceló (Ed.), *The Handbook of Environmental Chemistry, Vol. 20* (Vol. 20, pp. 243–305). Berlin, Heidelberg: Springer Berlin Heidelberg.
- Covaci, A., Gerecke, A. C., Law, R. J., Voorspoels, S., Kohler, M., Heeb, N. V., Leslie, H., et al. (2006). Hexabromocyclododecanes (HBCDs) in the environment and humans: a review. *Environmental science & technology*, 40(12), 3679–88.
- Crump, D., Chiu, S., & Kennedy, S. W. (2012). Effects of tris(1,3-dichloro-2-propyl) phosphate and tris(1-chloropropyl) phosphate on cytotoxicity and mRNA expression in primary cultures of avian hepatocytes and neuronal cells. *Toxicological sciences : an official journal of the Society of Toxicology*, 126(1), 140–8. doi:10.1093/toxsci/kfs015
- DCLG-UK. (2006). Fire Statistics, United Kingdom , 2006. London: Department for Communities and Local Government.
- DCLG-UK. (2011). Fire Statistics Great Britain, 2010 - 2011. London: Department for Communities and Local Government.

- Danon-Schaffer, M. (2010). *Polybrominated diphenyl ethers in landfills from electronic waste*. University of British Columbia, Vancouver, BC.
- Desmet, K., Schelfaut, M., & Sandra, P. (2005). Determination of bromophenols as dioxin precursors in combustion gases of fire retarded extruded polystyrene by sorptive sampling-capillary gas chromatography–mass spectrometry. *Journal of Chromatography A*, *1071*(1-2), 125–129. doi:10.1016/j.chroma.2004.12.019
- Dillon, S. E. (1998). Analysis of the ISO 9705 Room/Corner Test: Simulations, Correlations and Heat Flux Measurements (NIST-GCR-98-756). Gaithersburg, MD: National Institute of Standards and Technology.
- Dishaw, L. V., Powers, C. M., Ryde, I. T., Roberts, S. C., Seidler, F. J., Slotkin, T. A., & Stapleton, H. M. (2011). Is the PentaBDE replacement, tris (1,3-dichloro-2-propyl) phosphate (TDCPP), a developmental neurotoxicant? Studies in PC12 cells. *Toxicology and applied pharmacology*, *256*(3), 281–9. doi:10.1016/j.taap.2011.01.005
- D'Souza, M. V., Kasem, M. A., & Galbreath, M. (1981). Performance of protective linings for polystyrene insulation in a corner wall test. *Fire Technology*, *17*(2), 85–97. doi:10.1007/BF02479582
- EC. (2008a). European Union risk assessment report: Hexabromocyclododecane HBCDD CAS-No.: 25637-99-4. Luxembourg: European Commission, Swedish Chemicals Agency.
- EC. (2008b). European Union Risk Assessment Report: Tris (2-Chloro-1-methylethyl) phosphate TCPP. Luxembourg: European Commission, Ireland Chemicals Policy and Services.
- EC. (2011). Commission Regulation (EU) No 143/2011 of 17 February 2011. *Official Journal of the European Union*, *L44*(54), 2–6.
- ECHA. (2009). Data on manufacture, import, export, uses and releases of HBCDD as well as information on potential alternatives to its use. Helsinki, Finland: European Chemicals Agency, IOM Consulting.
- Ebert, J., & Bahadir, M. (2003). Formation of PBDD/F from flame-retarded plastic materials under thermal stress. *Environment international*, *29*(6), 711–6. doi:10.1016/S0160-4120(03)00117-X
- Eggen, T., Moeder, M., & Arukwe, A. (2010). Municipal landfill leachates: a significant source for new and emerging pollutants. *The Science of the total environment*, *408*(21), 5147–57.
- Env-Can. (2012). Proposed Risk Management Measure for Hexabromocyclododecane (HBCD). Gatineau. Quebec: Environment Canada, Health Canada, Chemicals Management Division.
- Eriksson, P., Fischer, C., Wallin, M., Jakobsson, E., & Fredriksson, A. (2006). Impaired behaviour, learning and memory, in adult mice neonatally exposed to hexabromocyclododecane (HBCDD). *Environmental toxicology and pharmacology*, *21*(3), 317–22. doi:10.1016/j.etap.2005.10.001
- FM. (1974). Foamed Polystyrene for Construction (Data Sheet 1-58). Norwood, MA: Factory Mutual.
- FM. (1978). Foamed Polystyrene for Construction (Data Sheet 1-58), revision. Norwood, MA: Factory Mutual.
- Fries, E., & Mihajlović, I. (2011). Pollution of soils with organophosphorus flame retardants and plasticizers. *Journal of environmental monitoring : JEM*, *13*(10), 2692–4.
- Gullett, B. K., Wyrzykowska, B., Grandesso, E., Touati, A., Tabor, D. G., & Ochoa, G. S. (2010). PCDD/F, PBDD/F, and PBDE emissions from open burning of a residential waste dump. *Environmental science & technology*, *44*(1), 394–9.
- Hall Jr., J. R. (2011). Fatal Effects of Fire. Quincy, MA: National Fire Protection Association.

- Hanari, N., Kannan, K., Okazawa, T., Kodavanti, P. R. S., Aldous, K. M., & Yamashita, N. (2006). Occurrence of Polybrominated Biphenyls, Polybrominated Dibenzo- p -dioxins, and Polybrominated Dibenzofurans as Impurities in Commercial Polybrominated Diphenyl Ether Mixtures. *Environmental Science & Technology*, 40(14), 4400–4405.
- Harrad, S., de Wit, C. A., Abdallah, M. A.-E., Bergh, C., Björklund, J. A., Covaci, A., Darnerud, P. O., et al. (2010). Indoor contamination with hexabromocyclododecanes, polybrominated diphenyl ethers, and perfluoroalkyl compounds: an important exposure pathway for people? *Environmental science & technology*, 44(9), 3221–31.
- Higginson, P. (1979). Floor Mounting in the Steiner Tunnel. Scarborough, Ontario: Underwriters Laboratories of Canada.
- Hites, R. A. (2011). Dioxins: an overview and history. *Environmental science & technology*, 45(1), 16–20.
- Hsu, J.-F., Guo, H.-R., Wang, H. W., Liao, C.-K., & Liao, P.-C. (2011). An occupational exposure assessment of polychlorinated dibenzo-p-dioxin and dibenzofurans in firefighters. *Chemosphere*, 83(10), 1353–9. doi:10.1016/j.chemosphere.2011.02.079
- IARC. (2010). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: FIREFIGHTING. Lyon: International Agency for Research on Cancer.
- ICBO. (1961). 1961 Uniform Building Code. Whittier, CA: International Conference of Building Officials.
- ICBO. (1976). 1976 Uniform Building Code. Whittier, CA: International Conference of Building Officials.
- ICC. (2000a). International Building Code. Washington DC: International Code Council.
- ICC. (2000b). International Residential Code. Washington DC: International Code Council.
- ICC. (2003a). International Building Code. Washington DC: International Code Council.
- ICC. (2003b). International Residential Code. Washington DC: International Code Council.
- ICC. (2006a). International Residential Code. Washington DC: International Code Council.
- ICC. (2006b). International Building Code. Washington DC: International Code Council.
- ICC. (2009a). International Residential Code. Washington DC: International Code Council.
- ICC. (2009b). International Building Code. Washington DC: International Code Council.
- ICC. (2012a). International Building Code. Washington DC: International Code Council.
- ICC. (2012b). International Residential Code. Washington DC: International Code Council.
- ISO. (1993). ISO 9705:1993 Full-scale room test for surface products. Geneva, Switzerland: International Organization for Standardization.
- Jones-Otazo, H. A., Clarke, J. P., Diamond, M. L., Archbold, J. A., Ferguson, G., Harner, T., Richardson, G. M., et al. (2005). Is house dust the missing exposure pathway for PBDEs? An analysis of the urban fate and human exposure to PBDEs. *Environmental science & technology*, 39(14), 5121–30.
- Kakimoto, K., Nagayoshi, H., Yoshida, J., Akutsu, K., Konishi, Y., Toriba, A., & Hayakawa, K. (2012). Detection of Dechlorane Plus and brominated flame retardants in marketed fish in Japan. *Chemosphere*, 89(4), 416–9.
- Lassen, C., Maag, J., Høiby, L., Vesterlykke, M., & Lundegaard, T. (2011). Alternatives to the use of flame retarded EPS in buildings. Oslo, Norway: Norwegian Climate and Pollution Agency (KLIF) and COWI A/S.
- LeMasters, G. K., Genaidy, A. M., Succop, P., Deddens, J., Sobeih, T., Barriera-Viruet, H., Dunning, K., et al. (2006). Cancer risk among firefighters: a review and meta-analysis of 32

- studies. *Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine*, 48(11), 1189–202.
- Lee, B. T. (1985). Standard room fire test development at the National Bureau of Standards. *Fire Safety: Science and Engineering (ASTM STP 882)* (pp. 29–44). Philadelphia: ASTM.
- Liu, D.-L., & Nazaroff, W. W. (2001). Modeling pollutant penetration across building envelopes. *Atmospheric Environment*, 35(26), 4451–4462. doi:10.1016/S1352-2310(01)00218-7
- Lorber, M. (2008). Exposure of Americans to polybrominated diphenyl ethers. *Journal of exposure science & environmental epidemiology*, 18(1), 2–19. doi:10.1038/sj.jes.7500572
- Marvin, C. H., Tomy, G. T., Armitage, J. M., Arnot, J. A., McCarty, L., Covaci, A., & Palace, V. (2011). Hexabromocyclododecane: current understanding of chemistry, environmental fate and toxicology and implications for global management. *Environmental science & technology*, 45(20), 8613–23.
- Mehaffey, J. R., Cuerrier, P., & Carisse, G. (1994). A model for predicting heat transfer through gypsum-board/wood-stud walls exposed to fire. *Fire and Materials*, 18(5), 297–305. doi:10.1002/fam.810180505
- Morris, S., Allchin, C. R., Zegers, B. N., Haftka, J. J. H., Boon, J. P., Belpaire, C., Leonards, P. E. G., et al. (2004). Distribution and Fate of HBCD and TBBPA Brominated Flame Retardants in North Sea Estuaries and Aquatic Food Webs. *Environmental Science & Technology*, 38(21), 5497–5504.
- Möller, A., Sturm, R., Xie, Z., Cai, M., He, J., & Ebinghaus, R. (2012). Organophosphorus flame retardants and plasticizers in airborne particles over the Northern Pacific and Indian Ocean toward the Polar Regions: evidence for global occurrence. *Environmental science & technology*, 46(6), 3127–34.
- NFPA. (2009). Standard method of fire tests for the evaluation of thermal barriers (NFPA 275). Quincy, MA: National Fire Protection Association.
- NICNAS. (2012). Priority existing chemical report No. 34: Hexabromocyclododecane. Sydney, Australia: National Industrial Chemicals Notification and Assessment Scheme.
- OEHAA. (2009). Brominated and chlorinated organic compounds used as flame retardants. Sacramento, CA: California Office of Environmental Health Hazard Assessment.
- OEHHA. (2011). OEHHA Proposition 65 tris(1,3-dichloro-2-propyl) phosphate (TDCPP). *Office of Environmental Health Hazard Assessment*. Retrieved July 20, 2012, from [http://oehha.ca.gov/prop65/prop65\\_list/102811list.html](http://oehha.ca.gov/prop65/prop65_list/102811list.html)
- POPRC. (n.d.). Chemicals proposed for listing under the Convention. Retrieved October 6, 2012, from <http://chm.pops.int/Convention/ThePOPs/ChemicalsProposedforListing/tabid/2510/Default.aspx>
- POPRC. (2011). UNEP/POPS/POPRC.7/19/Add.1 Addendum: Risk management evaluation on hexabromocyclododecane. Geneva, Switzerland: United Nations Environment Programme Persistent Organic Pollutants Review Committee.
- POPRC. (2012). UNEP/POPS/POPRC.8/4 Intersessional work on hexabromocyclododecane. Geneva, Switzerland: United Nations Environment Programme Persistent Organic Pollutants Review Committee.
- Posner, S., Roos, S., & Olsson, E. (2010). Exploration of Management options for HBCD. Molndal, Sweden: Swerea IVF.
- Puckett, J., Byster, L., Westervelt, S., Gutierrez, R., Davis, S., & Smith, T. (2002). Exporting Harm The High-Tech Trashing of Asia. Seattle, WA: Basel Action Network.

- Purser, D. A. (2000). The performance of fire retardants in relation to toxicity, toxic hazard, and risk in fires. In A. Grand & C. Wilkie (Eds.), *Fire retardancy of polymeric materials*. (pp. 449–99). New York: Marcel Dekker, Inc.
- Rose, A. (1971). Flammability of Lining and Insulating Materials (Canadian Building Digest DBD-141). Ottawa: National Research Council of Canada.
- Rose, A. (1975). Fire testing of rigid cellular plastics (IR-422). Ottawa: National Research Council of Canada.
- Schechter, A., Haffner, D., Colacino, J., Patel, K., Pöpke, O., Opel, M., & Birnbaum, L. S. (2010). Polybrominated diphenyl ethers (PBDEs) and hexabromocyclodecane (HBCD) in composite U.S. food samples. *Environmental health perspectives*, *118*(3), 357–62.
- Schechter, A., Szabo, D. T., Miller, J., Gent, T. L., Malik-Bass, N., Petersen, M., Paepke, O., et al. (2012). Hexabromocyclododecane (HBCD) Stereoisomers in U.S. Food from Dallas, Texas. *Environmental health perspectives*, *120*(9), 1260–4. doi:10.1289/ehp.1204993
- Schnipper, A., Smith-Hansen, L., & Thomsen, E. S. (1995). Reduced combustion efficiency of chlorinated compounds, resulting in higher yields of carbon monoxide. *Fire and Materials*, *19*(2), 61–64.
- Shaw, S. D., Blum, A., Weber, R., Kannan, K., Rich, D., Lucas, D., Koshland, C. P., et al. (2010). Halogenated flame retardants: do the fire safety benefits justify the risks? *Reviews on environmental health*, *25*(4), 261–305.
- Sjödin, A., Patterson, D. G., & Bergman, Å. (2001). Brominated Flame Retardants in Serum from U.S. Blood Donors. *Environmental Science & Technology*, *35*(19), 3830–3833.
- Stec, A. A., & Hull, T. R. (2011). Assessment of the fire toxicity of building insulation materials. *Energy and Buildings*, *43*(2-3), 498–506. doi:10.1016/j.enbuild.2010.10.015
- Suzuki, G., Someya, M., Takahashi, S., Tanabe, S., Sakai, S., & Takigami, H. (2010). Dioxin-like activity in Japanese indoor dusts evaluated by means of in vitro bioassay and instrumental analysis: brominated dibenzofurans are an important contributor. *Environmental science & technology*, *44*(21), 8330–6. doi:10.1021/es102021c
- UL-CA. (2010). Standard Method of Test for Surface Burning Characteristics of Flooring, Floor Coverings, and Miscellaneous Materials and Assemblies (CAN/ULC-S102.2-10). Toronto: Underwriters Laboratories of Canada.
- UNEP. (2012). UN experts target toxic flame retardant HBCD for control under global chemicals treaty. *Press release*. Retrieved October 20, 2012, from <http://chm.pops.int/Convention/Media/PressReleases/HBCDcontrolunderglobalchemicalstre aty/tabid/2895/Default.aspx>
- US EPA. (2008). Initial Risk-Based Prioritization of High Production Volume Chemicals. US Environmental Protection Agency.
- US-EPA. (2003). Waste Incinerator Dioxin Control and Emission Standards. US Environmental Protection Agency.
- US-EPA. (2006). IUR Data | Inventory Update Reporting (IUR) | US EPA. US EPA Office of Pollution Prevention and Toxics (OPPT).
- US-EPA. (2011). Premanufacture Notice (PMN) for P-10-476. *Federal Register*. Retrieved from <http://www.gpo.gov/fdsys/pkg/FR-2011-12-28/html/2011-33261.htm>
- Van den Berg, M., Birnbaum, L. S., Denison, M., De Vito, M., Farland, W., Feeley, M., Fiedler, H., et al. (2006). The 2005 World Health Organization reevaluation of human and Mammalian toxic equivalency factors for dioxins and dioxin-like compounds. *Toxicological*

- sciences : an official journal of the Society of Toxicology*, 93(2), 223–41.  
doi:10.1093/toxsci/kfl055
- Van den Eede, N., Dirtu, A. C., Neels, H., & Covaci, A. (2011). Analytical developments and preliminary assessment of human exposure to organophosphate flame retardants from indoor dust. *Environment international*, 37(2), 454–61.
- Van der Veen, I., & de Boer, J. (2012). Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity and analysis. *Chemosphere*, 88(10), 1119–53.
- WHO. (1998). Polybrominated dibenzo-p-dioxins and dibenzofurans (EHC 205). Geneva: World Health Organization.
- Wang, L.-C., Hsi, H.-C., Wang, Y.-F., Lin, S.-L., & Chang-Chien, G.-P. (2010). Distribution of polybrominated diphenyl ethers (PBDEs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) in municipal solid waste incinerators. *Environmental pollution (Barking, Essex : 1987)*, 158(5), 1595–602.
- Watkins, D. J., McClean, M. D., Fraser, A. J., Weinberg, J., Stapleton, H. M., Sjödin, A., & Webster, T. F. (2011). Exposure to PBDEs in the office environment: evaluating the relationships between dust, handwipes, and serum. *Environmental health perspectives*, 119(9), 1247–52.
- Weber, R., & Kuch, B. (2003). Relevance of BFRs and thermal conditions on the formation pathways of brominated and brominated-chlorinated dibenzodioxins and dibenzofurans. *Environment international*, 29(6), 699–710. doi:10.1016/S0160-4120(03)00118-1
- Weschler, C. J., & Nazaroff, W. W. (2008). Semivolatile organic compounds in indoor environments. *Atmospheric Environment*, 42(40), 9018–9040.  
doi:10.1016/j.atmosenv.2008.09.052
- Wichman, I. S. (2003). Material flammability, combustion, toxicity and fire hazard in transportation. *Progress in Energy and Combustion Science*, 29(3), 247–299.
- Williamson, R. B., & Baron, F. M. (1973). A corner fire test to simulate residential fires. *Journal of Fire and Flammability*, 4, 99–105.
- Williamson, R. B., & Mowrer, F. W. (2004). The role of interior finish in fire development. *Fire Protection Engineering, Fall(24)*, 26–29, 32–34, 36, 38–40.
- Zicherman, J. B., & Eliahu, A. (1998). Finish ratings of gypsum wallboards. *Fire Technology*, 34, 356–62.
- Zota, A. R., Rudel, R. A., Morello-Frosch, R. A., & Brody, J. G. (2008). Elevated house dust and serum concentrations of PBDEs in California: unintended consequences of furniture flammability standards? *Environmental science & technology*, 42(21), 8158–64.