Low GWP Spray Foam Expansion Agents: Why Performance also Matters

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ABSTRACT

The spray polyurethane foam industry is transitioning from foam expansion agents (FEA) with high global warming potential (GWP) to low GWP alternatives. However, having a low GWP is not the sole criterion for a FEA to minimize climate change potential of spray foam insulation. Historic FEAs with high GWP, HCFC-141b and HFC-245fa, were evaluated along with a low-GWP FEA option from DuPont, HFO-1336mzz-Z with similar thermal conductivity. In addition, an open cell spray foam using water/CO₂ as the blowing agent was compared which has a low GWP, but higher thermal conductivity. A holistic approach using life cycle methodology was used to calculate climate change potential across the entire supply chain, including raw material and spray foam production, spray foam installation, energy savings during product use, and end-of-life (EOL) disposal. A residential wall application was evaluated under two different installation scenarios. When insulation R-value can be kept constant across insulation options, the GWP of the FEA is key to achieving low product system climate change potential. When insulation thickness is restricted, FEA thermal performance also becomes critical to minimizing overall climate change potential.
INTRODUCTION AND OBJECTIVE

Concern about climate change has created demand for foam expansion agents (FEAs) with low Global Warming Potential (GWP) as well as improved thermal properties. In order to fully understand the impact an FEA will have on climate change potential (CCP) in spray polyurethane foam (SPF) applications, a lifecycle approach is taken. While SPFs are used in many applications, this study targets SPF’s in U.S. residential wall applications and takes into consideration not only the GWP of the FEA, but also production, installation and end-of-life greenhouse gas (GHG) emissions. Insulation use reduces the energy required to heat or cool a house. Differences in thermal performance of SPFs may also result in varying amounts of energy consumption and corresponding GHG emissions associated with the energy production and consumption. The relative GHG burdens from energy use are also included in this study. This study compares a spray foam system using HFO-1336mzz-Z, a zero ODP, low GWP FEA under development by DuPont, to spray foam systems using both historical and currently-used FEAs in this application, including HCFC-141b, HFC-245fa, and water/CO2 blown foam. This paper is an excerpt from a more detailed third party peer reviewed report as prescribed by ISO 14040/14044 for life cycle assessments [1]. This work and the peer reviewed paper expand on a previous study which did not include water/CO2 blown foam [2].

Life cycle methodology was used in this study to assess the climate change potential of various FEAs. Residential wall installation in the United States was chosen as the basis for this study. This includes modeling energy savings for representative residential homes (average floor area ~ 2450ft$^2$) [3]. Insulation requirements of residential walls in the United States are governed by the 2012 International Energy Conservation Code® (IECC) [4]. The code identifies several climate zones across the United States based on heating and cooling loads and other factors for which specific insulation requirements are identified, including the minimum allowable thermal resistivity, or R-value (ft$^2$°F/hr/BTU). Three climate zones were chosen for this study to show the dependence on both climate and regional influences of energy supply and building practice. Houston, TX, in climate zone 2, Baltimore, MD in climate zone 4, and Chicago, IL in climate zone 5 were selected as representative of major population centers with significantly different climate impacts.

The primary goal is to compare SPFs using various FEAs in residential wall applications to identify aspects of the lifecycle that have significant influence on climate change potential (CCP). CCP was evaluated for SPFs containing a range of FEAs, including HCFC-141b, HFC-245fa, water/CO$_2$, and HFO-1336mzz-Z. HFO-1336mzz-Z is a zero ODP, low GWP FEA with low thermal conductivity currently under development by DuPont [5].

SCOPE and METHODOLOGY

Functional Unit and Reference Flow

As per ISO 14044, life cycle comparisons are to be made among functional product systems. The functional unit captures the functionality of the product and provides a fair basis of comparison. For this study of SPFs, two functional units are selected which reflect the decision context of insulation installation- whether the insulation is installed to achieve a target R-value or a target thickness:

**R-Value Basis:** Reference Flow - One square-meter of installed SPF as used for residential wall insulation with a lifetime of 60 years and an R-value consistent with the 2012 IECC® for wood framed walls for the specific climate zone. For zone 2, R-13 (as measured in ft$^2$°F/hr/Btu) and for zone 4 and 5, R-20 is required. For a given climate zone, use-phase energy requirements are equivalent across all cases in this option since all options have the same R-value.

**Thickness Basis:** Reference Flow - One square-meter of installed SPF as used for residential wall insulation with a lifetime of 60 years and thickness to fill the wall frame cavity associated with the region of interest. This is 3.5 inches for climate zone 2 where all foams studied can achieve the minimum R-13 required in a 2”x4” wall frame. For climate zones 4 and 5, 5.5 inches of insulation are used based on a 2”x6” wall frame.

System Boundaries, Exclusions/Limitations and Key Assumptions

The system boundary of this study was Cradle-to-Grave (CTGr) meaning that all aspects of the value chain were captured from raw material extraction to end-of-life disposal. As shown in Figure 1, the following processes were included in the CTGr analysis: manufacturing of SPF formulation ingredients, SPF formulation manufacture, SPF installation in residential wall, SPF usage (including energy savings over SPF lifetime), and SPF end-of-life disposal.
Exclusions/Limitations

- Climate change potential is the primary impact category evaluated in this study. Climate change potential is currently a key driver in development and selection of alternative FEA in the SPF market and the subject of pending legislation in some regions.
- This study is limited to SPFs and does not include comparisons between additional in-kind competitors, such as extruded polystyrene (XPS) insulation or not-in-kind competitors, such as fiberglass insulation. These competitive insulations were not included such that differences among the compared insulations would highlight the impact of foam expansion agent selection, and not other potential differences between insulation types, such as air infiltration.
- This study is limited to wall applications based on the 2012 IECC®. Other applications, such as roof-top, or appliance insulation applications would require additional evaluation to address other FEA options or formulations, available thickness, installation techniques, energy savings, etc. Regions not covered by the IECC® are outside the scope of this study.
- The temporal scope for this study is set at a nominal 100 years. Emissions occurring during the use-phase and at end-of-life (EOL) are treated the same as emissions occurring during raw material production and during installation. A 60-year building life (and insulation useful life) is assumed based on the UL PCR [6]. A sensitivity analysis for SPF useful life is included.
- Wall construction beyond the spray foam insulation is excluded. Note that this exclusion would be inappropriate if an R-20 water/CO2 blown foam in a 2”x6” stud size wall construction were to be compared to an R-20 SPF installation with a different FEA in a 2”x4” wall construction, where the reduced wall construction requirements were based solely on the thermal conductivity performance of the FEA options evaluated.
- Transportation of SPF formulations and their packaging are excluded from the scope of this study based on their minimal impacts. Energy associated with dismantling and removal (D&R) of insulation is excluded from this study. However, emissions of FEA during D&R are included and estimated at 20% of the FEA remaining in the SPF at the end of the use-phase.
- Functional differences of the various spray foam options such as water or vapor barrier properties and structural properties of the spray foams are not incorporated into this evaluation.

Key Assumptions

*Sources for key assumptions, when appropriate, are provided when discussed in more detail below.*

- For the Thickness Basis, the wall cavity is assumed to be filled with insulation. Climate zones 4&5 are assumed to use 2”x6” wall construction. Climate zone 2 is assumed to use 2”x4” wall construction. SPFs must at least meet the minimum IECC® R-value for the region.
- 2012 IECC® R-value requirements are used for specific climate zones for residential wall. Zones 4&5 must meet R-20 while zone 2 must meet R-13.
- Air infiltration is assumed equivalent across all SPFs studied. The thickness required for the open-cell water/CO2 blown foam is assumed thick enough to make any potential differences with respect to air infiltration with closed cell foams negligible (< 0.02 liters s / m2) for both functional units.
- 15% of the FEA is emitted to atmosphere during installation. Differences in FEA volatility are likely to affect this value. For instance, HFC-245fa has a boiling point of 15°C, while HCFC-141b and HFO-1336mzz-Z both have boiling points above 30°C. Although the lower boiler HFC-245fa may have more emissions during installation actual installation emission data is not currently available to quantify the potential difference.
• 35% of the initial FEA is emitted during the use-phase. At the end-of-life, 20% of the FEA remaining in the insulation is assumed emitted during D&R. After removal, 83% of the insulation is then sent to landfill and 17% to incineration based on the typical U.S. municipal waste scenarios. All FEA sent to incineration is assumed to be destroyed. Half of the FEA still remaining in the insulation sent to landfill is assumed to be emitted to atmosphere while the remaining is assumed sequestered in the SPF throughout the temporal scope of this study. These assumptions result in about 77% of the FEA in the initial formulation being emitted to atmosphere at some time. A sensitivity analysis is performed to examine the effect of varying these key assumptions. Emissions at the end-of-life are influenced by how it is processed for disposal.
• 95% yield of SPF during installation is assumed.
• The R-value used to determine the energy requirements for the Thickness Basis and to determine the required insulation thickness for the R-Value Basis is an aged R-Value. For all closed cell SPF options, the aged R-Value for each formulation is calculated as 85% of the initial R-values provided by the SPF formulators. For the open cell SPF, all R-values provided were aged values. Further deterioration over time is not included in this study.

Impact Assessment Methodology

Climate change potential, expressed as kg CO$_2$ equivalent, is an important environmental impact identified for this study. IPCC 4th edition characterization factors based on a 100-yr time horizon were applied for climate change impacts [7]. This method was chosen based on international acceptance, guidance from the International Life Cycle Database (ILCD) [8] and other sources. This impact category and its respective category indicators were assessed at the mid-point level as there are currently no climate change end-point impact assessment methods with tolerable degrees of uncertainty. Details on the atmospheric lifetime and expected decomposition rates, routes, and products are detailed in the paper by Baasandorj, et.al. [9] This IPCC method, as interpreted by the TRACI 4.0 Impact assessment method developed by the U.S. Environmental Protection Agency (EPA) [10], is used with modification to include a characterization factor for HFC-1336mzz-Z [1]. Characterization factors from this method for the FEA evaluated in this study are shown in Table 1.

As per in the ISO standards for life cycle analysis, results from this study are based on a relative approach. They indicate potential environmental effects, and do not predict actual impacts on category endpoints, the exceeding of thresholds, or safety margins or risks [11,12].

<table>
<thead>
<tr>
<th>Foam Expansion Agent (FEA)</th>
<th>Global Warming Potential kg CO$_2$ eq per kg FEA</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCFC-141b</td>
<td>725</td>
<td>[7]</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>1030</td>
<td>[7]</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>8.9</td>
<td>[9]</td>
</tr>
</tbody>
</table>

DATA COLLECTION AND MODELING

Formulation Raw Materials

In practical application, many different ingredients are used in varying quantities in spray foam formulations. Formulators can use different types of ingredients which perform a given function within the spray foam formulation. For example, many different formulation catalysts exist to speed the rate of reaction during installation. Additionally, formulation ingredients can be manufactured from a variety of process technologies. Life cycle inventories (LCIs) were evaluated from multiple sources for each ingredient in the formulations. The highest and lowest Cradle-to-Gate (CTG) CCP for each formulation ingredient was used to assess the impact of LCI data on overall formulation CTG CCP. A base case LCI for each component was selected based on representativeness with respect to this study when distinguishable or an average of the available data. The range of LCI for formulation constituents are evaluated along with the range of use rates in a sensitivity analysis. Two of the main formulation ingredients are polyols and isocyanate. For polyol manufacturing, LCI data was taken from USLCI [13] and Plastics Europe [14]. Both these models result in a CTG CCP of 3.6 kg CO$_2$ eq per kg polyol. Polyol represents 30-50% of the formulation CTG CCP as shown below in Figure 2.

Methylene diphenyl diisocyanate (MDI) is the primary isocyanate used in spray foam applications. A life cycle model available in the literature and SimaPro™ LCA software from the American Chemical Council (ACC) [15] is used in this
study. The CTG CCP for MDI production is 2.5 kg CO$_2$ equivalent. Figure 2, below, shows isocyanate contributes roughly 20-50% of the manufacturing impacts depending on the SPF formulation.

Flame retardants, surfactants and formulation catalysts are additional ingredients in a SPF. In general, LCI data for these materials have a higher degree of uncertainty than the polyol and MDI. Surfactant CTG CCP ranged from 0.5 to 2.5 kg CO$_2$ eq / kg surfactant based on Ecoinvent models for ethoxylated alcohols and esterquat from various oils, linear alkylbenzene sulfonate (LAS), and others [17]. The base case was selected from the LAS model which is near the middle of this range at 1.6 kg CO$_2$ eq / kg surfactant. The amine based formulation catalyst was modeled based on the triethyamine ecoinvent model [17] at 2.5 kg CO$_2$ eq / kg catalyst. Other amine-based chemicals in ecoinvent have CTG CCP ranging from 0.5-5.6 kg CO$_2$ eq. Lastly a brominated polyol was assumed a likely flame retardant. This was modeled as the reaction of equal amounts of tetrabromophthalic anhydride (TBPA) and polyol resulting in roughly a 60wt% bromine product. The polyol portion of this additive is the same as modeled above. TBPA was modeled assuming the bromination of phthalic anhydride with HBr coproduct. The phthalic anhydride was modeled using the available Ecoinvent™ model [17]. Bromine was modeled as generated from the reaction of sodium bromide with chlorine. To be consistent with other steps, the HBr co-product was modeled as a credit based on the stoichiometric bromine equivalents. Stoichiometric yields are assumed and a token electricity use of 0.25 kWh / kg was assumed for each reaction step. Based on these assumptions, a brominated polyol has a CTG CCP of 3.3 kg CO$_2$ per kg. Due to the uncertainty and assumptions in this data, a range of 1.65 – 6.6 kg CO$_2$ eq / kg was estimated for use in a sensitivity analysis by halving or doubling the calculated value.

Foam expansion agents (FEAs) were also identified as one of the most important formulation ingredient for foam insulation from a CCP perspective. Of the four foam expansion agents evaluated in this study, three are halogenated organic chemicals. The production of halogenated organic chemicals generally involves precursors such as chlorine, hydrogen fluoride, ethylene dichloride, perchloroethylene, and carbon tetrachloride, among others. Most of these precursors are not produced at DuPont, so actual plant data was not directly available. As such, literature life cycle data, IHS Chemical Process Economics Program (PEP) reports, IHS Chemical Economics Handbook (CEH) reports, and toxic release inventory (TRI) data available from the TRI Explorer web-based program were used to develop the models required for the FEAs and their precursors [19,20,21,22,23,24]. As emissions of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) are important to this study, a common modeling approach was assumed when actual emissions were not available. For processes where emission data were not available, 0.1% fugitive emission of raw material feeds and products (0.01 – 0.2 % for sensitivity analysis based on DuPont experience) was assumed. Identified process emissions of halogenated species (i.e. non-fugitive emissions) were modeled as first being sent to a control device prior to emission to atmosphere. Incineration facilities were assumed to be 99.5% (98 – 99.99% for sensitivity analysis) effective at thermal conversion of these materials to CO$_2$, hydrogen fluoride (HF), and/or HCl. The HCl or HF emissions were modeled as though they are scrubbed using a sodium hydroxide (NaOH) solution at an efficiency of 99.5%. Use rates for NaOH in the scrubber for neutralization were included in the process models. These assumptions result in a significant uncertainty range of FEA manufacturing CCP impacts as highlighted below in Table 2, particularly for HFC-245fa and HFO-1336mzz-Z. Additional details for modeling precursors and FEAs are included in the detailed peer-reviewed paper [1].

Table 2 shows a summary of FEA manufacturing CTG CCP along with the direct global warming potential for each of the FEAs evaluated. Ranges are provided based on fugitive emission rate and incineration destruction efficiency assumptions. The GWP for HFO-1336mzz-Z is not part of the IPCC 4th edition GWP list, but the value of 8.9 kg CO$_2$ eq per kg HFO-1336mzz-Z was added to the impact assessment method [9].

<table>
<thead>
<tr>
<th>Foam Expansion Agent (FEA)</th>
<th>CTG CCP from energy kg CO2 eq / kg FEA</th>
<th>CTG CCP from Halogenated Organics kg CO2 eq / kg FEA</th>
<th>Total Manufacturing CTG CCP kg CO2 eq / kg FEA</th>
<th>Direct Global Warming Potential (GWP) kg CO2 eq / kg FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCFC-141b</td>
<td>3.8</td>
<td>1.1 (0.3 - 2.1)</td>
<td>4.9 (4.0 - 5.8)</td>
<td>725 [8]</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>5.0</td>
<td>1.6 (0.4 - 3.5)</td>
<td>6.6 (4.4 - 8.6)</td>
<td>1030 [8]</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>12.9 (12.8 - 13.3)</td>
<td>14.4 (5.6 - 42)</td>
<td>27.4 (18 - 55)</td>
<td>8.9 [11]</td>
</tr>
<tr>
<td>Water/CO2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1 [8]</td>
</tr>
</tbody>
</table>

* The low range value for HFC-245fa CTG CCP is based on McCulloch [25]
Other Key Models

**Energy savings due to insulation:** TRACETM Load 700 (by Trane®) was used to model energy savings incurred through usage of the spray foam insulation [25]. The software uses housing construction data from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to assess the energy and economic impacts of building-related parameters such as architectural features, comfort-system design, HVAC equipment selections, operating schedules etc. The software provides the heating and cooling load for the building through the year and the yearly average for the three locations considered. A 2-story residential building construction was modeled in the software employing applicable building codes and standards. To evaluate the energy savings from spray foam insulation use, walls with varying R-value were used to change heating and cooling loads. The energy savings for each option was calculated relative to water/CO₂ blown foam. A scenario of a wall without any insulation was not studied since the goal was to compare FEAs with one another and such a wall construction would not meet code. Energy sources for residential heating and cooling were taken from US Census data by the TRACETM 700 software. Residential cooling energy was assumed to be 100% electricity whereas heating was a mix of electricity and natural gas [25].

**Energy sources:** All residential cooling was modeled based on sub-regional grid electricity. Sub-regional low voltage electricity grid data is readily available in SimaPro software as provided by the USLCI database based on 2008 data from the Environmental Protection Agency (EPA) and Emissions and Generation Resource Integrated Database (eGRID) data [13,26]. Natural gas (51.2%), electricity (30.3%), fuel oil (9%), and propane or bottled gas (6.5%) account for 97% of all fuel sources for houses in the United States per the 2000 U.S. census data [27]. Models for natural gas combustion and fuel oil combustion from the US-EI database were used along with the electricity models above at their relative use rates to model residential heating. Propane use was modeled using the natural gas combustion as a proxy. Use rates were normalized to 100%.

CCP impacts per kWh for residential heating and cooling and the specific geographic sub-regions used for each city of interest in this study are tabulated by region in Table 3. Data is also provided for the U.S. average electricity grid and an additional energy grid used in the sensitivity analysis.

| Table 3. Residential Heating and Cooling Supply Climate Change Potential per kWh By Region |
|---------------------------------|-----------------|---------|-------|-------|-------|
| Energy Supply                  | Units           | US Ave | Chicago | Baltimore | Houston | Portland |
| Electricity Grid Sub-region    |                 |        |        |         |         |         |
| Residential Cooling            | kg CO2 eq / kWh | 0.69   | 0.85   | 0.53    | 0.68    | 0.50    |
| Residential Heating            | kg CO2 eq / kWh | 0.42   | 0.47   | 0.36    | 0.42    | 0.35    |

**End of Life (EOL) – Incineration & Landfill:** A US-EI model for incineration of polyurethane, was used to model incineration of SPF at the end of life [28]. This model includes CO₂ emissions associated with the combustion of polyurethane. All of the FEA sent to incineration was assumed to be combusted.

A US-EI model for landfill of polyurethane, was used to model the landfill process of SPF at the EOL [28]. Separate from this model, 50% of the FEA sent to landfill was assumed to be emitted within the temporal scope of this study.

**Foam insulation recipe**

The details of the formulations are strategically held intellectual property for SPF formulation suppliers. For this study, under confidential agreement, various SPF formulation suppliers provided the formulation data. The formulation data was provided in terms of parts by weight of major foam insulation components such as isocyanate, polyol and FEAs, and ranges for minor components such as flame retardants, catalyst and surfactants. In addition, the corresponding foam densities and initial R values (in specific cases, aged R values) were also provided. To protect the proprietary information, formulation data was grouped by FEA type and loading rate and then aggregated for use in this paper.

Since the goal of this study is to examine the effect of FEA type and usage rate (loading), formulation recipes were gathered for spray foam formulations using HCFC-141b, HFC-245fa and HFO-1336mzz-Z with varying loading rates as well as for water/CO₂ blown foam. Although HFO-1336mzz-Z formulations are not yet available commercially; formulators were still able to provide tested formulation options for this product. Three FEA loading groups are described in this evaluation as “Low”, “Mid”, and “High,” which correspond to FEA loading of 3-5 wt%, 5-9 wt% and 9-12 wt% of the total formulation, respectively. As HCFC-141b is no longer a commercial product, only limited data was available, with no formulation data available for HCFC-141b formulations within the “Low” or “High” FEA loading groups. Water/CO₂ blown foam was evaluated only at one FEA loading.
The foam densities, initial R-values, and aged R-values for each aggregated formulation, are shown along with the actual aggregated FEA loading in Table 4. The relative aggregated impacts from each part of the formulation are shown in Figure 2. For all formulations evaluated, the polyol, FEA, and isocyanate combined account for more than 90% of the CTG CCP. The thicknesses required for each formulation for the R-value Basis and the effective R-values for the Thickness Basis are shown in Table 5.

Table 4: Average Formulation and Performance Data, Aggregated by FEA Loading

<table>
<thead>
<tr>
<th>Property</th>
<th>Actual Foam</th>
<th>Expansion Agent</th>
<th>Foam Density</th>
<th>R-value, initial</th>
<th>R-value, aged</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foam Expansion Agent Loading</td>
<td>Actual Foam</td>
<td>Expansion Agent</td>
<td>Foam Density</td>
<td>R-value, initial</td>
</tr>
<tr>
<td></td>
<td>[wt%]</td>
<td>[wt%]</td>
<td>[lb/ft³]</td>
<td>[ft²-f-h°F/ Btu / inch]</td>
<td>[ft²-f-h°F/ Btu / inch]</td>
</tr>
<tr>
<td></td>
<td>Low (3-5wt%)</td>
<td>Mid (5-9wt%)</td>
<td>High (9-12wt%)</td>
<td>Water/CO2</td>
<td>Low (3-5wt%)</td>
</tr>
<tr>
<td>Actual Foam</td>
<td>HFC-141b</td>
<td>n/a</td>
<td>8.8%</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Expansion Agent</td>
<td>HFC-245fa</td>
<td>3.7%</td>
<td>6.3%</td>
<td>10.5%</td>
<td>n/a</td>
</tr>
<tr>
<td>Foam Density</td>
<td>HFO-1336mzz-Z</td>
<td>3.7%</td>
<td>7.4%</td>
<td>10.5%</td>
<td>n/a</td>
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<tr>
<td>Water</td>
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<td>n/a</td>
<td>n/a</td>
<td>9.5%</td>
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<td>R-value, initial</td>
<td>HFC-141b</td>
<td>n/a</td>
<td>2.7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>[ft²-f-h°F/ Btu / inch]</td>
<td>HFC-245fa</td>
<td>2.8</td>
<td>2.8</td>
<td>2.1</td>
<td>n/a</td>
</tr>
<tr>
<td>Foam Density</td>
<td>HFO-1336mzz-Z</td>
<td>2.8</td>
<td>2.5</td>
<td>2.3</td>
<td>n/a</td>
</tr>
<tr>
<td>Water</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.5</td>
</tr>
<tr>
<td>R-value, aged</td>
<td>HFC-141b</td>
<td>n/a</td>
<td>2.7</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>[ft²-f-h°F/ Btu / inch]</td>
<td>HFC-245fa</td>
<td>6.3</td>
<td>6.8</td>
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<td>n/a</td>
<td>n/a</td>
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</tr>
</tbody>
</table>

Figure 2. Relative Contributions to CTG Climate Change Potential of Formulation Components based on Aggregated Formulation data. Excludes Installation, Use-phase, and End-of-Life.
Table 5: Insulation Thickness / Effective R-value, by FEA, FEA loading, and Case

<table>
<thead>
<tr>
<th>FEA</th>
<th>FEA Loading</th>
<th>Thickness Basis, Inches</th>
<th>Thickness Basis, R-Value Basis</th>
<th>Thickness Basis, Effective</th>
<th>Thickness Basis, Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Houston, R-13</td>
<td>R-20</td>
<td>3.5” Cavity</td>
<td>5.5” Cavity</td>
</tr>
<tr>
<td>HFC-141b</td>
<td>Mid (5-9wt%)</td>
<td>2.11</td>
<td>3.24</td>
<td>21.6</td>
<td>34.0</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>Low (3-5wt%)</td>
<td>2.43</td>
<td>3.74</td>
<td>18.7</td>
<td>29.4</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>Mid (5-9wt%)</td>
<td>2.26</td>
<td>3.47</td>
<td>20.1</td>
<td>31.7</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>High (9-12wt%)</td>
<td>1.89</td>
<td>2.90</td>
<td>22.6</td>
<td>35.5</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>Low (3-5wt%)</td>
<td>2.39</td>
<td>3.68</td>
<td>19.0</td>
<td>29.9</td>
</tr>
<tr>
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<td>Mid (5-9wt%)</td>
<td>2.10</td>
<td>3.24</td>
<td>21.6</td>
<td>34.0</td>
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<tr>
<td>HFO-1336mzz-Z</td>
<td>High (9-12wt%)</td>
<td>1.89</td>
<td>2.90</td>
<td>24.1</td>
<td>37.9</td>
</tr>
<tr>
<td>Water</td>
<td>n/a</td>
<td>3.33</td>
<td>5.13</td>
<td>13.7</td>
<td>21.5</td>
</tr>
</tbody>
</table>

**Direct Emissions at Installation**

During installation, the foam formulation “A-side” (which contains the isocyanate) is combined with the formulation “B-side” (which consists of the polyol, FEA, catalyst, fire retardant and surfactant) while being simultaneously sprayed onto the surface to be insulated. The polyol reacts with the isocyanate to form polyurethane. The foam expansion agent expands the foam to the target foam density.

During the installation process, some of the FEA is emitted directly to the environment and is not contained within the spray foam insulation. FEA emissions during SPF installation are estimated to be between 10-15% of the FEA in the original formulation [30, 31, 32]. For this study, a 15% loss rate is used based on the IPCC guidelines [30, 31]. As all of the foam expansion agents evaluated are greenhouse gases, this direct emission will contribute toward life cycle climate change potential. Both HCFC-141b and HFC-245fa have a significantly higher GWP than either HFO-1336mzz-Z or water/CO$_2$, as shown in Table 1, above.

Additionally, during the installation process some surplus foam insulation is typically generated and discarded as waste. This can come from overfilling the wall cavity with foam, which then must be cut off so that the foam is level with the wood framing. This study assumes a 5% yield loss of SPF during installation, i.e. 5 wt% of the SPF generated is discarded as waste during the installation process. The burdens associated with manufacturing and disposing of this waste foam, as well as FEA emissions from the waste foam, were taken into account and included in the burdens identified as “yield loss” in the results of this study. For the R-Value Basis, overfilling would provide higher R-value and would likely not require removal. However, for the sake of this study, a 5% yield loss was still assumed for this case.

As shown in Figure 3 below, based on an overall R-value of R-13, life cycle CCP through installation is significantly influenced by direct emissions of the FEA for HCFC-141b and HFC-245fa installations. For the HFO-1336mzz-Z insulation, direct emissions of the FEA do impact the lifecycle CCP; however, the relative magnitude of these GHG contributions is small due to the low GWP of HFO-1336mzz-Z. As FEA loading increases, the amount of FEA per square meter of insulation and R-value per inch increases while at the same time the foam density decreases. Therefore, as FEA loading increases for both HFC-245fa and HFO-1366mzz-Z, less insulation is required and the burdens associated with formulation manufacture decrease. For the HFC-245fa insulation, where direct emissions of the FEA are a significant contributor to the lifecycle GHG emissions, increasing the FEA loading also increases these direct FEA emissions as well as the CTG CCP. For the HFO-1336mzz-Z insulation, the reduction in formulation manufacturing as FEA loading increases exceeds the minimal increases in direct FEA emissions, resulting in an overall decrease in CTG CCP as FEA loading increases.
Direct Emissions during Use & End-of-Life

During the use-phase of closed-cell spray foam some amount of the FEA will diffuse out of the foam and be emitted to the atmosphere. In addition to having direct CCP impacts for the FEA emissions, extensive leaking of the FEA over the life of the insulation may affect the R-value of the insulation. As FEA is replaced in the closed cell foams with air, the insulation R-value may decrease. The amount of FEA emitted during the use-phase is a function of both the leak rate and the number of years of use. In this study, 35% of the initial FEA loading was assumed to be emitted during the SPF use-phase of 60 years.

Additionally, FEA is emitted at end-of-life during the dismantling and removal (D&R) process and if the foam is shredded or sent to a landfill. Material sent for incineration at the end-of-life avoids additional direct emissions, but incur climate change potential from combustion of both the FEA and the insulation. During D&R, 20% of the remaining FEA is assumed to be released [29]. The ultimate fate of the insulation is assumed to mirror the municipal waste not recycled or composted, i.e. 83% is land-filled and 17% is incinerated [34]. Just as FEA leaks from insulation during the use-phase, FEA may diffuse from land-filled SPF over time. For this base case in this study, half of the FEA remaining in the insulation after D&R which is sent to landfill is assumed to be emitted to atmosphere. During incineration, all of the FEA was assumed to be combusted, resulting in CO$_2$ emissions from both the FEA and the rest of the spray foam insulation.

The insulation lost as yield loss also contains FEA, but does not have a 60-year use-phase prior to final disposal. For simplicity, the emissions of FEA from the foam which is discarded during installation are assumed to be in proportion to those emitted from the installed insulation. These use-phase and EOL emissions from the yield loss were included with the yield loss burdens in the figures breaking down the source of burdens which follow. A mass balance for both the FEA and the spray foam insulation is shown in Figure 4.
Figure 4: Mass Balance for a Sample Aggregated Formulation producing 1m² of installed insulation. FEA emissions and fate are tracked. FEA sent to incineration is assumed destroyed. Half of the FEA in landfill is assumed to be emitted in the temporal scope of this study, while the remaining FEA is assumed to be sequestered.

RESULTS

R-Value Basis

Including the direct FEA emissions during use and end-of-life to the cradle-to-installation data from above provides the basis for the R-Value case. These emissions differentiate water/CO₂ blown foam and the HFO-1336mzz-Z foam from the HCFC-141b and HFC-245fa foams with regard to lifecycle GHG emissions. Results for Houston, where code requires R-13 installation, are shown in Figure 5a. Results for both Baltimore and Chicago, where R-20 is required, are shown in Figure 5b. Both figures use the same scale for ease in comparison. For HCFC-141b and HFC-245fa, the emissions of the FEA during installation, the use-phase of the foam insulation and at end-of-life provide the largest contribution of lifecycle CCP for both R-13 and R-20 systems. Due to the low GWP of the HFO-1336mzz-Z, its emissions do not play a significant role in lifecycle
CCP, which are still largely influenced by raw material manufacturing. For all three regions, both HFO-1336mzz-Z and water/CO\textsubscript{2} blown foam installations provide insulation with less than 20 kg CO\textsubscript{2} eq, cradle-to-grave (CTGr) per square meter of insulation while HCFC-141b and HFC-245fa installations range from 89 – 242 kg CO\textsubscript{2} eq per square meter of insulation depending on FEA loading and region. Due to a significantly lower foam density, the water/CO\textsubscript{2} blown foam has the lowest CCP of these options for the R-Value Basis, where differences in thermal conductivity are not a factor.

**Figure 5.** Cradle-to-Grave Climate Change Potential for Spray Foam Insulation, (a) R-13 Basis – Houston, (b) R-20 Basis – Baltimore, Chicago. CCP reductions due to reduced energy consumption during the use-phase of the insulation are excluded because all formulations have a consistent R-value.
Thickness Basis

The purpose of all residential wall insulation products is to reduce the amount of energy required to heat and/or cool a residential building by decreasing the overall heat transfer coefficient of the building walls. Adding even small amounts of insulation can have a large effect on the overall heat transfer. As additional insulation is added to a wall the overall heat transfer coefficient decreases; however, at diminishing returns since overall heat transfer is inversely-proportional to the amount of R-value added. Overall residential energy savings is a function of the decrease of the overall heat transfer through a residential wall in this study. It is also a function of the type of heating and cooling systems used, the heating degree days (HDD) or cooling degree days (CDD) of a particular geographical region, as well as other factors. The energy savings for a specific insulation thickness were calculated using TRACETM Load 700 software as previously described. Figures 6a, b and c compare the climate change potential (CCP) for Houston Baltimore, and Chicago respectively. Burdens associated with manufacture, installation, use, and end-of-life are shown above the ‘zero’ line in the figures. Credits for energy savings relative to water/CO$_2$ blown foam are shown below the ‘zero’ line. Net CTGr CCP are tabulated in each figure and identified by the dashed blue line across each bar for each FEA installation. All three graphs are presented with the same scale for ease in comparison among the regions.

When comparing on an equal thickness basis, incremental differences in R-value and subsequent energy savings have an impact on the overall CTGr GHG emissions. Regional differences are shown to have a significant relative effect on energy savings, with increased savings associated with colder climates. For a given FEA loading and region, all of the halogenated FEA installations provide similar energy savings compared to water/CO$_2$ blown foam. For HFO-1336mzz-Z, these energy savings relative to water/CO$_2$ blown foam are larger than the identified formulation and installation burdens for all regions and FEA loadings. The net GHG CTGr emissions for HFO-1336mzz-Z decrease as climatic conditions become colder since the energy savings increase significantly while manufacture and installation burdens increase marginally (due to an increase in wall cavity thickness from 3.5” to 5.5” across the cases evaluated). For HCFC-141b and HFC-245fa, the direct emissions during installation, use, and end-of-life are more significant than the energy savings relative to water/CO$_2$ blown foam, even in the Chicago region and at low FEA loadings. Incremental energy savings relative to water/CO$_2$ blown foam increase with FEA loading. However, for high GWP FEA, the benefit gained by increasing FEA loading is largely offset by increases in incremental FEA emissions during product use and end-of-life.
Figure 6. Cradle-to-Grave Climate Change Potential on an equal thickness basis. Energy savings are normalized to water/CO₂ blown foam, i.e. results represent incremental differences of energy savings as compared to a water/CO₂ blown foam baseline. Energy savings based on (a) Houston, TX (b) Baltimore, MD (c) Chicago, IL. Net CTGr CCP is tabulated.
Uncertainty and Sensitivity Analysis

The analysis of FEA options in spray foam installations for residential wall has the potential for significant uncertainty. Key uncertainties are regional electricity grid mix and its effect on energy savings during the use phase, the amount of FEA emitted during installation, use, and at end-of-life, uncertainties in manufacturing CTG CCP for the formulation components, and uncertainties in the lifespan of the building. Evaluation of these uncertainties are presented below, relative to the base case.

ELECTRICITY MIX IMPACTS ON CCP REDUCTION DUE TO ENERGY SAVINGS

Electricity grid CCP potential can vary significantly by region based on the different fuel sources used. The three cities evaluated in this study present high, low, and average carbon intensity for electricity generation as shown in Table 3 above. Here the results from Baltimore for the Thickness Basis were evaluated with electricity sub-regional impacts from RFCE, RFCW, ERCT, and NWPP (the Northwest sub-region of the WECC. NWPP represents an electricity grid which has low carbon intensity due to high hydroelectricity use and represents a region in the US with the same climate zone as Baltimore. Future electricity supply is also likely trend towards more renewable energy resulting in lower CCP per kWh produced. If the evaluation considers just alternate geography with different CCP per kWh from the electricity grid mix, then the CCP credits from energy savings relative to water/ CO$_2$ blown foam for will be reduced proportionally.

Table 6 shows a comparison of the CCP from energy savings (w.r.t. water/CO$_2$ FEA), the sum of all other CCPs and the net CCP using the four electricity grid for the Thickness Basis case for Baltimore, MD. For all closed cell foam options, the change to a cleaner electricity grid mix represented by the NWPP grid results in a 3-5 kg CO$_2$ equivalent increase in net CCP due to CCP credits from energy savings during the use-phase. The change to higher carbon intensity (low CCP) electricity grid represented by the RFCW grid results in a 28-45 kg CO$_2$ eq. decrease in net CTGr CCP. The lower the carbon intensity in the grid, the less CCP credits accumulated based on energy savings relative to water/ CO$_2$ blown foam. The reduction in benefits for the NWPP subregion is limited because the RFCE grid also has relatively low carbon intensity. For an extreme case, where the electricity supply is, for instance, 100% from hydroelectricity, energy savings benefits could be essentially eliminated, resulting in results in proportion to those shown for the R-Value basis. However, even for the US sub-regional grid with the lowest carbon intensity, the HFO-1336mzz-Z FEA options would still provide the lowest CTGr CCP SPF installation option for residential walls. On the other extreme, even the US sub-regional grid with the highest carbon intensity would not result in the HCFC-141b or HFC-245fa FEA options providing lower net CTGr CCP than the HFO-1336mzz-Z or water/ CO$_2$ blown foam options. In addition, the HFO-1336mzz-Z FEA options would remain the lowest CTGr CCP Thickness Basis option with increased savings relative to the water/ CO$_2$ blown foam. In summary for this sensitivity analysis, the overall conclusions are not limited within the range of carbon intensity of current US sub-regional grids.
### Table 6: Electricity Grid Impacts on Thickness Basis Results - Baltimore Region

<table>
<thead>
<tr>
<th>FEA EMISSIONS DURING INSTALLATION, USE, AND END-OF-LIFE</th>
</tr>
</thead>
</table>
| Due to the high influence of the FEA emissions during installation, use and end-of-life, an uncertainty analysis was performed where the amount of FEA emitted during these lifecycle stages is varied. The base case assumed 15% FEA emissions during installation, 35% FEA emissions during use, 20% of the remaining FEA in the insulation is released during D&R, 87% of the insulation is sent to landfill where half of the remaining FEA is emitted during the temporal scope of this study, and 17% of the insulation is sent to incineration where the FEA still remaining is destroyed. These assumptions result in 76.6% of the initial FEA being emitted to atmosphere. Although the FEA emitted is varied in this analysis, it is not assumed to affect the aged R-Value used in the evaluation. In other words, reduced emissions during installation and use for a best case scenario are still expected to be high enough that the aged R-values used are still appropriate, and increased emissions for the worst case assumption are assumed to occur during the EOL since the maximum expected emission during use was identified at 50% of the original formulation [31]. For the best case scenario, 10% FEA emissions during installation [29], and 0.2% FEA emissions per year during the use phase were assumed, resulting in 22% emissions at the end of the use-phase. During D&R, an additional 8% of the original FEA was assumed to be emitted and 100% of the insulation is assumed to be incinerated such that only 30% of the FEA from the formulation is emitted to atmosphere. For the worst case, the same assumptions for installation and use-phase FEA emissions were assumed, resulting in 50% of the FEA being emitted by the end of the use-phase. At EOL, the insulation was assumed to be shredded, releasing the remaining FEA to atmosphere. Therefore the range of FEA emissions evaluated is 30% for the best case, 76.6% for the base case, and 100% for the worst case.

Results for this sensitivity are shown using the Chicago, IL geography for the R-Value basis and R-20 Thickness Basis in Figures 7a and 7b, respectively. As expected, the percentage of FEA emitted has a large influence on relative CTGr CCP for the high GWP FEA cases. However, even with only 30% emissions and using the ‘low’ FEA loading case for HFC-245fa (i.e. the lowest of the high GWP FEA installations), the CTGr CCP remains significantly higher than all HFO-1336mzz-Z and water/CO₂ blown foam cases for the R-Value Basis. While the magnitude of the differences between the high GWP FEA installations and the HFO-1336mzz-Z and water/CO₂ blown foam varies significantly with the percentage of FEA emitted, the trends and potential conclusions are not different over the cases and range evaluated. However, for the Thickness Basis, “low” FEA loading cases at 30% FEA emissions for HCFC-141b and HFC-245fa result in marginally lower net CCP than the water/CO₂ blown case. The HFO-1336mzz-Z options remain lower than all other FEA options for the

<table>
<thead>
<tr>
<th>FEA</th>
<th>FEA Loading</th>
<th>CCP Source</th>
<th>Electricity Sub-Regional Grid Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RFCE</td>
</tr>
<tr>
<td>HCFC-141b</td>
<td>Mid (5-9%wt%)</td>
<td>CCP from Energy Savings</td>
<td>-59</td>
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<tr>
<td></td>
<td>Low (3-5%wt%)</td>
<td>CCP from Energy Savings</td>
<td>-43</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>Mid (5-9%)</td>
<td>CCP from Energy Savings</td>
<td>-52</td>
</tr>
<tr>
<td></td>
<td>High (9-12%)</td>
<td>CCP from Energy Savings</td>
<td>-64</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>Mid (5-9%)</td>
<td>CCP from Energy Savings</td>
<td>-59</td>
</tr>
<tr>
<td></td>
<td>Low (3-5%)</td>
<td>CCP from Energy Savings</td>
<td>-45</td>
</tr>
<tr>
<td>Water/CO₂</td>
<td></td>
<td>CCP from Energy Savings</td>
<td>0</td>
</tr>
</tbody>
</table>
Thickness Basis. Under the assumptions of this analysis, FEA emission rates during installation, use, and at EOL are shown to have very limited effects on the HFO-1336mzz-Z options. Therefore, for constant thickness installations where FEA emissions are limited during installation and use and the insulation is incinerated at EOL, high GWP FEA options at low FEA loadings have similar CCP to water/CO₂ blown SPF residential wall installations. However, HFO-1336mzz-Z provides the lowest CCP option for the Thickness Basis at any FEA emission rate or FEA loading within the limitations and assumptions of this study.
FORMULATION VARIATION AND LCA MODEL UNCERTAINTY

As previously noted, uncertainty exists in the use rate of minor formulation components such as flame retardant, catalyst, and surfactant. Foam density also varied among formulations based on the primary data provided. In addition, uncertainty in the LCA models used for these materials as well as for polyol, and MDI exist. Also, the modeling assumptions, particularly for halogenated emissions for the various FEA production routes can be varied to yield differences in the LCI. This uncertainty analysis evaluates potential combinations of use rate and LCI for the materials in the formulations to show the sensitivity of the formulation impacts relative to the R-value Basis and Thickness Basis for the Chicago, IL. The use rates of flame retardant, formulation catalyst and surfactant were allowed to vary across the ranges identified by the SPF formulators. As formulations are aggregated, these ranges influence the amount of FEA and MDI required per kg of insulation as well.

Figure 8 shows the variability for each installation option for the R-20 Basis. The minimum, base case, and maximum CTG CCP values were generated through the formulation variations. For the high GWP FEA options, differences within a given FEA for the minimum case result in a 3% to 15% reduction in CCP with respect to the base case and an increase from 4 to 20% for the maximum case. Most of this variation is driven by the percentage of FEA used in the formulation which varies due to the range of use rates of other materials. The higher the FEA used, the more FEA is available for emission. The magnitude of variation from high to low for the high GWP FEA options is 17-57 kg CO₂ eq. Variation within a given FEA loading for HFO-1336mzz-Z is also driven by the FEA in the formulation, but the changes are due to the burdens associated with formulation manufacture. Burdens for HFO-1336mzz-Z options are reduced with respect to the base case by 17% to 25% for the minimum case and increased 17% to 63% for the maximum case. Despite the higher percentage of variation, the magnitude of variation for the HFO-1336mzz-C FEA options is lower at 15-21 kg CO₂ eq. The general conclusions are not affected by these variations in formulation use rate and LCI uncertainty for the R-Value case. Variations identified in the water/CO₂ blown foam case are negligible.
Sensitivity Analysis: Effect on total impact of variation of Formulation Material Use Rate and LCI Uncertainty - Cradle-to-Grave Climate Change Potential. Chicago geography – R-20 Basis. CCP reductions due to reduced energy consumption during the use-phase of the insulation are excluded because all formulations have a consistent R-value

Variation for formulation material use rate and LCI uncertainty for the Thickness Basis case in Chicago is higher than that for the R-Value Basis due to the increased insulation use as seen in Figure 9. For the high GWP FEA options differences for a given FEA and FEA loading result in a 5% to 35% reduction in CCP with respect to the base case for the minimum case and an increase from 7% to 45% for the maximum case. This translates to a variation of 28 – 84 kg CO₂ per m² from the minimum to maximum cases. For the HFO-1336mzz-Z options differences across the FEA loadings result in a 4% to 15% reduction in CCP with respect to the base case for the minimum case and an increase from 16% to 21% for the maximum case. HFO-1336mzz-Z installations see a variation of 23-44 kg CO₂ eq per m² across the low and high cases depending on FEA loading. The variation for HFO-1336mzz-Z can once again, be mainly attributed to the higher uncertainty and higher absolute value of FEA manufacturing burdens for HFO-1336mzz-Z. However, this range of variation does not change the trends observed from the base case for the Thickness Basis. The magnitude of the variation is not significant enough to change or limit the conclusions which can be drawn.
For the R-Value Basis, building life has no influence on the results of this study since energy savings over time are compared relative to water/CO\textsubscript{2} blown foam as opposed to being compared to a no insulation case. Since all insulation options in the R-Value Basis have the same R-value, energy savings are equivalent. This conclusion is limited by the assumption made for this study that the aged-R-Value does not continue to deteriorate over the temporal range of this study.

For the Thickness Basis, energy savings are proportional to the number of years the insulation is installed assuming a constant aged R-value. While the life of the insulation is expected to match the life of the building for spray foam applications, the life of the residential house may vary. As opposed to evaluating a range of potential life spans for a house, the concept of payback time, or a breakeven point is used for this sensitivity. Relative to the water/CO\textsubscript{2} blown foam case, all other installation options incur more climate change potential associated with manufacture, installation, and FEA emissions. However, the reduced thermal conductivity of these other options provides for CCP reduction from energy savings during the use phase. At some point in time, the energy savings accrued will reduce the relative impact to that equal to the burdens for the water/CO\textsubscript{2} blown foam case. The baseline Thickness Basis case which assumes a 60-yr building life identified HFO-1336mzz-Z as having lower net cradle-to-grave CCP than the water/CO\textsubscript{2} blown foam, so the breakeven point for HFO-1336mzz-Z under the base case scenario is less than 60 years. The other FEA options were all higher than water/CO\textsubscript{2} blown foam such that the breakeven point is greater than 60 years. Table 7 identifies the breakeven point, in years, for each installation option relative to water/CO\textsubscript{2} blown foam. HFO-1336mzz-Z has a breakeven point with the water/CO\textsubscript{2} blown foam installation between 9 and 36 years depending mainly on the region and FEA loading under the base case assumptions for this study. HFC-245fa has a breakeven point with water/CO\textsubscript{2} blown foam installation between 9 and 36 years depending mainly on the region and FEA loading, and sub-regional electricity grid carbon intensity. HCFC-141b has a breakeven point between 122 and 309 years for the Mid FEA Loading case depending on the region, particularly due to the sub-regional electricity grid carbon intensity. Calculated breakeven points greater than 100 years are beyond the temporal boundaries of this study.

**BUILDING & INSULATION LIFE**

For the R-Value Basis, building life has no influence on the results of this study since energy savings over time are compared relative to water/CO\textsubscript{2} blown foam as opposed to being compared to a no insulation case. Since all insulation options in the R-Value Basis have the same R-value, energy savings are equivalent. This conclusion is limited by the assumption made for this study that the aged-R-Value does not continue to deteriorate over the temporal range of this study.

For the Thickness Basis, energy savings are proportional to the number of years the insulation is installed assuming a constant aged R-value. While the life of the insulation is expected to match the life of the building for spray foam applications, the life of the residential house may vary. As opposed to evaluating a range of potential life spans for a house, the concept of payback time, or a breakeven point is used for this sensitivity. Relative to the water/CO\textsubscript{2} blown foam case, all other installation options incur more climate change potential associated with manufacture, installation, and FEA emissions. However, the reduced thermal conductivity of these other options provides for CCP reduction from energy savings during the use phase. At some point in time, the energy savings accrued will reduce the relative impact to that equal to the burdens for the water/CO\textsubscript{2} blown foam case. The baseline Thickness Basis case which assumes a 60-yr building life identified HFO-1336mzz-Z as having lower net cradle-to-grave CCP than the water/CO\textsubscript{2} blown foam, so the breakeven point for HFO-1336mzz-Z under the base case scenario is less than 60 years. The other FEA options were all higher than water/CO\textsubscript{2} blown foam such that the breakeven point is greater than 60 years. Table 7 identifies the breakeven point, in years, for each installation option relative to water/CO\textsubscript{2} blown foam. HFO-1336mzz-Z has a breakeven point with the water/CO\textsubscript{2} blown foam installation between 9 and 36 years depending mainly on the region and FEA loading under the base case assumptions for this study. HFC-245fa has a breakeven point with water/CO\textsubscript{2} blown foam installation between 104 and 206 years, with variability due to regional climatic differences, FEA loading options, and sub-regional electricity grid carbon intensity. HCFC-141b has a breakeven point between 122 and 309 years for the Mid FEA Loading case depending on the region, particularly due to the sub-regional electricity grid carbon intensity. Calculated breakeven points greater than 100 years are beyond the temporal boundaries of this study.
Table 7. Building Life - Breakeven Point with Water/CO\textsubscript{2} Blown Foam

<table>
<thead>
<tr>
<th>Foam Expansion Agent</th>
<th>FEA Loading</th>
<th>Houston</th>
<th>Baltimore</th>
<th>Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCFC-141b</td>
<td>Mid (5-9wt%)</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>Low (3-5wt%)</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>Mid (5-9wt%)</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>High (9-12wt%)</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>Low (3-5wt%)</td>
<td>15</td>
<td>36</td>
<td>15</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>Mid (5-9wt%)</td>
<td>18</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>HFO-1336mzz-Z</td>
<td>High (9-12wt%)</td>
<td>21</td>
<td>28</td>
<td>12</td>
</tr>
</tbody>
</table>

These breakeven points are relative to the water/\textsubscript{CO\textsubscript{2}} blown foam case. Climate change potential breakeven points relative to no insulation case would be about 2 years for HFO-1336mzz-Z and between 10-25 years for HCFC-141b and HFC-245fa depending on FEA loading and region.

For residential housing applications with short lifetimes, i.e. less than 12-15 years for Chicago, less than 28-36 years for Baltimore, and less than 15-21 years for Houston, HFO-1336mzz-Z installations would be more equivalent to water/\textsubscript{CO\textsubscript{2}} blown foam options. As building life is extended, the advantages of HFO-1336mzz-Z relative to water/\textsubscript{CO\textsubscript{2}} blown foam are extended. The breakeven point for the high GWP FEA options is far enough into the future that assumptions around energy grid burdens, code requirements, and perhaps even regional weather patterns may no longer be appropriate.

**CONCLUSION**

Raw material manufacturing, installation, product use, and end-of-life all contribute to the lifecycle climate change potential of SPF insulation products. As such, selection of a foam expansion agent to provide the lowest cradle-to-grave climate change potential should be based on more than just the direct GWP of the foam expansion agent. This study for residential walling applications highlights the importance of the formulation, the specific application, and the thermal performance, in addition to the FEA GWP of the alternatives. These conclusions are specific to this residential wall application. Furthermore, the \textsubscript{CCP} from energy savings during the use phase are presented as relative to the water/\textsubscript{CO\textsubscript{2}} blown foam option. Therefore, results in this study are not absolute with respect to \textsubscript{CCP}. Therefore, these results should not be used out of the context of residential wall spray foam applications.

For R-Value Basis installations, for all formulations evaluated, both manufacturing CTG climate change potential and direct emissions from the FEA can be significant. For the high GWP FEAs evaluated in this study, HCFC-141b and HFC-245fa, the dominating contributor to \textsubscript{CCP} is the direct emission of the FEA during installation, use, and at end-of-life. This is true for the base case where 77\% of the FEA is assumed emitted to atmosphere at some point during the life of the insulation. This remains true across the entire 30\%-100\% range of FEA emission rates evaluated in an uncertainty analysis. As such, formulations with lower FEA loadings for these high GWP FEA options have lower CTG\textsubscript{R} CCP. For this constant R-value Basis, for low GWP FEA options such as HFO-1336mzz-Z and water/\textsubscript{CO\textsubscript{2}} blown foam, the manufacturing burdens of the formulations drive the overall CTG\textsubscript{R} CCP. Increased FEA loading marginally decreases the CTG\textsubscript{R} GHG emissions for HFO-1336mzz-Z. Due to its low GWP, the direct emissions for HFO-1336mzz-Z are completely off-set by the reduced insulation requirements as FEA loading is increased. Both the HFO-1336mzz-Z and the water/\textsubscript{CO\textsubscript{2}} blown foam installations result in lower CTG\textsubscript{R} CCP for all FEA loadings and regions evaluated. The water/\textsubscript{CO\textsubscript{2}} blown foam, based on the low GWP of direct FEA emissions and a very low foam density, had the lowest CTG\textsubscript{R} CCP for the constant R-value Basis. However, there are potential applications beyond those studied in this paper where water/\textsubscript{CO\textsubscript{2}} blown foam may not be able to provide the required (or desired) R-value in the available wall cavity. For example, based on the data in this study, water/\textsubscript{CO\textsubscript{2}} blown foam can not provide R-20 insulation in a 2”x4” wall construction (wall thickness of 3.5 inches) due to the high thermal conductivity of the product. As such, thermal performance of the insulation still matters in regards to making the SPF a viable option for the given application. Since this case assumes constant R-value, energy savings during the use phase are equivalent for each formulation. Therefore regional effects are only influenced by the amount of insulation required by code and building life assumptions have no influence on the results or conclusions.

For installations where insulation is applied to a set thickness, such as filling a wall cavity, thermal performance matters and relative energy savings must also be included in the evaluation. For the Thickness Basis as defined in this study, the direct emission of FEA remains the primary GHG emission contributor for the high GWP FEAs. GHG emission reductions from the energy savings relative to water/\textsubscript{CO\textsubscript{2}} blown foams for the high GWP FEAs are lower than the burdens from direct emissions. However, for installations using HFO-1336mzz-Z, which has both low thermal conductivity and a low GWP, the GHG emission reductions from energy savings relative to water/\textsubscript{CO\textsubscript{2}} blown foam more than off-set the direct impacts and the additional GHG emissions associated with manufacture of the formulation. Increased FEA loading leads to lower GHG emissions from energy savings relative to water/\textsubscript{CO\textsubscript{2}} blown foam. For HFC-245fa, the increased loading also results in

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increased direct emissions of FEA, and an overall increase in CTGr CCP. For HFO-1336mzz-Z, the GHG emission reductions from energy savings far outweigh the minor additional direct emissions, leading to a decrease in overall CTGr CCP as FEA loading increases. As regions get colder and as HFO-1336mzz-Z loading increases, the GHG emissions from energy savings relative to water/CO2 blown foams also increase. As seen in the R-value Basis, water/CO2 blown foam is consistently lower than the high GWP FEA options for this case. However, for all FEA loadings evaluated and all regions studied, HFO-1336mzz-Z results in the lowest CTGr CCP for the Thickness Basis.

Sensitivity analyses for lower carbon intensity electricity grid mix and an uncertainty analysis for formulation uncertainty confirm the trends identified above and do not limit the conclusions within the ranges evaluated. Uncertainty analysis for FEA emission rate during installation, use, and end-of-life both confirm the trends and conclusions evaluated in the base case for this study for the other FEA options with respect to HFO-1336mzz-Z. In a best case scenario regarding FEA emissions for the low FEA loading option for HFC-245fa in Chicago, CCP energy savings provide enough CCP reduction such that the net CCP burdens are lower than those for water/CO2 blown foam. However, HFO-1336mzz-Z still provides the lowest CTGr CCP for the Thickness basis at all FEA loadings and in all regions studied. An uncertainty analysis on building life has no influence on the R-value basis since energy savings are measured relative to water/CO2 blown foam and all cases have equivalent R-values. However, for the Thickness Basis, breakeven building life for HFO-1336mzz-Z installations was identified to be between 10-23 years relative to water/CO2 blown foam depending on region and FEA loading. So, although HFO-1336mzz-Z installations have the lowest CTGr CCP for all installation options and regions evaluated for the Thickness Basis base case assumption of a 60-yr building life, water/CO2 blown foams become more competitive when building life is shorter. As building life increases from the base case, all halogenated FEA options evaluated eventually breakeven with the water/CO2 blown foam option due to energy savings during the use phase. However, for HCFC-141b and most of the HFC-245fa installations, this breakeven point occurs beyond the 100-year temporal scope of this study. These breakeven points are far enough in the future that many of the assumptions of this study may no longer be valid; such as electricity GHG emissions factors.

In conclusion, FEA selection for spray foam installations in residential walling applications for the sake of reducing GHG emissions requires evaluation of the basis for determining the thickness of insulation and evaluation of code requirements relative to FEA performance. High GWP FEA options were consistently identified as resulting in higher burdens than HFO-1336mzz-Z and water/CO2 blown foams. The magnitude of these differences can be reduced, but remains significant even for the low FEA loading applications and/or installations with reduced insulation thickness. When thickness is not limited by the wall cavity such that a common R-value can be achieved across all formulations, both HFO-1336mzz-Z and water/CO2 blown foam provide significant reductions in CCP compared to the high GWP FEAs, with water/CO2 blown foams shown to have the lowest CTGr CCP. However, in applications where a constant thickness of insulation is applied or when R-value is not held constant, such as filling the available wall cavity, thermal performance becomes important. For these cases, provided a reasonable building lifetime is achieved, HFO-1336mzz-Z, a low GWP FEA with low thermal conductivity, provides the lowest CTGr climate change potential for SPF residential wall insulation systems.

FUTURE WORK

Although foam expansion agents are used in a number of applications and regions, this evaluation only examines residential wall applications in the United States. Different applications and regions come with different competitive landscapes, performance criteria, product lifetimes, codes and regulations, thickness requirements and limitations, disposal scenarios, energy consumption, as well as other lifecycle implications. By performing additional application and region-specific LCA studies, comparative environmental benefits for each unique application will be better understood and guide decision-makers. Comparisons with insulation options other than spray foam will likely require evaluation of differences in air infiltration. This study suggests GHG emission reductions from energy savings will be of higher importance when comparing applications where thickness is substantially limited.

REFERENCES


**BIOGRAPHY**

**Todd Krieger, P.E:** Todd is a senior consultant within DuPont Engineering Research & Technology (DuET) with over 10 years of experience in the application of LCA for various DuPont businesses. He is a Life Cycle Assessment Certified Professional from the American Center of Life Cycle Assessment (ACLCA) and a member of the ACLCA Advisory Board. He received his Bachelor of Chemical Engineering from the University of Delaware and is a certified Professional Engineer (P.E.) in the state of Delaware.

**Christopher Johnas:** Chris is currently a consultant working for DuPont Sustainable Solutions (DSS) with over 3 years of experience as an LCA practitioner. Chris has completed several life cycle assessments for various DuPont products including DuPont Cellulosic Ethanol. He received his bachelor of Chemical Engineering from the University at Buffalo (SUNY).

**Dr. Shaibal Roy:** Shaibal is an engineering consultant within DuPont Engineering Research and Technology (DuET). He has practiced LCA for about a year in the areas of bio-materials and Fluoro-chemicals. He earned his doctorate in multiphase reaction engineering from Washington University in St. Louis, USA and a Bachelors degree in chemical engineering from IIT Kharagpur, India.

**Helen Walter-Terrinoni:** Helen is managing the next generation, low-GWP foam expansion agent development program at DuPont and has been evaluating and working on LCA's for insulation for 3 years. She received a Bachelor of Chemical Engineering and a Master of Chemical Engineering with a concentration in Environmental Engineering from Syracuse University.