the ATHENA™ Sustainable Materials Institute

A LIFE CYCLE INVENTORY OF SELECTED COMMERCIAL ROOFING PRODUCTS

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Preface

This report has been prepared as part of a continuing program to extend the knowledge base of the ATHENA™ Sustainable Materials Institute, a not-for-profit organization dedicated to helping the building community meet the environmental challenges of the future. The data developed in this report will be used in ATHENA™, the Institute's systems model for assessing the relative life cycle environmental implications of alternative building or assembly designs.

Institute studies and publications fall into two general categories: investigative or exploratory studies intended to further general understanding of life cycle assessment as it applies to building materials and buildings; and individual life cycle inventory studies which deal with specific industries, product groups or building life cycles stages. All studies in this latter category are firmly grounded on the principles and practices of life cycle assessment (LCA), and follow our published Research Guidelines, which define boundary or scope conditions and ensure equal treatment of all building materials and products in terms of assumptions, research decisions, estimating methods and other aspects of the work.

The integration of all the Institute's life cycle inventory data is a primary function of ATHENA™ itself, and we therefore caution that individual industry life cycle study reports may not be entirely stand-alone documents in the sense that they tell the whole story about an individual set of products. For example, this report deals with the manufacture of selected roofing products, while a separate report deals with on-site roof construction. ATHENA™ also generates various composite measures that can be best described as environmental impact indicators, a step toward the ultimate LCA goal of developing true measures of impacts on human and ecosystem health.

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A Life Cycle Inventory of Selected Commercial Roofing Products

1.0 INTRODUCTION

This report provides supporting documentation for life cycle inventories of several materials used in commercial roofing applications. The work was commissioned by the ATHENA™[1] Sustainable Materials Institute as part of the continuing sries of life cycle analyses of building materials. The life cycle inventory modeling was conducted using Franklin Associates' data and SimaPro 5 software (Beta version) from PRé Consultants. Electronic copies of the life cycle inventory models are provided with this report.

1.1 Materials Analyzed

The following roofing materials are analyzed in this study:

- Styrene Butadiene Styrene (SBS) modified bitumen roofing membrane;
- Ethylene Propylene Diene Monomer (EPDM) rubber roofing membrane;
- Polyvinyl Chloride (PVC) roofing membrane; and
- Polyisocyanurate (PIC) roofing insulation.

The analysis is limited to the primary constituents of each material. Unless specifically noted otherwise, the analysis does not include reinforcing materials (unless they are a requisite part of the material, as in SBS modified bitumen roofing membrane), fire retardants, fillers, surface coatings, facings, etc. This analysis does not include application or installation of the roofing product, nor is disposal at end-of-life included.

1.2 Report Structure

Each of the following sections of the report deals with one of the four materials analyzed, including the following information:

- a brief description of the material and its production;
- a flow diagram showing the main process steps in the production of the material in the form in which it is used in roofing applications;
- a list of assumptions made in conducting the life cycle inventory;
- a cradle-to-production table; and
- a list of references for all processes in the production of the material.

References are listed at the end of the report.

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[1] ATHENA™ is a registered trademark of the ATHENA™ Sustainable Materials Institute.

2.0 SBS Modified Bitumen Roofing Membrane

In polymer modified bitumens, chemical modifiers (polymers) are added to bitumen (asphalt) to increase the material's flexibility and elasticity, as well as to improve cohesive strength, toughness and resistance to flow at high temperatures. Modified bitumen membranes are composed of three primary elements: asphalt flux, polymer modifiers (in this case, SBS), and reinforcements. Reinforcing materials may include polyester, fiberglass, or a polyester/fiberglass laminate. Secondary elements include fillers, fire-retardant additives, and surfacing, such as sand, ceramic mineral granules, and poly film. Modified bitumen materials are strong and offer long-lasting protection from weather and UV exposure. A flow diagram for the production of SBS modified bitumen membrane is shown in Figure 1.

The styrene-butadiene-styrene terpolymer is a thermoplastic rubber whose molecular structure combines a rubbery midblock with two plastic endblocks. The polymer may be synthesized by the sequential polymerization of all three blocks or sequential polymerization of two blocks followed by coupling. The plastic endblock phase regions, called domains, act as crosslinks between the ends of the rubber chains, serving to lock the rubber chains and their inherent entanglements in place. This terpolymer consists of 35 percent styrene and 65 percent butadiene.

To produce SBS modified bitumen roofing membrane, SBS is first ground in a trigonal mill or cryogenically ground and hammered. The SBS is mixed with asphalt in an insulated mixing tank maintained at a temperature of 400° F using hot oil circulating around the outside of the tank in tubes. An electric motor at the top of the tank drives a shaft with mixing and cutting blades. The SBS modified bitumen is discharged to a holding tank, through which the polyester nonwoven substrate is fed, saturating the substrate. The coated substrate is fed through rollers that regulate the thickness of the coated material. Finally, the membrane passes through water-cooled rollers to cool the product before it is fed onto rolls for shipment.

2.1 Assumptions

The LCI model for SBS modified bitumen membrane is based on the following information and assumptions.

- Based on information provided by Firestone representatives, for a typical SBS modified bitumen membrane used in Canada, about 94% of the weight is SBS modified bitumen (68% asphalt, 12% SBS, and 20% limestone filler). The remaining 6% of the weight of the product is polyester nonwoven substrate (75% polyester nonwoven, 25% urea formaldehyde resin).

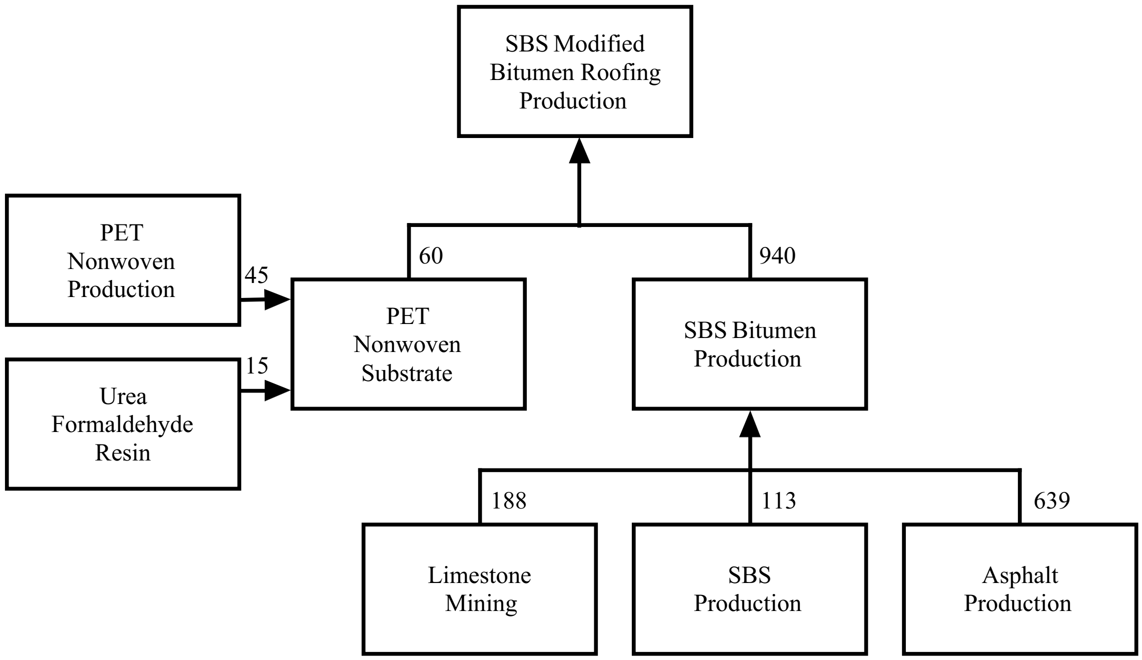

Figure 1: Flow diagram for the manufacture of 1,000 kilograms of SBS Modified Bitumen Roofing Membrane.

- According to Firestone representatives, there are no waterborne process emissions from the SBS modified bitumen membrane process described above. Process atmospheric emissions of hydrocarbons or other organics are captured and burned, creating carbon dioxide emissions. These carbon dioxide emissions are included in this report.

- Data for the step to produce SBS from styrene and butadiene were not available. Data for the polymerization of styrene butadiene rubber (SBR) from styrene and butadiene are used as a surrogate. Raw material amounts were available for SBS.

- Data for production of SBS modified bitumen (electricity for mixer, natural gas to heat oil) were estimated from SBR compounding data.

- Data for application of SBS modified bitumen to substrate (electricity to drive rollers, etc.) is assumed to be negligible and not included in this report.

Data for the production of SBS modified bitumen membrane is shown in Table 1. This table contains aggregated data for all process steps, beginning with raw material extraction and continuing through production of the membrane.

Table 1

Total Cradle to Production Life Cycle Data for 1 Kilogram of SBS Modified Bitumen Roofing Membrane

Raw Materials	Unit	Total
crude oil (feedstock) FAL	g	748
limestone	g	195
natural gas (feedstock) FAL	g	80.4
salt	µg	37.5
water	g	8.58
Energy Usage (1)	**Unit**	**Total**
coal FAL	MJ LHV	3.22
crude oil FAL	MJ LHV	1.84
energy from hydro power	MJ LHV	0.165
natural gas FAL	MJ LHV	7.7
uranium FAL	MJ LHV	1.06
wood/wood wastes FAL	MJ LHV	0.00166
Atmospheric Emissions	**Unit**	**Total**
acrolein	µg	3.99
aldehydes	mg	58.8
ammonia	mg	30.6
As	µg	35
Be	µg	3.29
benzene	µg	7.54
Cd	µg	33.2
Cl2	µg	161
CO	g	2.05
CO2 (fossil)	g	780
CO2 (non-fossil)	mg	203
cobalt	µg	29.6
Cr	µg	52.6
dichloromethane	µg	16.9
dioxin (TEQ)	pg	21.8
ethylene glycol	mg	30.7
ethylene oxide	mg	4.37
formaldehyde	µg	13.4
HCl	mg	20.3
HF	mg	2.78
Hg	µg	12
kerosene	µg	102
metals	µg	81.5
methane	g	2.25
Mn	µg	72.5
N2O	mg	2.69
naphthalene	ng	325
Ni	µg	439
n-nitrodimethylamine	ng	842
non methane VOC	g	8.43
NOx	g	2.73
organic substances	mg	301
particulates	g	1.8
Pb	µg	87.9
phenol	µg	12.2
Sb	µg	10.4
Se	µg	37.8
SOx	g	11.7
tetrachloroethene	µg	3.8
tetrachloromethane	µg	6.45
trichloroethene	µg	3.77

(Continued)

Waterborne Wastes	**Unit**	**Total**
Acid as H+	mg	12.3
B	mg	15
BOD	mg	97.7
Ca	µg	87.5
Cd	µg	614
chromate	µg	25.6
Cl-	mg	618
COD	mg	377
Cr	µg	628
cyanide	ng	913
dissolved solids	g	14.2
Fe	mg	16.7
fluoride ions	µg	405
H2SO4	mg	3.75
Hg	ng	48.2
hydrocarbons	mg	3.95
metallic ions	mg	18.3
Mn	mg	9.53
Na	µg	161
NH3	mg	33.9
Ni	pg	0.021
nitrate	µg	38.2
oil	mg	2.78E+02
organic carbon	mg	13.9
other organics	mg	27.8
Pb	µg	1.53
phenol	µg	64
phosphate	mg	2.5
sulphate	mg	530
sulphide	mg	5.7
suspended solids	mg	473
Zn	µg	338

Solid Wastes	**Unit**	**Total**
solid waste	g	83.1

Nonmaterial Emissions	**Unit**	**Total**
radioactive substance to air	Bq	5.59E+03

(1) The energy usage for this material utilizes the Franklin Associates fuel data from 1998.

3.0 EPDM Membrane

EPDM is an elastomeric polymer synthesized from ethylene, propylene, and a small amount of diene monomer. It is classified as a thermoset material since the polymer's molecular structure is "set" as a result of heating during the manufacturing process, cross-linking the polymer chains. EPDM compounds have been shown to exhibit a high degree of stability under conditions of exposure to ultraviolet light, ozone, and extremes of both high and low temperatures. They are resistant to some chemicals found on roofs, such as acids, alkalis, certain oils and oxygenated solvents. They are not, however, resistant to aromatic, halogenated or aliphatic solvents, or other materials such as cooking grease or animal fats. EPDM membranes are compounded to have a high tensile strength and high elongation when not reinforced. They are highly flexible and pliable, making them able to accommodate structural movement and high and low temperature thermal stresses. A flow diagram for the production of EPDM membrane is shown in Figure 2.

EPDM membrane is produced by feeding EPDM, carbon black, and filler into a Bambury mixer, used to mix high viscosity materials. The slabs of material from the mixer are calendared into two half-thickness films that are in turn calendared into a single membrane of the desired thickness. In this way, any voids that may occur in one of the layers do not compromise the integrity of the final membrane. Calendared sheets are seamed and rolled onto steel cores, using a thin layer of plastic as a separator to prevent the rolled material from sticking to itself. The rolls are then cured in an autoclave to thermoset the material. The cured material is unrolled, cut to size, and fed onto rolls for shipment.

3.1 Assumptions

The LCI model for EPDM membrane is based on the following information and assumptions.

- According to Firestone representatives, a typical composition by weight for EPDM membrane is 30% carbon black, 6% kaolin clay, and the balance EPDM. Some oil is also added, but no data on the type or quantity of oil were available for this report.

- According to Firestone representatives, there are no waterborne process emissions from the EPDM membrane process described above.

- A common composition of EPDM monomer is 96% ethylene-propylene (at 68% ethylene and 32% propylene) and 4% diene. This composition comes from discussions with UniRoyal Chemical.

- North American data was not available for carbon black production. European data from SimaPro was substituted for North American data.

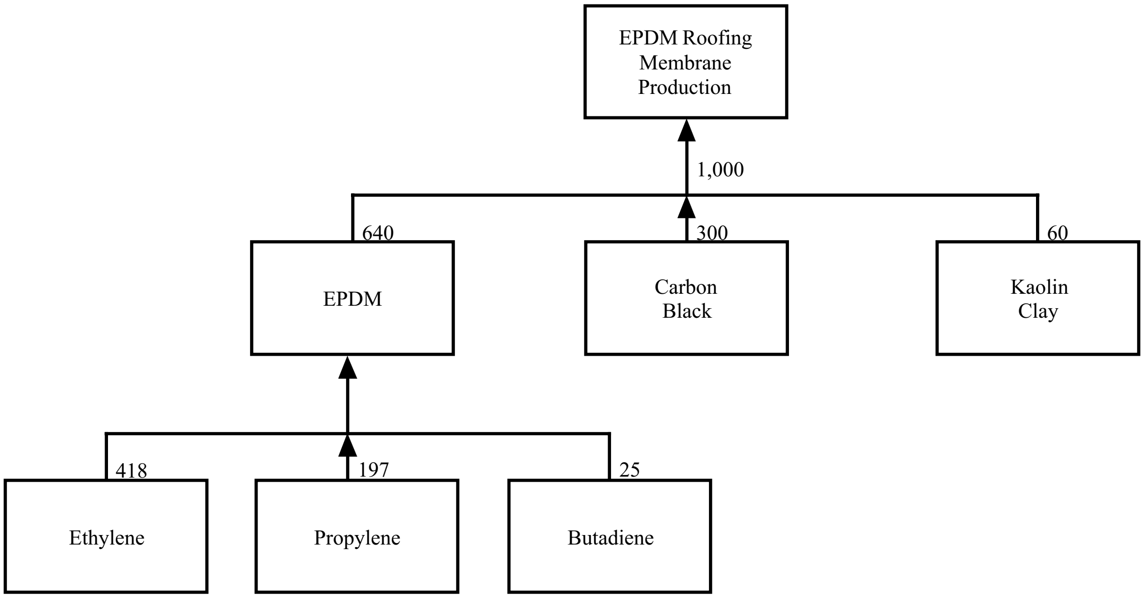

Figure 2: Flow diagram for the manufacture of 1,000 kilograms of EPDM Roofing Membrane.

- No data is available for the preferred diene (ethylidene norbornene) in this industry, so data for the production of butadiene were used as a surrogate. Butadiene is used in the production of ethylidene norbornene (ENB); therefore several steps (including condensation, distillation, and purification steps of the ENB) were omitted due to lack of data. The diene part of EPDM is only 4% and so the omission is not expected to change the outcome of the LCI.

- Data for the polymerization of EPDM was not available for this report. The polymerization of SBR was used as a surrogate.

- Data for compounding the EPDM, carbon black and clay was not available for this report. The compounding of SBR was used as a surrogate.

- No data were available for EPDM calendaring. Calendaring data for plastics is used as a surrogate. EPDM autoclave data is estimated from specifications provided by Crossing Rubber Company.

Data for the production of EPDM membrane is shown in Table 2. This table contains aggregated data for all process steps from raw material extraction through production of the membrane.

Table 2

Total Cradle to Production Life Cycle Data for 1 Kilogram of EPDM Roofing Membrane

Raw Materials	**Unit**	**Total**
crude clay	g	81.9
crude oil (feedstock) FAL	kg	1.24
limestone	g	31
natural gas (feedstock) FAL	g	243

Energy Usage (1)	**Unit**	**Total**
coal FAL	MJ LHV	14.2
crude oil FAL	MJ LHV	22.7
energy from hydro power	MJ LHV	0.755
natural gas FAL	MJ LHV	24.5
uranium FAL	MJ LHV	4.87
wood/wood wastes FAL	MJ LHV	0.00909

Atmospheric Emissions	**Unit**	**Total**
acrolein	µg	18.4
aldehydes	mg	67.3
ammonia	mg	9.8
As	µg	355
Be	µg	26.8
benzene	µg	26.7
Cd	µg	514
Cl2	µg	203
CO	g	4.95
CO2 (fossil)	kg	5.3
CO2 (non-fossil)	g	1.08
cobalt	µg	452
Cr	µg	449
dichloromethane	µg	78
dioxin (TEQ)	pg	101
formaldehyde	µg	61.8
HCl	mg	93
HF	mg	12.8
Hg	µg	109
kerosene	µg	468
metals	µg	434
methane	g	7.79
Mn	µg	424
N2O	mg	11.5
naphthalene	µg	1.66
Ni	mg	6.92
n-nitrodimethylamine	µg	3.89
non methane VOC	g	18.8
NOx	g	17.7
organic substances	mg	50.3
PAH's	µg	379
particulates	g	5.3
Pb	µg	571
phenol	µg	58.6
Sb	µg	159
Se	µg	297
SO2	g	20.5
Soot	mg	379
SOx	g	49.5
tetrachloroethene	µg	17.5
tetrachloromethane	µg	29.9
trichloroethene	µg	17.4

(Continued)

Waterborne Wastes	Unit	Total
Acid as H+	mg	39.4
B	mg	116
BOD	mg	63.9
Ca	µg	403
Cd	mg	1.92
chromate	µg	413
Cl-	g	1.93
COD	mg	592
Cr	mg	1.92
crude oil	mg	9.1
cyanide	µg	2.85
dissolved solids	g	42.9
Fe	mg	73.3
fluoride ions	mg	1.87
H2SO4	mg	29.1
Hg	ng	151
hydrocarbons	mg	152
metallic ions	mg	22.8
Mn	mg	42.1
Na	µg	742
NH3	mg	2.92
nitrate	mg	5.1
oil	mg	819
organic carbon	mg	42
other organics	mg	102
Pb	µg	1.91
phenol	µg	74.7
phosphate	mg	16.5
sulphate	g	1.73
sulphide	mg	17.9
suspended solids	g	1.46
Zn	mg	1.02

Solid Wastes	Unit	Total
solid waste	g	355

Nonmaterial Emissions	Unit	Total
radioactive substance to air	kBq	25.8

(1) The energy usage for this material utilizes the Franklin Associates fuel data from 1998.

4.0 PVC MEMBRANE

PVC membranes are thermoplastic membranes, which differ from thermosets in that there is no cross-linking of the polymer chains; they can therefore be repeatedly softened by heating, and hardened again when cooled. PVC membranes are often reinforced and exhibit a high degree of resistance to fire, bacterial growth, industrial chemical atmospheres, root penetration, and extreme weather conditions. PVC membranes are chemically incompatible with bituminous materials. A flow diagram illustrating the main steps in the production of PVC membrane is shown in Figure 3.

PVC is produced by suspension, emulsion, mass, or solution polymerization of vinyl chloride monomer (VCM). Resin production data in this report represent suspension polymerization. In the suspension process, VCM and initiators are mixed with water and kept in the form of aqueous droplets by agitation and suspension stabilizers. The polymerization generally is carried out in a nitrogen atmosphere in large agitated reactors. The reaction time is typically about 12 hours, and conversion of VCM approaches 90 percent. After polymerization, the unreacted monomer is removed and recycled. The polymer is blended with additives and modifiers and centrifuged to remove water. The resin is then dried and packaged for shipment.

PVC resin must be compounded with other materials (additives and plasticizers) to make a usable product. Plasticizers are used to impart varying degrees of flexibility and to improve the heat stability. All PVC compounds must contain a heat stabilizer to prevent the material from degrading during processing.

PVC, plasticizer, and other additives are heated and kneaded in an internal mixer until the material is quickly fused into a uniform, molten mass. Some initial heat is supplied to begin the interaction of resin and plasticizer, then the mechanical work of mixing supplies much of the required heat for complete fusion and blending.

To produce PVC roofing membrane, the molten material is fed through calendaring rolls that form the material into sheets of the desired thickness. The cooled material is put on rolls for shipment.

Some environmental groups are advocating a phase-out of PVC use. They claim that some PVC plasticizers and additives have been shown to cause a variety of adverse health effects. It is true that some chloride pollutants are emitted during the production of PVC, and if PVC is burned, hydrogen chloride gas and dioxins are released. Opponents of these environmental groups claim that much of the debate over PVC is not supported by scientific evidence and has become political in nature. These groups point to countries, such as the Netherlands, Belgium, and Germany, which were becoming anti-PVC, but have done further research and have lifted many of their PVC restrictions.

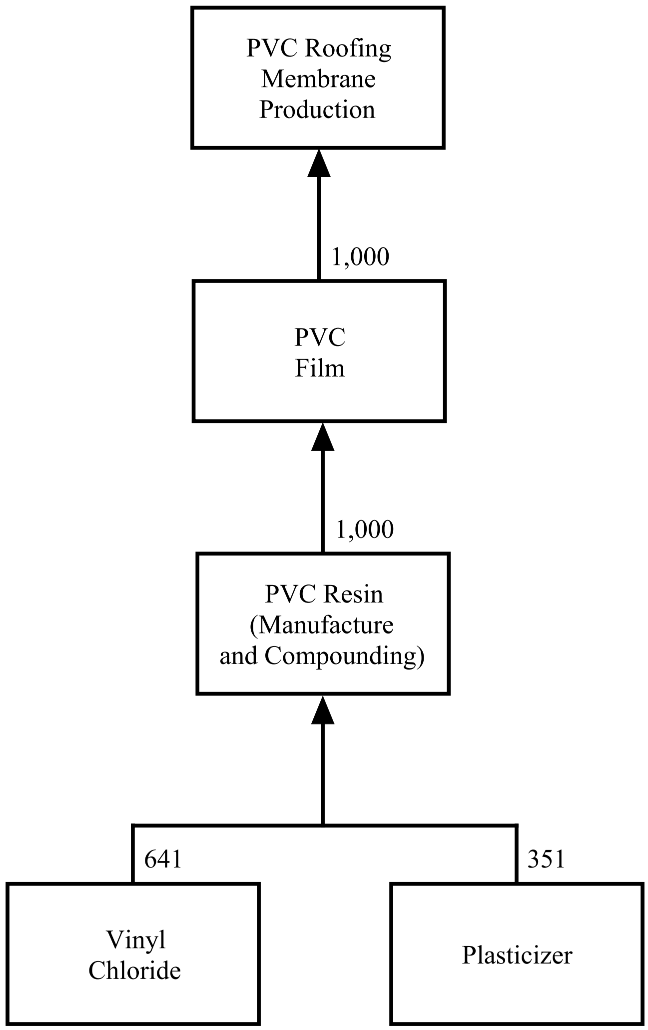

Figure 3: Flow diagram for the manufacture of 1,000 kilograms of PVC Roofing Membrane.

4.1 Assumptions

The LCI model for PVC membrane is based on the following information and assumptions.

- PVC resin production data are based on suspension polymerization.

- Plasticizers make up from 25 to 50 percent of the weight of the PVC. 35 percent is the figure used in this study. According to industry contacts, phthalates are being replaced by ethyl vinyl acetate (EVA) materials as common plasticizers. This report uses EVA as the plasticizer.

- Other additives combined account for less than 5 percent of the PVC compound. These other additives are not included in this analysis due to the highly confidential nature of specific additives and their negligible weight. There is the possibility that metals or metalloids may be emitted in the production of these other additives; if this is the case, these are not included in this LCI.

- The calendaring data is from a 1992 Society of the Plastics Industry life cycle inventory.

Table 3 shows data for the production of PVC membrane. The data set is an aggregation of all process steps from raw material extraction through production of the membrane.

Table 3

Total Cradle to Production Life Cycle Data for 1 Kilogram of PVC Roofing Membrane

Raw Materials	**Unit**	**Total**
crude oil (feedstock) FAL	g	164
limestone	g	24.8
natural gas (feedstock) FAL	g	504
salt	g	341

Energy Usage (1)	**Unit**	**Total**
coal FAL	MJ LHV	11.4
crude oil FAL	MJ LHV	2.35
energy from hydro power	MJ LHV	0.588
natural gas FAL	MJ LHV	25.8
uranium FAL	MJ LHV	3.75
wood/wood wastes FAL	MJ LHV	0.00506

Atmospheric Emissions	**Unit**	**Total**
acrolein	µg	14.2
aldehydes	mg	32.4
ammonia	mg	4.75
As	µg	68.2
Be	µg	7.76
benzene	µg	26
Cd	µg	23.5
Cl2	mg	33.1
CO	g	5.46
CO2 (fossil)	kg	2.34
CO2 (non-fossil)	mg	632
cobalt	µg	24.9
Cr	µg	116
dichloromethane	µg	60.1
dioxin (TEQ)	pg	77.4
formaldehyde	µg	47.4
HCl	mg	71.5
HF	mg	9.86
Hg	µg	138
kerosene	µg	361
metals	µg	253
methane	g	9.35
Mn	µg	210
N2O	mg	9.48
naphthalene	µg	1.05
Ni	µg	308
n-nitrodimethylamine	µg	2.99
non methane VOC	g	14
NOx	g	9.63
organic substances	mg	48.7
particulates	g	1.81
Pb	µg	64.1
phenol	µg	41.6
Sb	µg	8.8
Se	µg	103
SOx	g	45.9
tetrachloroethene	µg	13.5
tetrachloromethane	µg	22.7
trichloroethene	µg	13.4

(Continued)

Waterborne Wastes	**Unit**	**Total**
Acid as H+	mg	81.8
B	mg	40.6
BOD	mg	564
Ca	µg	311
Cd	mg	2.69
chromate	µg	16
Cl-	g	2.71
COD	g	2.65
Cr	mg	2.69
cyanide	µg	3.99
dissolved solids	g	60
Fe	mg	58.1
fluoride ions	mg	1.44
H2SO4	mg	10.1
Hg	ng	520
metallic ions	mg	5.01
Mn	mg	33.7
Na	µg	572
NH3	mg	1.46
Ni	ng	191
nitrate	µg	136
oil	g	1.08
organic carbon	mg	87.2
other organics	mg	91.5
Pb	ng	609
phenol	µg	26.3
phosphate	mg	9.23
sulphate	g	2.28
sulphide	mg	37.2
suspended solids	g	1.8
Zn	mg	1.62
Solid Wastes	**Unit**	**Total**
solid waste	g	319
Nonmaterial Emissions	**Unit**	**Total**
radioactive substance to air	kBq	19.8

(1) The energy usage for this material utilizes the Franklin Associates fuel data from 1998.

5.0 PIC INSULATION

Polyisocyanurate insulation is commonly used in roofing applications. PIC foams are thermoset plastics which do not melt and flow when exposed to high temperatures, making them ideal for applications where fire resistance is necessary. PIC foam is stable over a large temperature range and can be used in roof systems that use hot asphalt. PIC exhibits low density, good adhesion to facing materials, low water absorption, and low vapor transmission. A flow diagram for the production of PIC foam is shown in Figure 4.

The chemistry of manufacturing PIC is very similar to the manufacture of polyurethane (PUR). PIC is a type of polyurethane. Rigid PUR foam is produced by the reaction of a polyether-based polyol and methylenediphenyl isocyanate in an equimolar mixture with HCFC-141b as the blowing agent. The molar ratio of isocyanate to polyol equals 1 for rigid PUR foam. PIC rigid foam manufacture is essentially the same, but uses a polyester polyol. To encourage the formation of aromatics which have a high heat resistance the molar ratio for PIC foam manufacture is roughly 2.5. Some of the additional isocyanate trimerizes in a self-addition reaction to form isocyanurate rings giving stability to enhance fire-resistance properties.

The current blowing agent used in PIC foam insulation in Canada is primarily HCFC-141b. An industry contact reports that, in Canada, HCFCs are being phased out of the manufacture of PIC, and hydrocarbons are being used in their place; however, HCFC is still the primary blowing agent in use. According to Firestone, pentane (currently used in Europe) is the most likely replacement, although there are associated flammability risks during processing as well as environmental concerns, since pentane is a VOC.

5.1 Assumptions

The LCI model for PIC insulation is based on the following information and assumptions.

- The formulation used for the PIC foam insulation is 62.5 percent MDI, 25 percent polyol, and 12.5 percent HCFC-141b, with a 10% loss of the blowing agent during the manufacturing process. The blowing agent HCFC-141b was assumed to be the current blowing agent for the PIC foam insulation.

- The blowing agent HCFC-141b was assumed to be produced from 1,1,1 trichloroethane (methyl chloroform) and hydrogen fluoride, as this is a common method of production. No data was available for the 1,1,1 trichloroethane production. Surrogate data was used from the production of vinyl chloride monomer, which is an intermediate used to form 1,1,1 trichloroethane. CFC-11 production data were used as a surrogate for the production of HCFC-141b. According to Dr. Richard Crooker of Elf Atochem, the heating processes of the HCFC-141b and CFC-11 blowing agents are similar; however, the purification process for the HCFC-141b goes a couple of steps beyond distillation. Therefore, the surrogate data may understate the actual process by small amounts.

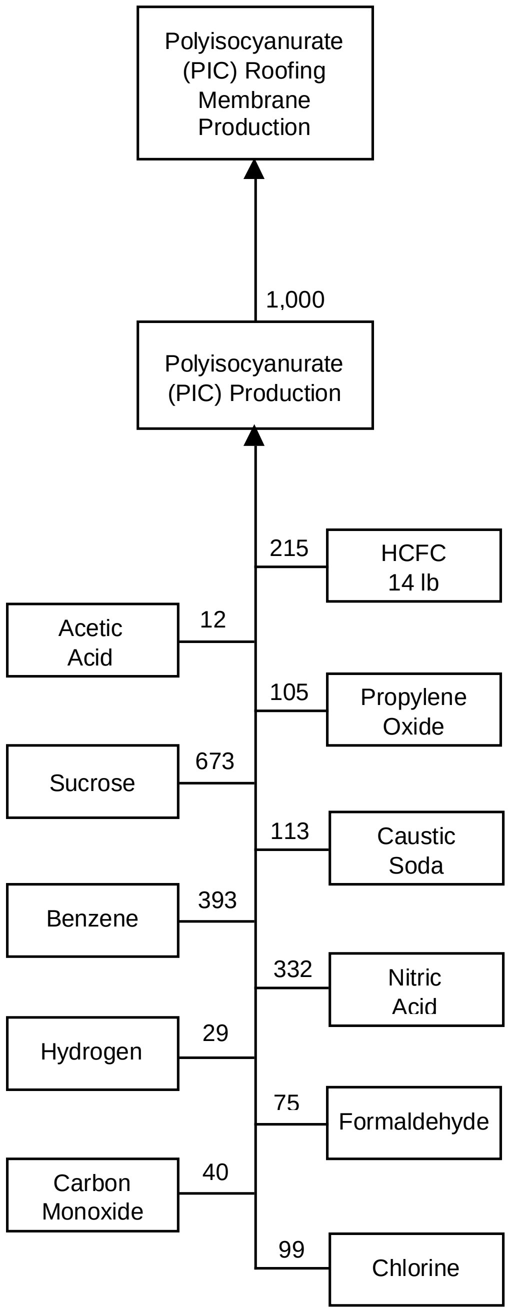

Figure 4: Flow diagram for the production of 1,000 kilograms of Polyisocyanurate (PIC) Roofing Membrane.

- According to Brook Boynton of ICI Polyurethanes, using polyether polyol data from the manufacture of polyurethane to represent the polyester polyol in PIC would have an insignificant effect on life cycle energy results. He also stated that approximately 10 percent of the HCFC-141b blowing agent used to produce PIC foam is lost to the atmosphere. ICI Polyurethanes further commented that HCFCs are being phased out in the manufacture of PIC in Canada, with hydrocarbons being used in their place.

- Data for the production of PIC roofing insulation are shown in Table 4. The table contains aggregated data for all process steps beginning with raw material extraction and continuing through production of the foam insulation.

Table 4

Total Cradle to Production Life Cycle Data for 1 Kilogram of PIC Roofing Insulation

Raw Materials	**Unit**	**Total**
crude oil (feedstock) FAL	g	482
limestone	g	49.7
natural gas (feedstock) FAL	g	203
salt	g	96.4
water	g	42.9
Energy Usage (1)	**Unit**	**Total**
coal FAL	MJ LHV	9.3
crude oil FAL	MJ LHV	3.95
energy from hydro power	MJ LHV	0.452
natural gas FAL	MJ LHV	19.3
uranium FAL	MJ LHV	2.89
wood/wood wastes FAL	MJ LHV	0.00424
Atmospheric Emissions	**Unit**	**Total**
acid	mg	5.78
acrolein	µg	10.9
aldehydes	mg	47.1
ammonia	mg	184
As	µg	94.5
Be	µg	9.66
benzene	µg	27.1
Cd	µg	66.1
Cl2	µg	300
CO	g	9.93
CO2 (fossil)	kg	2.01
CO2 (non-fossil)	g	7.39
cobalt	µg	55.4
Cr	µg	155
dichloromethane	µg	46.4
dioxin (TEQ)	pg	59.7
formaldehyde	µg	36.6
HCFC-141b	g	12.5
HCl	mg	55.3
HF	mg	13.2
Hg	µg	126
kerosene	µg	279
metals	µg	210
methane	g	5.85
Mn	µg	239
N2O	mg	8.09
naphthalene	ng	855
Ni	µg	822
n-nitrodimethylamine	µg	2.31
non methane VOC	g	12.8
NOx	g	8.22
organic substances	mg	476
particulates	g	1.85
Pb	µg	110
phenol	µg	32.8
propylene oxide	mg	60.9
Sb	µg	19.5
Se	µg	93.5
SOx	g	29.3
tetrachloroethene	µg	10.4
tetrachloromethane	µg	17.6
trichloroethene	µg	10.3

(Continued)

Waterborne Wastes	**Unit**	**Total**
Acid as H+	g	1.43
B	mg	38.7
BOD	g	1.08
Ca	µg	240
Cd	mg	1.54
chromate	µg	46.2
Cl-	g	1.55
COD	g	2.45
Cr	mg	1.55
cyanide	µg	2.28
dissolved organics	mg	135
dissolved solids	g	38.7
Fe	mg	47.4
fluoride ions	mg	1.11
H2SO4	mg	9.68
Hg	ng	398
hydrocarbons	mg	119
metallic ions	mg	13.6
Mn	mg	27.6
Na	µg	441
NH3	mg	12
Ni	ng	170
nitrate	µg	105
Nitrogen	mg	254
oil	mg	634
organic carbon	g	1.91
other organics	mg	276
Pb	µg	1.3
phenol	mg	171
phosphate	mg	5.96
Sodium hydroxide	mg	183
sulphate	g	1.34
sulphide	mg	11.3
suspended solids	g	1.48
Zn	µg	729

Solid Wastes	**Unit**	**Total**
solid waste	g	289

Nonmaterial Emissions	**Unit**	**Total**
radioactive substance to air	kBq	15.3

(1) The energy usage for this material utilizes the Franklin Associates fuel data from 1998.

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