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Wire and Cable Insulation and Jacketing: Life-Cycle Assessments For Selected Applications

Executive Summary

Office of Pollution Prevention and Toxics
Design for the Environment Program
U.S. Environmental Protection Agency

Executive Summary

1. Introduction

The U.S. Environmental Protection Agency's (EPA) Design for the Environment (DfE) Program, the Toxics Use Reduction Institute (TURI) at the University of Massachusetts Lowell, and wire and cable industry stakeholders formed a partnership to identify and investigate the environmental impacts of selected products, processes, and technologies in the wire and cable industry. This EPA-funded Wire and Cable Project (WCP) is a voluntary, cooperative partnership consisting of individual wire and cable manufacturers, supply chain members (e.g., additive and resin suppliers), and trade association members.

The wire and cable industry manufactures a wide range of products that support a multitude of applications. Key functional components of traditional wire and cable insulation and jacketing include polymer systems, heat stabilizers that may contain lead, and flame retardants. These materials and other ingredients impart electrical insulation, physical stability, and fire performance properties, but have been identified as materials of potential environmental concern or as materials for which industry stakeholders have expressed a desire to identify and evaluate alternatives.

The partnership set out to evaluate the life-cycle environmental impacts of the current standard material formulations and alternative formulations for heat stabilizers, flame retardants, and polymer systems for selected wire and cable products. The project partners selected the following different product types (with defined functionality and specifications) for investigation:

- Category 6, riser-rated communication cable (CMR);
- Category 6, plenum-rated communication cable (CMP); and
- Non-metallic sheathed low-voltage power cable, as used in building wire (NM-B).

The project partners chose these products because together they (1) contain materials common to many wire and cable applications, (2) typically contain materials for which alternatives are being sought, and (3) represent a significant share of the wire and cable market.

This report focuses primarily on the comparison of lead-stabilized and lead-free cable constructions. The CMR and CMP analyses include the full life cycle of the cables. Zero-halogen constructions of lead-free CMR cables and NM-B cables were analyzed in the WCP project; however, the data were only sufficient to carry out cradle-to-gate analyses (i.e., life-cycle stages from material extraction and processing to jacketing and, in the case of NM-B cable, insulation compounding). As there were no differences identified among flame retardants used within a product type, the comparative analyses in this project do not include a comparison of alternative flame retardants. The general constructions of each alternative are presented in Table 1. Note that the comparative analyses conducted in this study are within a cable type and not among cable types, because CMR, CMP, and NM-B cables serve different functions and should not be compared in this context.

Table 1

Insulation and Jacketing Resins of Each Cable Alternative

Cable Construction	CMR[a]			CMP[a]		NM-B[b]	
	Leaded	**Lead-free**	**Zero-halogen**	**Leaded**	**Lead-free**	**Leaded**	**Lead-free**
Insulation resin	HDPE[c]	HDPE[c]	HDPE[c]	FEP[e]	FEP[e]	PVC[d]	PVC[d]
Jacketing base resin	PVC[d]	PVC[d]	non-PVC[f]	PVC[d]	PVC[d]	PVC[d]	PVC[d]
Jacketing base stabilizer material(s)	Lead	Calcium/ zinc	non-Pb[f]	Lead	Calcium/ zinc	Lead	Calcium/ zinc

[a] Wire conductors are unshielded twisted pairs, 8 conductors in 4 pairs of equal gauge bare copper.

[b] Wire conductors are 12-gauge, 2-conductor copper with ground wire.

[c] High-density polyethylene.

[d] Polyvinyl chloride (PVC) is compounded with various additives, including heat stabilizers and flame retardants.

[e] Fluorinated ethylene propylene (FEP), a perfluoropolymer, is a copolymer of tetrafluoro-ethylene (TFE) and hexafluoro-propylene. The most commonly used perfluoropolymer insulators in CMP cable are FEP and MFA (a copolymer of TFE and perfluoro-methylvinyl-ether); however, the research in this study is based on FEP-insulated cables only.

[f] Proprietary.

2. Previous Research

Major resins used in CMR, CMP, and NM-B cables include polyvinyl chloride (PVC), high-density polyethylene (HDPE), and fluorinated ethylene propylene (FEP). Substantial research has been conducted on PVC and its life-cycle impacts; however, very little of the work has focused specifically on the use of PVC in wire and cable applications. The European Union recently completed a study that presents an overview of the publicly available information on PVC LCAs. Although the study found that detailed information does exist concerning the PVC life cycle from raw material extraction to PVC production, it concluded that a potentially relevant gap exists for the wire and cable compounding, use, and end-of-life (EOL) phases (Baitz *et al.*, 2004). Another LCA was conducted on two cable types: PVC-insulated and -jacketed cable and polyethylene-insulated and -jacketed cable (Simonson *et al.*, 2001). This LCA is not specific to the same Category 6 cable constructions types identified for the WCP analysis; however, some relevant information was gleaned for this study. Finally, although information is available for the production of polyethylene, no studies detailing its life cycle in wire and cable have been performed, and little to no life-cycle information is publicly available for FEP.

Lead-based heat stabilizers are added to PVC for wire and cable applications because they provide long-term thermal stability and electrical resistance, with low water absorption. Without heat stabilizers, PVC resins begin to degrade by dehydrochlorination at temperatures of 160ºC, which is below the PVC processing temperature (Mizuno *et al*., 1999). Although lead additives to PVC are cost- and performance-competitive, they have potential adverse health and environmental effects. In looking at the life cycle of the lead compounds, releases of lead into the ambient or workplace environment may occur from the mining or processing of lead, or from recycling or disposing of products containing lead. Lead is a heavy metal that has been linked to developmental abnormalities in fetuses and children that ingest or absorb lead, primarily from paints or emissions from leaded gasoline. Small amounts of lead cause hypertension in adults and permanent mental dysfunction, and the Department of Health and Human

Services has determined that lead acetate and lead phosphate may reasonably be anticipated to be carcinogens, based on animal studies. Further, lead is a toxic chemical that persists and bioaccumulates in the environment (DHHS, 1999). The toxic nature of lead has resulted in efforts around the globe to reduce its use.

In a study by DuPont, copper wire was found to be the largest single contributor to most environmental impact categories for CMR and CMP cables (Krieger *et al*., 2007). However, the amount of copper wire is constant across the alternatives analyzed (e.g., the mass of copper in a length of CMR baseline cable is the same as in the CMR lead-free alternative). Because the WCP partnership focuses on materials and processes that might be substantially different among cable alternatives, copper wire was not included in the assessments, and the Krieger *et al*. results are not germane to the analyses in the WCP study.

Comprehensive information about life-cycle impacts and risks of both the standard (lead-based) and alternative materials used in functionally equivalent cable alternatives is needed to assist the wire and cable industry in identifying formulations that have the least impact on health and the environment, while still meeting cost and performance goals (cost and performance testing were not included in this study; however, alternatives were compared on functionally equivalent bases).

3. Methodology

The analysis in this report was conducted consistent with the ISO 14040 series, which stipulates four phases of an LCA: goal definition and scoping, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation. This study conducts the first three phases and part of the interpretation phase. Interpretation includes analyses of major contributions, sensitivity analyses, and uncertainty analyses, as necessary to determine if the goals and scope are met. However, conclusions as to selecting an alternative or making recommendations are left to users as such conclusions can depend on subjective methods of interpreting the data. Further, no comparative assertions as defined in ISO 14040 are made about the superiority or equivalence of one product versus another. The scope and methods for the LCI, LCIA, multivariate uncertainty analysis, and sensitivity analysis are summarized below.

3.1 Scope

In a comparative LCA, product systems are evaluated on a functionally equivalent basis. The functional unit normalizes data based on equivalent use to provide a reference for relating process inputs and outputs to the inventory and impact assessment across alternatives. The product systems evaluated in this project are standard lead-based, lead-free, and zero-halogen (in the case of CMR) alternative wire insulation and cable jacketing formulations, as used in telecommunication installations in the United States. Each of the cable types is evaluated in separate analyses, because each type serves a different function. The functional unit for each cable type is the insulation and jacketing used in a linear length of cable (one kilometer), which would be used to transmit a signal that meets common Underwriters Laboratories (UL) performance requirements and fire safety specifications for the product types listed in Table 1. Most telecommunications network cables are expected to achieve a minimum service life of 10 to 15 years; NM-B cables have a service life of 25 to 40 years.

The analyses in this LCA attempt to model industry averages, with a focus on the comparison of similarly functioning cables. Thus, materials or activities that are similar across alternatives have been excluded. For example the copper conductor, which is the same gauge wire for both the leaded and lead-free alternatives within a cable type, is excluded. Also, transportation is assumed to be similar across alternatives, and is also excluded. The geographic focus of the manufacturing data is the United States; however remaining life-cycle processes cover a global geographic region, as appropriate.

3.2 Life-Cycle Inventory

The LCI tallies the material and energy inputs and the environmental releases throughout the products' life cycles. LCI data were collected for the following life-cycle stages: materials extraction and processing ("upstream"), manufacturing, and EOL. Each is described in the following subsections. The processes included in the life cycle are presented in Figure 1, and the number of primary data sets collected is presented in Table 2. The LCI data were compiled into the GaBi4 LCA software tool (PE & IKP, 2003) to assist with data organization and LCA analyses.

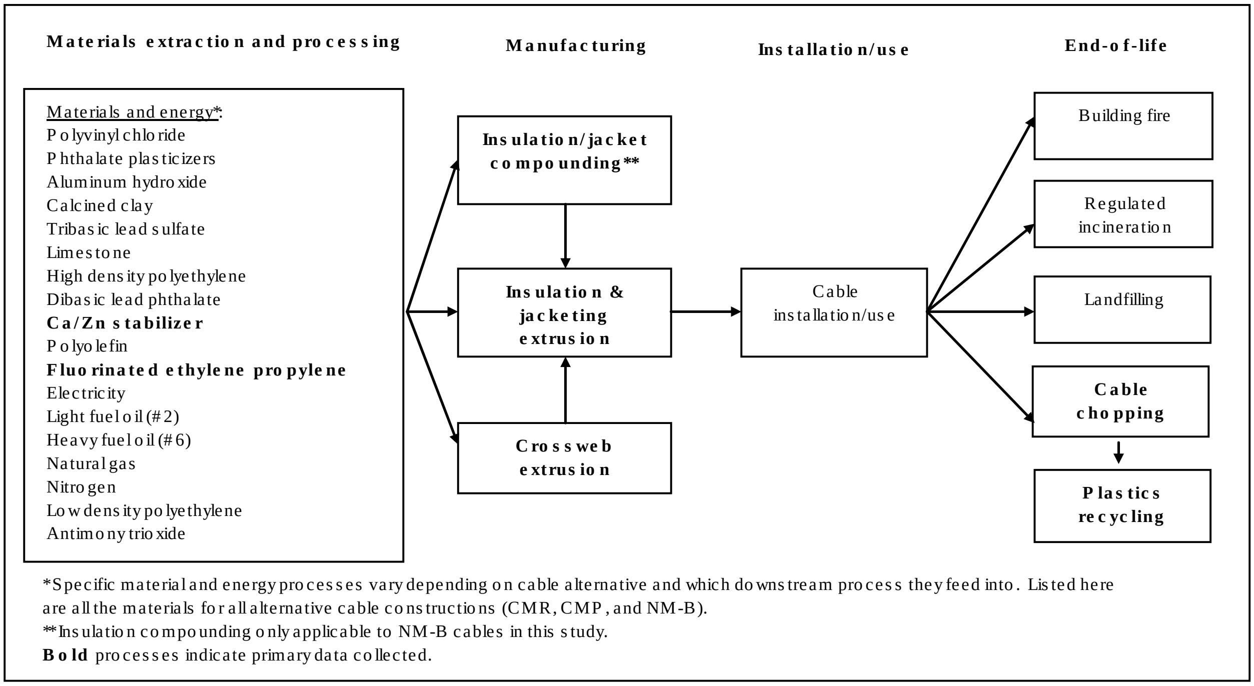
3.2.1 Upstream

The extraction and processing of the major materials used in manufacturing CMR, CMP, and NM-B cables are collectively labeled the "upstream" life-cycle stage. The upstream materials that were included were determined by compiling the bills of materials for each cable alternative from compounders of jacketing resins and cable extruders/manufacturers (where insulation extrusion, twinning, cabling, and jacketing extrusion is conducted). Decision rules were employed to select which upstream materials should be included as processes modeled in the life cycle. Materials that constituted greater than 5 percent by mass were given priority. Materials that constituted between 1 percent and 5 percent were targeted for inclusion; however, they were given less priority if there was difficulty in obtaining upstream process data. In addition to these mass decision rules, materials of known or potential environmental concern were included, as were materials that are unique to a cable and are the basis of the comparison. For example, the lead-based stabilizers are of environmental concern due to the presence of lead and were selected for inclusion. In addition, the calcium/zinc-based stabilizers used in the lead-free alternatives were also included as they are the substitute heat stabilizer material.

Primary or secondary data were collected for most of the materials identified for inclusion using the decision rules. However, data for a few materials, such as some flame retardants and other fillers in the compounded PVC jacketing resin were not found. For the CMR baseline cable, 94 percent of the cable mass is accounted for in the upstream processes, 90 percent for the CMR lead-free alternative, and 7 percent for the CMR zero-halogen alternative. For CMP, 92 percent of the baseline cable construction, and 92 percent in the lead-free alternative; and for NM-B, 88 percent of the baseline, and 85 percent of the lead-free alternative were included. FEP and Ca/Zn stabilizers were the only upstream processes where primary data were collected. Otherwise, secondary data were collected for each of the other upstream processes indicated in Figure 1.

A variety of secondary data sources were used, including PlasticsEurope for PVC and HDPE data (Boustead, 2005a; Boustead, 2005b); *Ecobilan* for phthalate plasticizer data (*Ecobilan*, 2001); Andersson *et al*. for aluminum trihydrate data (Andersson *et al*., 2005); and GaBi4 databases (PE & IKP, 2003) for limestone and calcium fillers, electricity generation, natural gas, light fuel oil, and heavy fuel oil. Although some data are several years old, they represent materials that have been processed for many years and thus we assume they are produced using mature technologies that are expected to be representative of current processes.

Using a high-medium-low scale, the overall inventory for the upstream life-cycle stage was given a subjective data quality measure of "medium to low" due to the extensive use of secondary data and the absence of some of the upstream data.



*Specific material and energy processes vary depending on cable alternative and which downstream process they feed into. Listed here are all the materials for all alternative cable constructions (CMR, CMP, and NM-B).
**Insulation compounding only applicable to NM-B cables in this study.
Bold processes indicate primary data collected.

Figure 1. Generic process flows for all alternatives

Table 2

Number of Primary Data Sets Collected

Process	CMR			CMP		NM-B	
	Leaded	Lead-free	Zero-halogen	Leaded	Lead-free	Leaded	Lead-free
Upstream:							
Insulation resin	0	0	0	2	2	0	0
Heat stabilizer	0	2	0	0	2	0	2
Manufacturing:							
Crossweb	1	1	0	1	1	N/A	N/A
Compounding	3	2	1	2	2	3	2
Cable mfg	1	2	0	1	2	1	0
End-of-life:							
Cable chopping	1	1	1	1	1	1	1
Thermoplastics recycling	1	1	1	1	1	1	1

3.2.2 Manufacturing

Primary data were collected for 3 product/component manufacturing processes: 1) jacketing resin compounding, 2) crossweb manufacturing, and 3) cable manufacturing, which includes insulation extrusion, twinning, cabling, and jacketing extrusion. Data from multiple companies were averaged together for similarly functioning materials or products. In the case of the cable manufacturing process, a major discrepancy was identified, leading to a large amount of uncertainty, particularly in the energy requirements for cable manufacturing. Discrepancies in the extrusion energy of leaded versus lead-free cable were the result of asymmetric cable manufacturer data. The extrusion process for leaded cable relied on data from only one company, while the process for lead-free manufacturing relied on two data sets, one of which showed substantially higher energy use. A parameter was included in an uncertainty analysis that corrected for this discrepancy. Otherwise, where multiple datasets were available, no other major discrepancies were observed in the data. The analysis of the NM-B life cycle included compounding processes for jacketing and insulation, while excluding cable extrusion and use. The analysis of the zero-halogen CMR cable with the two alternatives mentioned above included the cable jacketing process, while excluding cable extrusion and use.

The inventory data collected included input and output flows. Inputs included materials (primary product materials and process materials), electricity, fuel and water input flows. Outputs included products, co-products, air emissions, water emissions, and solid and hazardous waste output flows. Data for a process were compiled per unit of the material being produced. For example, an input of electricity to make the crossweb would be reported as a number of megajoules (MJ) per kilogram of crossweb. When the individual process data are incorporated into the full life-cycle model, the data are all scaled to the functional unit of one kilometer of cable length. Thus, in the above example, the MJ of energy per functional unit are scaled by the amount of crossweb needed to produce one kilometer of finished cable.

Manufacturing data were limited because multiple datasets were obtained for only a few processes, as shown in Table 2. Nonetheless, there are not a large number of manufacturers of these cables in the United States and those that supplied data likely represent a large market share. The overall inventory for the manufacturing life-cycle stage was given a subjective data quality measure of "medium."

After manufacturing, the cables are installed and used for their intended purpose. In this study, the installation/use phase was not modeled, except to scale the functional unit of cable. No other materials or activities in the installation/use phase were expected to vary significantly among alternatives and therefore this phase was not modeled further.

3.2.3 End-of-life

After installation, a cable can reach its EOL either by being consumed in a structure fire, recycled, landfilled, or incinerated. Probabilities are given to each EOL disposition to model the possibility of any one of these dispositions occurring. Estimated probabilities of occurrence are not readily available in the literature for all dispositions. Reliable data were used when available; however, in the absence of sound data, we employed best professional judgment or simply made midpoint assumptions within reasonable ranges of data and varied the assumptions in the uncertainty analysis (see Section 3.4). EOL stages were not included in the formulation of the CMR zero-halogen or NM-B life-cycle models.

The percentage of cables consumed in a building fire was not easily ascertained. Therefore, we first calculated the percentage of structures expected to have CMR or CMP cables that are involved in fires based on U.S. Fire Administration data from 2000 and 2005 (USFA, 2000a; USFA, 2000b; USFA, 2005). Since there is not sufficient quantitative information regarding the percent of cable burned in a fire, in our base analysis we used a default estimate that 10 percent of the cables are actually consumed in the fire, and varied this estimate in the uncertainty analysis, assuming substantial uncertainty (see Section 3.4). We chose 10 percent as a central estimate because fire protection methods would skew actual burn percentages toward the lower end. In addition, it should be noted that the percent of CMP cables burned would likely be lower than the percent of CMR cables burned due to different fire safety standards; however, they would both be in the range of the uncertainty analysis and, because the CMR is not being compared to the CMP, it does not affect the analyses in this report.

In our EOL model, the cables that do not end in a fire are consequently recycled, incinerated, or landfilled. The Bureau of International Recycling estimated that 95 percent of cables are recycled, due to the high economic value of the copper (Bartley, 2006). For the remaining cables not burned in a fire or sent to recycling, we assumed they are either landfilled or incinerated. The percentage to landfilling or incineration was assumed to be the same as the percent of municipal solid waste (MSW) sent to incineration (19 percent) and landfilling (81 percent) (USEPA, 2005c). Therefore, of all cables not burned (i.e., removed at EOL), 95 percent would be sent to recycling, 4 percent directly to landfills, and 1 percent directly to incineration. We assumed that cables sent to recycling were chopped, which is the most common cable recycling technique in the United States. Primary data were collected from one chopping facility. Once the cables are chopped, copper is sent to a copper smelter for recovery (which is beyond the scope of this analysis), and the remaining resins are recycled, landfilled, or incinerated. The percent of chopped resin that is recycled is highly uncertain. A European Commission study completed in 2000 (Plinke *et al*., 2000) provides an upper estimate that 20 percent of resin in cables sent for recycling is sent to thermoplastic recycling.[1] Our base analysis assumed a mostly arbitrary point of 10 percent of the resins going to thermoplastic recycling. This parameter was then varied in the uncertainty analysis. We assume that the remainder of the chopped resin is incinerated or landfilled (in the same MSW proportions described above).

Process data (input and output flows) for the fire, landfilling, and incineration processes were derived from the inventory data for the PVC cables in the Simonson *et al*. study (2001), because both the CMR and CMP cables in this study are PVC-jacketed. Therefore, the HDPE and FEP insulations are not included; however, for each cable type, the mass of HDPE or FEP insulation used is similar across the lead and lead-free alternatives, eliminating this as an important limitation. The major differences between the alternative cable constructions are the lead and lead-free stabilizers. Thus, for the lead-stabilized alternatives, these inventories were supplemented with estimates on lead outputs, which were absent from the existing data. Chopping and post-chopping thermoplastic recycling data were collected from primary data sources.

For the landfilling process, data were lacking on the leachability of lead; however, based on communication with an expert in leachability testing, we assumed that the percentage of lead leached from chopped cable is 10 percent, and 1.5 percent for un-chopped leaded cable (which is directly landfilled after use) (Townsend, 2007). Using these estimates as direct outputs to water from the landfilling process would assume complete failure of any landfill leachate system. Based on the uncertainty of the leachate estimate and the unknown failure rate of landfill linings, the leachate estimate

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[1] Note that this estimate is from a historical point in time (2000) and other factors such as different recycling rates, international shipping of wires and cables, and the introduction of new technologies since the study was done could affect the accuracy of this bounding estimate.

for the base calculations is assumed to be 50 percent of the above estimated leachate percentages, and this 50 percent estimate is varied in the uncertainty analysis.

The major limitations of the EOL LCI are the use of secondary inventory data for the fire, landfilling, and incineration processes, which are based on PVC cables, and the uncertainty in the percentage estimates of EOL cables going to the various EOL dispositions. Thus, the disposition percentage estimates are included in the uncertainty analysis; and the overall EOL inventory is given a subjective data quality measure of "low."

3.3 Life-Cycle Impact Assessment

The mandatory elements of an LCIA, as outlined in ISO 14042 and incorporated into this study, include selecting impact categories, classifying the inventory into appropriate impact categories, and characterizing the impacts of each category (i.e., calculation of category indicator results). This LCIA presents comparative impacts of alternative cable constructions for 14 impact categories. Three categories are direct loading measures of the inventory: non-renewable resource use, energy use, and particulate matter impacts. One impact category converts the inventory mass of waste to be landfilled into the volume of landfill space used (note this excludes materials such as mining overburden and tailings, which are not deposited into landfills, yet do occupy land space). Five impact categories use equivalency factors to translate relevant inventory flows into impacts: global warming, stratospheric ozone depletion, photochemical smog, air acidification, and water eutrophication. There are five toxicity categories that use hazard values as relative scoring of the inherent toxicity of a material. We included four human health toxicity categories, which consider occupational and public receptors and are calculated for both cancer and chronic non-cancer impacts. The fifth toxicity category is aquatic ecotoxicity. The units for each category are presented with the results in Section 4 of this Executive Summary.

The equivalency factors used for calculating impacts come from a variety of published sources (Geibig and Socolof, 2005). Hazard values (HV) are calculated for the toxicity categories based on the methods developed for and reviewed by EPA for a previous DfE LCA (Geibig and Socolof, 2005). These methods are a revised version of earlier methods (Swanson *et al.*, 1997; Socolof *et al.*, 2001; Socolof *et al.*, 2000).

The HV method is based on developing relative scores for potentially toxic materials. First, toxicity data are collected for the chemicals of interest for specific endpoints, depending on the impact category. For cancer impacts, the toxicity data are either slope factors that provide the probabilities of cancer risks or weight of evidence measures that give qualitative categories of potential carcinogenesis. For chronic non-cancer impacts, the no-observed adverse effect level (NOAEL) or the lowest observed adverse effect level (LOAEL) is used to calculate relative toxicity. The aquatic ecotoxicity category is based on chronic and acute fish toxicity data (no observed effect concentration [NOEC] and lethal doses to 50 percent of the exposed population [LC_{50}]). For all materials that cannot be excluded as non-toxic, and for which there are existing toxicity data, the toxicity value for a chemical or chemical compound is compared to the geometric mean of all available toxicity values. This provides a relative "hazard value" for each chemical. When chemical toxicity data are lacking, the chemical is assigned the geometric mean value as a default such that chemicals lacking data are not ignored. An example of the equation used for chronic non-cancer public toxicity is as follows:

$$HV = \frac{1/\,LOAEL\ \ (chemical\ i)}{1/\,LOAEL\ \ (geo\ \ mean)}$$

where HV is the hazard value of chemical *i* for non-cancer effects.

Since a low LOAEL value indicates high toxicity, the hazard value takes the reciprocal of the LOAEL for a chemical divided by the reciprocal of the geometric mean of all the collected LOAELs. Thus, the greater the HV, the greater is the potential toxicity. The HV is then multiplied by the inventory amount for a chemical classified for a toxicity category, and the indicator results are presented as kilograms of toxic equivalents. Thus, these categories are consistent with other categories for which increasing indicator values represent increasing impacts (i.e., environmental burdens).

The public cancer and non-cancer impact categories use output inventory data as surrogates for exposure, and then apply the hazard value to calculate the indictor. Due to the complexity of the cable life cycles and the multitude of chemicals in the inventory of the cables, this is a screening-level approach designed to incorporate as many chemicals as possible. As such, this method does not specifically incorporate fate and transport of chemicals through the environment. If toxicity impacts are of particular concern to a stakeholder, further investigation can be targeted based on the initial impact results to help identify potential relative risks.

Occupational impacts are often not included in LCAs because environmental output data do not lend themselves well to modeling occupational exposures. However, in order to approximate potential occupational exposures, we used material inputs as the potential exposure parameter, which are then multiplied by the appropriate hazard value to calculate the indicator results. The major limitation to this approach is that the inputs depend on the upstream boundaries of the datasets used to build the LCA (i.e., which inputs are included), making asymmetric dataset comparisons problematic. Accordingly, we have tried to minimize the impact of asymmetric datasets by excluding certain material flows from this impact category. Despite its weaknesses, the information gleaned from the occupational toxicity impact categories outweighs the potential drawbacks of the method, and users of the results from this LCA have been alerted to the low data quality of the occupational toxicity impact categories.

Final LCIA results for each impact category are the sum of all indicators for all materials in each life-cycle process that are classified into the appropriate impact category. Indicator results are then compared across functionally equivalent alternatives of a cable type (e.g., CMR leaded versus CMR lead-free cable).

3.4 Monte Carlo-Based Uncertainty Analysis

Monte Carlo methods were used to examine the contribution of uncertainty in various life-cycle processes to each impact category result. A built-in Monte Carlo function found in the GaBi4 software package (PE & IKP, 2003) was used to generate probabilistic impact category results. Four parameters within the life-cycle processes were chosen as highly uncertain and were modeled as uniform distributions. Uniform distributions were chosen in this case because they allow parameters to assume extreme bounds without presuming any more knowledge about the actual parameter distribution. The majority of the parameters selected as highly uncertain came from EOL processes.

The parameter representing the percentage of cable consumed in fire was selected as highly uncertain due to the lack of information about building cable burned in fire. As mentioned before, the frequency of fires in buildings containing the cables of interest was known, thus the natural extreme bounds were that anywhere from 0 percent to 100 percent of the cable contained in these buildings would burn in the fire (equivalent to 0-1.1 percent of all cable installed). However, we chose 10 percent as a central estimate because fire protection methods would skew actual burn percentages toward the lower end, and bounded the distribution at 0 and 20 percent. The percentage of cable resins going to recycling was another source of substantial uncertainty in the end-of-life. Using the European-based upper estimate, the expected extreme bounds of 0 percent and 20 percent of the chopped cable resins being recycled were chosen. As described earlier, the parameter representing the percentage of lead leached into the ground assumed that 0-100 percent of the leachate would ultimately escape any landfill lining and leachate collection system (equivalent to 0-1.5 percent of total lead escaping for cable directly landfilled or equivalent to 0-10 percent of total lead escaping for cable resins landfilled after chopping). The final uncertainty distribution represented a data discrepancy for extruding energy data. Inconsistent and highly divergent energy values led to high uncertainty for the extruding data. Thus, the range of the data sets collected as primary data for the lead-free cable were used to set the bounds of the uncertainty analysis, given that none of the data could be identified as anomalous. Because the leaded cable pulled energy use values from only one data set, a proxy data set that produced an equivalent uncertainty range in extrusion energy use was incorporated. A uniform distribution was used to bound the energy used in the leaded and lead-free cable extrusion inventories.

In the Monte Carlo analysis, the variables described above were run simultaneously, to observe the distribution of the total LCIA indicator results given the ranges of uncertainties. Five thousand simulations were run to generate a mean of the LCIA indicator results and various percentile ranges around the mean.

3.5 Sensitivity Analysis

The range of results from the Monte Carlo analysis comes from the concurrent variation of four parameters (percent of cables burned in fire, percent of plastics recycled, lead leachability, and extrusion energy use). Therefore, a sensitivity analysis was necessary to assess the magnitude of each parameter’s contribution. A built-in sensitivity analysis function from the GaBi4 software was used to determine the amount of variance in each impact category attributable to each of the dynamic parameters.

4. Results

4.1 CMR

The LCIA indicator results for the CMR leaded and lead-free cables are given in Table 3. Impact point estimates from the modeled life cycles are given, along with a descriptive statistic describing distribution overlap generated from the Monte Carlo-based uncertainty analysis. The point estimates are generated using the most probable values of all model inputs, or a midpoint default value when adequate information was lacking to determine the most probable value of a particular parameter.

The results given in Table 3 are intended to show the *relative* difference *between alternatives* for *each* impact category, but are not intended to compare the significance of impact categories to *one another*. Simply because one impact category has a greater difference between alternatives does not indicate that its impacts are greater or more significant than those of another impact category. Likewise, a large difference in impacts within a particular category does not indicate significance of the impacts. Indicator results would need to be normalized to some reference point to determine if the relative difference shown in the graph represents some type of significance.

Table 3

CMR LCIA Results – Full life-cycle: Baseline and Lead-free.

Impact Category	Units per km Cable	Baseline Impact Indicator	Pb-free Impact Indicator	Percent Change	Quality Rating	Possible Signif. Diff.[a]
NRR	kg	142	121	-15%	M	
Energy	MJ	2070	1970	-5%	M	
Landfill space	m^3	0.0166	0.0181	9%	M	
Global warming	kg CO_2-equiv.	90.3	83.5	-8%	M	
Ozone depletion	kg CFC 11-equiv.	5.91E-06	4.95E-06	-16%	L	
Smog	kg ethene-equiv.	0.125	0.134	7%	M	
Acidification	kg SO_2-equiv.	0.731	0.678	-7%	M	
Air particulates	kg	0.0782	0.0815	4%	M	
Eutrophication	kg phosphate-equiv.	0.00902	0.00756	-16%	M	
Pot. occ. noncancer	kg noncancertox-equiv.	71.8	77.6	8%	M	Y
Pot. occ. cancer	kg cancertox-equiv.	3.53	3.69	5%	M-L	Y
Pot. public noncancer	kg noncancertox-equiv.	1460	279	-81%	M	Y
Pot. public cancer	kg cancertox-equiv.	0.834	0.837	0.3%	M-L	
Pot. aq. ecotox	kg aqtox-equiv.	17.5	0.113	-99%	M	Y

[a] "Y" indicates the alternatives were significantly different at 80 percent confidence (this confidence interval was used as it was part of a built-in program in GaBi4).
NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity; equiv. = equivalents; Signif. Diff. = significant difference.

The point estimates from the deterministic impact analyses give a mix of results. The leaded cable has lower impact indicators than the lead-free (see Table 3) in landfill space use, photochemical smog formation, particulate matter emissions, potential occupational non-cancer and cancer toxicity, and potential public cancer toxicity. The lead-free cable has lower impact indicators in non-renewable resource use, energy use, global warming potential, ozone depletion potential, air acidification, eutrophication potential, potential public non-cancer toxicity, and potential aquatic ecotoxicity.

However, comparing the probabilistic impact results of the leaded and lead-free CMR cables, it is clear that many of the 10th-90th percentile ranges overlap. This is the case for all of the impact categories except potential public non-cancer toxicity and aquatic toxicity for which the lead-free cable generates lower impact indicators, and potential occupational cancer and non-cancer for which the leaded cable generates lower impact indicators. The overlap of a number of impact results emphasizes that accurately specified parameter uncertainty should play a significant role in the interpretation of life-cycle impact analyses.

The results from the uncertainty analysis show substantial variability in a number of the impact categories (not reported in Table 3). For the leaded cable results, the categories with high variability were non-renewable resource use, public chronic non-cancer toxicity, aquatic ecotoxicity, ozone depletion potential, and eutrophication potential, whose standard deviations were 22 percent, 35 percent, 47 percent, 29 percent, and 27 percent of their means, respectively. For the lead-free cables, the results also show substantial variability in a number of impacts: non-renewable resources (standard deviation = 20 percent), aquatic ecotoxicity (standard deviation = 22 percent), ozone depletion potential (standard deviation = 27 percent), and eutrophication potential (standard deviation = 25 percent).

When interpreting the results, it is also important to consider the underlying data quality. Overall subjective data quality measures are given to each impact category based on the inventory data (e.g., primary versus secondary data), and impact characterization methods (e.g., availability of toxicity data). For CMR cables, a "medium" data quality measure is assigned to the following impact categories: non-renewable resources, energy, landfill space, public global warming, photochemical smog, air acidification, particulate matter, water eutrophication, potential occupational chronic non-cancer toxicity, and potential aquatic ecotoxicity. Potential public and occupational cancer toxicity are given a "medium to low" rating, given that most inventory flows contributing to potential cancer toxicity did not have cancer toxicity data and were thus based on default hazard values. Ozone depletion is given a "low" rating based on the lack of upstream data regarding brominated ozone depleting compounds likely generated during the production of brominated phthalate materials.

As shown in Table 4, the top contributing process for half of all impact category results for the CMR cable alternatives was the generation of electricity (needed to power the cable extrusion process in the cable manufacturing life-cycle stage). Electricity generation was the top process in the baseline cable case for 6 categories: non-renewable resource use, energy use, global warming, ozone depletion, air acidification, and eutrophication. For the lead-free cable alternative, the generation of electricity for cable extrusion was the top contributing process for the same 6 impact categories, plus the potential public non-cancer toxicity and potential aquatic toxicity impact categories. Jacketing resin production was the top contributing process for photochemical smog formation, air particulates, and potential public cancer toxicity for both cable alternatives. Municipal solid waste landfilling was the top contributing process to potential public non-cancer toxicity and potential aquatic ecotoxicity in the baseline case. Lead from landfilling was the top flow contributing to potential public non-cancer toxicity and potential aquatic ecotoxicity. Finally, the compounding of the jacketing was the top contributing process to the potential occupational non-cancer and cancer toxicity impact categories for both cable alternatives. This helps identify potential areas of environmental improvement; however, it must be noted that these results are in the context of the comparison of resin systems and their additives, so focusing on top contributors identified here does not provide the complete impacts from the entire cable (e.g., the copper conductor is excluded).

The partial life-cycle comparison of CMR zero-halogen cable to the two other alternatives presented above is not presented in detail here, as only very limited data were available on both the upstream and manufacturing stages. The point estimates from the deterministic impact analyses show that the cradle-to-gate life cycle of the zero-halogen alternative yields greater impacts in all categories except for occupational non-cancer than the baseline and lead-free cases. This is due to its far greater use of energy during the compounding of the cable jacketing.

Table 4

CMR Summary of Top Contributors to LCIA Results – Full life cycle: Baseline and Lead-free.

Impact Category	Baseline		Pb-free	
	Top Process	**Top Flow**	**Top Process**	**Top flow**
NRR	Electricity generation	Inert rock	Electricity generation	Inert rock
Energy	Electricity generation	Natural gas	Electricity generation	Natural gas
Landfill space	MSW landfill	PVC waste	MSW landfill	PVC waste
Global warming	Electricity generation	Carbon dioxide	Electricity generation	Carbon dioxide
Ozone depletion	Electricity generation	CFC 11	Electricity generation	CFC 11
Smog	Jacketing resin production	VOC (unspecified)	Jacketing resin production	VOC (unspecified)
Acidification	Electricity generation	Sulfur dioxide	Electricity generation	Sulfur dioxide
Air particulates	Jacketing resin production	Dust	Jacketing resin production	Dust
Eutrophication	Electricity generation	Chemical oxygen demand	Electricity generation	Chemical oxygen demand
Pot. occ. noncancer	Jacketing compounding	FR #2 (non-halogen)[a]	Jacketing compounding	FR #2 (non-halogen)[a]
Pot. occ. cancer	Jacketing compounding	Phthalates[b]	Jacketing compounding	Phthalates[b]
Pot. public noncancer	MSW landfill	Lead (water)	Electricity generation	Sulfur dioxide (air)
Pot. public cancer	Jacketing resin production	Nitrogen oxides (air)[b]	Jacketing resin production	Nitrogen oxides (air)[b]
Pot. aq. ecotox	MSW landfill	Lead	Electricity generation	Chlorine (dissolved)

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity; PVC = polyvinyl chloride; MSW = municipal solid waste; CFC = chlorofluorocarbon; VOC = volatile organic compound; FR = flame retardant.

[a] Proprietary.

[b] To calculate impact results, these flows were given default toxicity hazard values due to lack of toxicological data.

4.2 CMP

The LCIA results for the CMP leaded and non-leaded cables are given in Table 5. Impact point estimates from the modeled life cycles are given, along with a descriptive statistic describing distribution overlap generated from the Monte Carlo-based uncertainty analysis. The point estimates are generated using the most probable values of all model inputs, or a midpoint default value where adequate information was lacking to determine the most probable value of a particular parameter.

Table 5

CMP LCIA Results – Full life cycle: Baseline and Lead-free

Impact Category	Units per km Cable	Baseline Impact Indicator	Pb-free Impact Indicator	Percent Change	Quality Rating	Possible Signif. Diff.[a]
NRR	kg	237	219	-8%	M	
Energy	MJ	3770	3570	-5%	M	
Landfill space	m^3	0.0132	0.0144	9%	M	
Global warming	kg CO_2-equiv.	181	171	-5%	M	
Ozone depletion	kg CFC 11-equiv.	0.00116	0.00110	-5%	L	Y
Smog	kg ethene-equiv.	0.0886	0.0868	-2%	M	
Acidification	kg SO_2-equiv.	0.877	0.819	-7%	M	
Air particulates	kg	0.0746	0.0726	-3%	M	
Eutrophication	kg phosphate-equiv.	0.0125	0.0114	-9%	M	
Pot. occ. noncancer[b]	kg noncancertox-equiv.	49.2	46.8	-5%	M	Y
Pot. occ. cancer[b]	kg cancertox-equiv.	2.16	2.22	3%	M-L	Y
Pot. public noncancer	kg noncancertox-equiv.	952	358	-62%	M	Y
Pot. public cancer	kg cancertox-equiv.	0.735	0.701	-5%	M-L	
Pot. aq. ecotox	kg aqtox-equiv.	8.64	0.151	-98%	M	Y

[a] "Y" indicates the alternatives were significantly different at 80 percent confidence (this confidence interval was used as it was part of a built-in program in GaBi4).

[b] FEP production, which came from 2 primary datasets, was modeled with 2 industrial precursor chemicals functioning as inputs; production of PVC, the other major resin used in CMP cables, and which came from a secondary dataset, was modeled as if all of the materials came from ground (mining of inert or low-toxicity inputs), and did not explicitly include industrial precursor chemicals. In order to be more consistent across resins, the contributions from industrial precursor chemicals in the FEP supply chain were removed prior to calculation of the potential occupational toxicity results.

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity; equiv. = equivalents; Signif. Diff. = significant difference.

Comparison of the point estimates from the CMP leaded and lead-free deterministic impact analyses yielded slightly different results to those found in the CMR analysis (Table 4). According to the point estimates, the lead-free cable had lower impact indicators (i.e., less environmental burden) in all of the categories except for the use of landfill space and potential occupational cancer toxicity.

Similar to the CMR results, only a few impact categories did not have overlapping 10^{th}-90^{th} percentile ranges: ozone depletion, potential occupational non-cancer and cancer toxicity, potential public chronic non-cancer toxicity, and potential aquatic ecotoxicity. This suggests greater certainty that observed differences between the alternatives are real for those five categories. Non-renewable resource use, energy use, landfill space use, global warming potential, photochemical smog potential, air acidification potential, eutrophication potential, particulate matter emissions, and potential public cancer toxicity all exhibit overlap. Thus, there is less certainty that the lead-free cable is substantially different from the leaded cable for these impact categories.

The CMP leaded cable results show less relative variability (i.e., standard deviation normalized by the mean value) than those of the CMR leaded cable overall (not shown in Table 4). However, the potential public chronic non-cancer toxicity and potential aquatic ecotoxicity indicators still display substantial variability (standard deviations are 27 percent and 47 percent of their means, respectively). For the CMP lead-free cable, results show substantially less relative variability than those of the CMR lead-free cable, with no impact indicators' standard deviations exceeding 20 percent of their mean.

As described for CMR results, a "medium" data quality measure for CMP results is assigned to the following impact categories: non-renewable resources, energy, landfill space, public global warming, photochemical smog, air acidification, particulate matter, water eutrophication, potential occupational chronic non-cancer toxicity, and potential aquatic ecotoxicity. Potential public and occupational cancer toxicity are given a "medium to low" rating, given that most inventory flows contributing to potential cancer toxicity did not have cancer toxicity data, and were thus based on default hazard values. Ozone depletion is given a "low" rating based on the lack of upstream data regarding brominated ozone-depleting compounds likely generated during the production of brominated phthalate materials.

Table 6 shows the generation of electricity was the top contributor to the following five impact categories for the lead-free cable: non-renewable resources, air acidification, and eutrophication, potential public non-cancer toxicity, and potential aquatic ecotoxicity impact categories. For the baseline cable, electricity generation was top contributor to three impact categories: non-renewable resources, air acidification, and eutrophication. For both CMP cable alternatives, the production of insulation resin (FEP) and jacketing resin (PVC), were each top contributors to three impact categories. FEP production was top contributor for both alternatives in energy use, global warming, and ozone depletion. PVC production was top contributor for both alternatives in photochemical smog, particulate matter, and potential public cancer toxicity. For the baseline CMP cable, the top contributing process to potential public non-cancer toxicity and potential aquatic ecotoxicity was municipal solid waste landfilling. For both of these categories, the top material flow contributor was lead assumed to leach from the landfill into groundwater. For both cable alternatives, the municipal solid waste landfilling process also dominated the landfill space use impact category. This information helps identify potential areas of environmental improvement; however, it must be noted that these results are in the context of the comparison of resin systems and their additives, so focusing on top contributors identified here does not provide the complete impacts from the entire cable (e.g., the copper conductor is excluded).

4.3 NM-B

The LCIA results for the NM-B leaded and non-leaded cables are given in Table 7. The statistic indicating overlap of the 10th to 90th percentile range is not shown, as no uncertainty analysis was deemed necessary for the NM-B cable.

Comparison of the point estimates from the leaded and lead-free deterministic impact analyses for NM-B cable yielded similar results to those of CMP. According to the point estimates, the lead-free cable had lower impact indicators (i.e., less environmental burden) in all of the categories except for occupational non-cancer toxicity and photochemical smog. The latter had no change.

Table 6

CMP Summary of Top Contributors to LCIA Results – Full life cycle: Baseline and Lead-free.

Impact Category	Baseline		Pb-free	
	Top process	Top flow	Top Process	Top flow
NRR	Electricity generation	Inert rock	Electricity generation	Inert rock
Energy	Insulation resin production	Natural gas	Insulation resin production	Natural gas
Landfill space	MSW landfill	PVC Waste	MSW landfill	PVC Waste
Global warming	Insulation resin production	Carbon dioxide	Insulation resin production	Carbon dioxide
Ozone depletion	Insulation resin production	Refrigerant #5[a]	Insulation resin production	Refrigerant #5[a]
Smog	Jacketing resin production	VOC (unspecified)	Jacketing resin production	VOC (unspecified)
Acidification	Electricity generation	Sulfur dioxide	Electricity generation	Sulfur dioxide
Particulate matter	Jacketing resin production	Dust	Jacketing resin production	Dust
Eutrophication	Electricity generation	Chemical oxygen demand	Electricity generation	Chemical oxygen demand
Pot. occ. noncancer[c]	Natural gas production	Natural gas[b]	Natural gas production	Natural gas[b]
Pot. occ. cancer[c]	Jacketing compounding	Flame retardant #3[b]	Jacketing compounding	Flame retardant #3[b]
Pot. public noncancer	MSW landfill	Lead (water)	Electricity generation	Sulfur dioxide (air)
Pot. public cancer	Jacketing resin production	Nitrogen oxides (air)[b]	Jacketing resin production	Nitrogen oxides (air)[b]
Pot. aq. ecotox	MSW landfill	Lead	Electricity generation	Chlorine (dissolved)

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity; PVC = polyvinyl chloride; MSW = municipal solid waste; HCFC = hydrochlorofluorocarbon; VOC = volatile organic compound.

[a] Proprietary.

[b] To calculate impact results, these flows were given default toxicity hazard values due to lack of toxicological data.

[c] FEP production, which came from 2 primary datasets, was modeled with 2 industrial precursor chemicals functioning as inputs; production of PVC, the other major resin used in CMP cables, and which came from a secondary dataset, was modeled as if all of the materials came from ground (mining of inert or low-toxicity inputs), and did not explicitly include industrial precursor chemicals. In order to be more consistent across resins, the contributions from industrial precursor chemicals in the FEP supply chain were removed prior to calculation of the potential occupational toxicity results.

Table 7

NM-B Results – Partial life cycle: Baseline and Lead-Free

Impact Category	Units per km Cable	Baseline Impact Indicator	Pb-free Impact Indicator	Percent Change	Quality Rating
NRR	kg	70.6	59.7	-15%	M
Energy	MJ	1530	1440	-6%	M
Landfill space	m^3	0.00251	0.00221	-12%	M-L
Global warming	kg CO_2-equiv.	52.2	48.3	-7%	M
Ozone depletion	kg CFC 11-equiv.	9.79E-07	6.61E-07	-33%	L
Smog	kg ethene-equiv.	0.119	0.119	0%	M
Acidification	kg SO_2-equiv.	0.479	0.449	-6%	M
Air particulates	kg	0.0862	0.0759	-12%	M
Eutrophication	kg phosphate-equiv.	0.00169	0.00135	-20%	M
Pot. occ. noncancer	kg noncancertox-equiv.	20.0	26.7	33%	M
Pot. occ. cancer	kg cancertox-equiv.	8.23	7.08	-14%	M-L
Pot. public noncancer	kg noncancertox-equiv.	189	171	-10%	M
Pot. public cancer	kg cancertox-equiv.	0.828	0.798	-4%	M-L
Pot. aq. ecotox	kg aqtox-equiv.	0.0894	0.0626	-30%	M

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity.

As in the CMR and CMP results, a "medium" data quality measure for NM-B results is assigned to the following impact categories: non-renewable resources, energy, landfill space, public global warming, photochemical smog, air acidification, particulate matter, water eutrophication, potential occupational chronic non-cancer toxicity, and potential aquatic ecotoxicity. Potential public and occupational cancer toxicity are given a "medium to low" rating, given that most inventory flows contributing to potential cancer toxicity did not have cancer toxicity data, and were thus based on default hazard values. Ozone depletion is given a "low" rating based on the lack of upstream data regarding brominated ozone-depleting compounds likely generated during the production of brominated phthalate materials.

In the NM-B analysis, which excludes the extrusion process and subsequent downstream processes, the production of the jacketing resin, PVC, more often dominated impacts (8 impact categories), followed by electricity generation from compounding (2 impact categories), then limestone production (1 category), insulation compounding (1 category), jacketing compounding (1 category), and phthalate production (1 category) (see Table 8). These results identify processes that could be the focus of environmental improvement opportunities. However, it must be noted that these results are in the context of the comparison of resin systems and their additives, so focusing on top contributors identified here does not provide the complete impacts from the entire cable (e.g., the copper conductor is excluded from the analysis).

Table 8

NM-B Summary of Top Contributors to LCIA Results – Partial life cycle: Baseline and Lead-free.

	Baseline		Pb-free	
Impact Category	**Top process**	**Top flow**	**Top Process**	**Top flow**
NRR	Jacketing resin production	Inert rock	Jacketing resin production	Natural gas
Energy	Jacketing resin production	Natural gas	Jacketing resin production	Natural gas
Landfill space	Limestone production	Treatment residue (mineral)	Limestone production	Treatment residue (mineral)
Global warming	Jacketing resin production	Carbon dioxide	Jacketing resin production	Carbon dioxide
Ozone depletion	Electricity generation	CFC-11	Electricity generation	CFC-11
Smog	Jacketing resin production	VOC (unspecified)	Jacketing resin production	VOC (unspecified)
Acidification	Jacketing resin production	Sulfur dioxide	Jacketing resin production	Sulfur dioxide
Air particulates	Jacketing resin production	Dust	Jacketing resin production	Dust
Eutrophication	Electricity generation	Chemical oxygen demand	Electricity generation	Chemical oxygen demand
Pot. occ. noncancer	Insulation compounding	FR #2 (non-halogen)[a]	Insulation compounding	FR #2 (non-halogen)[a]
Pot. occ. cancer	Jacketing compounding	Plasticizer #2[a,b]	Jacketing compounding	Phthalate plasticizer #5[a,b]
Pot. public noncancer	Jacketing resin production	Sulfur dioxide (air)	Jacketing resin production	Sulfur dioxide (air)
Pot. public cancer	Jacketing resin production	Nitrogen oxides (air)[b]	Jacketing resin production	VOC (unspecified) (air)[b]
Pot. aq. ecotox	Phthalate production	Copper (+1, +2)	Phthalate production	Copper (+1, +2)

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity; CFC = chlorofluorocarbon; VOC = volatile organic compound; FR = flame retardant.

[a] Proprietary.

[b] To calculate impact results, these flows were given default toxicity hazard values due to lack of toxicological data.

4.4 Sensitivity Analysis

The sensitivity analysis was used to probe the contributions of each stochastic parameter to overall impact uncertainty. Results of the analyses for the CMR/CMP baseline versus lead-free comparisons, shown in Table 9, give the largest contributing parameter along with the percent variance in the impact result attributable to this dominant parameter.

It is evident from Table 9 that one parameter is responsible for most of the variation in impacts for each cable type: the energy used for cable extrusion. However, for the CMR and CMP leaded cables, the uncertainty in the potential public chronic non-cancer toxicity and the potential aquatic ecotoxicity categories are dominated by the landfill leachate parameter, and for all cables, thermoplastic recycling dominates the landfill space use indicators.

Table 9

Sensitivity Analysis[a,b]

Impact Category	CMR		CMP	
	Leaded	**Lead-free**	**Leaded**	**Lead-free**
Non-renewable resources	E (98)	E (98)	E (98)	E (97)
Energy	E (>50)[c]	E (>50)[c]	E (>50)[c]	E (>50)[c]
Landfill space	TR (63)	TR (65)	TR (88)	TR (86)
Global warming	E (98)	E (97)	E (99)	E (98)
Ozone depletion	E (98)	E (98)	E (98)	E (98)
Smog	E (99)	E (99)	E (99)	E (99)
Acidification	E (94)	E (92)	E (92)	E (92)
Air particulates	E (98)	E (98)	E (98)	E (98)
Eutrophication	E (98)	E (98)	E (98)	E (98)
Pot. occ. non-cancer toxicity	E (97)	E (96)	E (96)	E (95)
Pot. occ. cancer toxicity	E (98)	E (97)	E (97)	E (97)
Pot. public non-cancer toxicity	L (83)	E (98)	L (78)	E (97)
Pot. public cancer toxicity	E (86)	E (96)	E (90)	E (96)
Pot. aq ecotox	L (90)	E (98)	L (90)	E (98)

[a] Results are reported as the dominant parameter (percentage of the overall impact result variance for which it is responsible).
[b] Pot. = potential; occ. = occupational; TR = thermoplastics recycling; L = lead lost from landfill; E = extrusion energy.
[c] Actual percentage withheld to protect confidentiality.

5. Summary

Life-cycle impact indicators were calculated for 14 impact categories to compare leaded and lead-free cable resin constructions for Category 6 CMR, Category 6 CMP, and NM-B cables. Point estimate results were calculated using aggregated industry data from both primary and secondary data sources, along with documented estimates or default values for the disposition of cables at their end-of-life. For estimates with the greatest uncertainty, a Monte Carlo uncertainty analysis was conducted to identify the likelihood that observed differences were real.

The point estimate results from the CMR impact assessment showed mixed results for both leaded and lead-free cable types, though the disparities between the cable alternative impact scores for most impact categories were minimal. In eight impact categories, the lead-free cable construction had less environmental burden; however, six of those categories generated inconclusive results due to the large uncertainty. In other words, overlap of the 10th and 90th percentiles eliminates the possibility of statistically significant differences. The following two categories that had less environmental burden for the lead-free cable did *not* have overlapping uncertainty ranges: potential public chronic non-cancer toxicity and potential aquatic ecotoxicity. Of the six categories that showed lower burden for the *leaded* cable, only two did not have overlapping results due to uncertainty: potential occupational cancer and non-cancer toxicity. The point-estimate results from the cradle-to-gate comparison of the baseline, the lead-free, and the zero-halogen CMR alternatives showed that the zero-halogen cable had far greater environmental burden in all of the categories except for potential occupational non-cancer toxicity.

The point estimates from the CMP cable comparisons showed all categories except for landfill space use and occupational cancer toxicity had fewer impacts for the lead-free compared to the leaded cables. However, only five categories did not have overlapping 10th and 90th uncertainty ranges: potential occupational cancer and non-cancer toxicity, potential public chronic non-cancer toxicity, potential aquatic ecotoxicity, and ozone depletion, suggesting greater confidence in these results.

The point estimates from the NM-B cradle-to-gate cable comparisons showed all categories except for potential occupational non-cancer toxicity had fewer impacts for the lead-free compared to the leaded cables. No uncertainty or sensitivity analyses were deemed necessary for this comparison.

6. Conclusions

The major material and process contributors to overall environmental burden for all cable types can be broken down into three principal categories:

- upstream material production and use,
- energy sources and use, and
- end-of-life disposition.

The upstream production and use of certain materials in wire and cable formulations has a significant effect on many of the overall life-cycle impact category results. The materials that contribute to cable-associated environmental burden are, in order of decreasing impact, lead heat stabilizers, jacketing and insulation resins, phthalate plasticizers, and filler materials (e.g., calcined clay and limestone).

Aside from the use of leaded and lead-free heat stabilizers, the life-cycle inventories of the various wire and cable products examined in this study did not show large material differences in formulation between leaded and lead-free alternatives. However, in a number of instances, small formulation differences yielded impact result discrepancies. Upon further investigation of this issue, including consultation with a number of primary data contributors, it remained unclear whether these slight material differences arise as artifacts of asymmetrical upstream datasets for the leaded and lead-free products or are indicative of actual “global” differences between alternatives (i.e., industry-wide differences in cable formulations). As this is the case, the leaded and lead-free heat stabilizers are the only materials that differentiate the alternatives with a high degree of certainty. This is not to say that the other material differences found in this study should be ignored. It is possible that asymmetry in the markets for both leaded and lead-free products (i.e., companies that provide one product but do not provide the alternative), or actual intra-company formulation differences lead to a “global” difference in the material formulations. However, given the lack of information about the proportion of market share modeled, we cannot determine such a “global” difference with certainty. Consequently, companies that are looking for ways to reduce impacts through material formulation are encouraged to examine the difference in impacts due to choice of stabilizer, as this represents the most certain result of formulation differences. The environmental impacts resulting from the use of lead heat stabilizers are seen primarily at the product EOL, and therefore are discussed below.

The production and use of a number of other upstream materials results in substantial environmental burden. The production of jacketing and insulation resins contribute substantially to a number of impact categories in both CMR and CMP cable, including energy use and non-renewable resources, potential public cancer toxicity (NO_x and VOC production), air acidification, air particulate production, and photochemical smog production. Additionally, phthalate plasticizers were major contributors to the potential occupational cancer toxicity impacts, especially in the case of CMR cable where they represented a far higher fraction of the overall cable mass than in CMP cable.

Energy sources throughout the wire and cable life cycle, particularly electricity generation for use in upstream material production and cable extrusion, played an enormous role in the overall environmental burden of wire and cable products analyzed here. For the CMR cable alternatives, the generation of electricity for cable extrusion was the top contributing process in 6 and 8 impact categories for the baseline and lead-free cables, respectively. For the CMP cable alternatives, the generation of electricity for cable extrusion was the top contributing process in 3 and 5 impact categories for the baseline and lead-free cables, respectively. For the NM-B cable alternatives, the generation of electricity for cable extrusion was the top contributing process in 3 and 5 impact categories for the baseline and lead-free cables, respectively. Additionally, the sensitivity analysis (Table 7) revealed that the large impact uncertainty ranges for both the CMR and CMP cable were mostly attributable to the uncertainty in the energy needed for cable extrusion. This was the case for all categories except potential public non-cancer toxicity and potential aquatic ecotoxicity, where leachate uncertainty dominated in the baseline cable, and landfill space use, where the percent of resins recycled after chopping had a greater effect on the results for both cable alternatives. The range of extrusion energy, modeled using a uniform uncertainty distribution, was quite large (>50 percent of the aggregated value in both directions), so the resulting sensitivity of the model results to this parameter was not entirely surprising. However, the fact that the uncertainty associated with the use of energy during cable extrusion is based on actual inter-company variability is a reminder that the sample size of the primary/secondary datasets used, and the product or material market share represented by these datasets is important in determining the accuracy of the life-cycle modeling effort. These findings suggest that identifying opportunities for reducing energy inputs would likely have a large effect on the overall environmental burden of wire and cable products.

This study found that the end-of-life stage generates the most sizeable impact differences between baseline leaded cable and lead-free cable. For both CMR and CMP, the difference between the two cables was most pronounced in the potential public chronic non-cancer (CMR: 1,460 versus 279; CMP: 952 versus 358 kg noncancertox-equivalent) and potential aquatic ecotoxicity impacts (CMR: 17.5 versus 0.113; CMP: 8.64 versus 0.151 kg aqtox-equivalent), with the lead-free cables displaying much lower impacts in these categories. The sensitivity analysis showed that the lead leachability assumptions are responsible for the majority of the variability in these impact results. Therefore, given that the LCIA methodology is a screening-level assessment of potential toxicity effects, the results of this study indicate that further investigation into the leachability of lead from cables disposed of in landfills is warranted, as well as a more targeted evaluation on the potential toxicity and health risks.

EOL disposition choices for wire and cable products are complicated by the trade-offs inherent to the processes themselves. The sequestration of wire and cable waste by landfilling is not without its source of hazards. The release of methane from landfilled resins impacts global warming potential, and the PVC waste could become, over long periods of time, a source of other halogenated emissions. Incineration, while advantageous from a landfill space use perspective, results in airborne lead emissions, which are problematic from a public health standpoint. Thermoplastic recycling is energy-intensive and creates new waste streams, which must then be landfilled. Thus, the choices are not straightforward, and depend, among other things, on regulatory standards, economic incentives, and the value placed on different environmental burdens.

The uncertainty analysis revealed that several impact categories are sensitive to the variabilities defined here. Further refinement of the inventory data and EOL assumptions that are the subject of the uncertainty analyses would help reduce uncertainties and lead to more reliable study results. In addition, LCA results such as those presented here provide a type of screening analysis where differences across alternatives in various impact categories are shown in the context of uncertainty. In some instances discernable differences cannot be inferred; however, where more significant differences are likely (e.g., potential public non-cancer and potential aquatic ecotoxicity), further refinement is warranted, such as using health risk assessment techniques to begin to identify human and ecological health risks.