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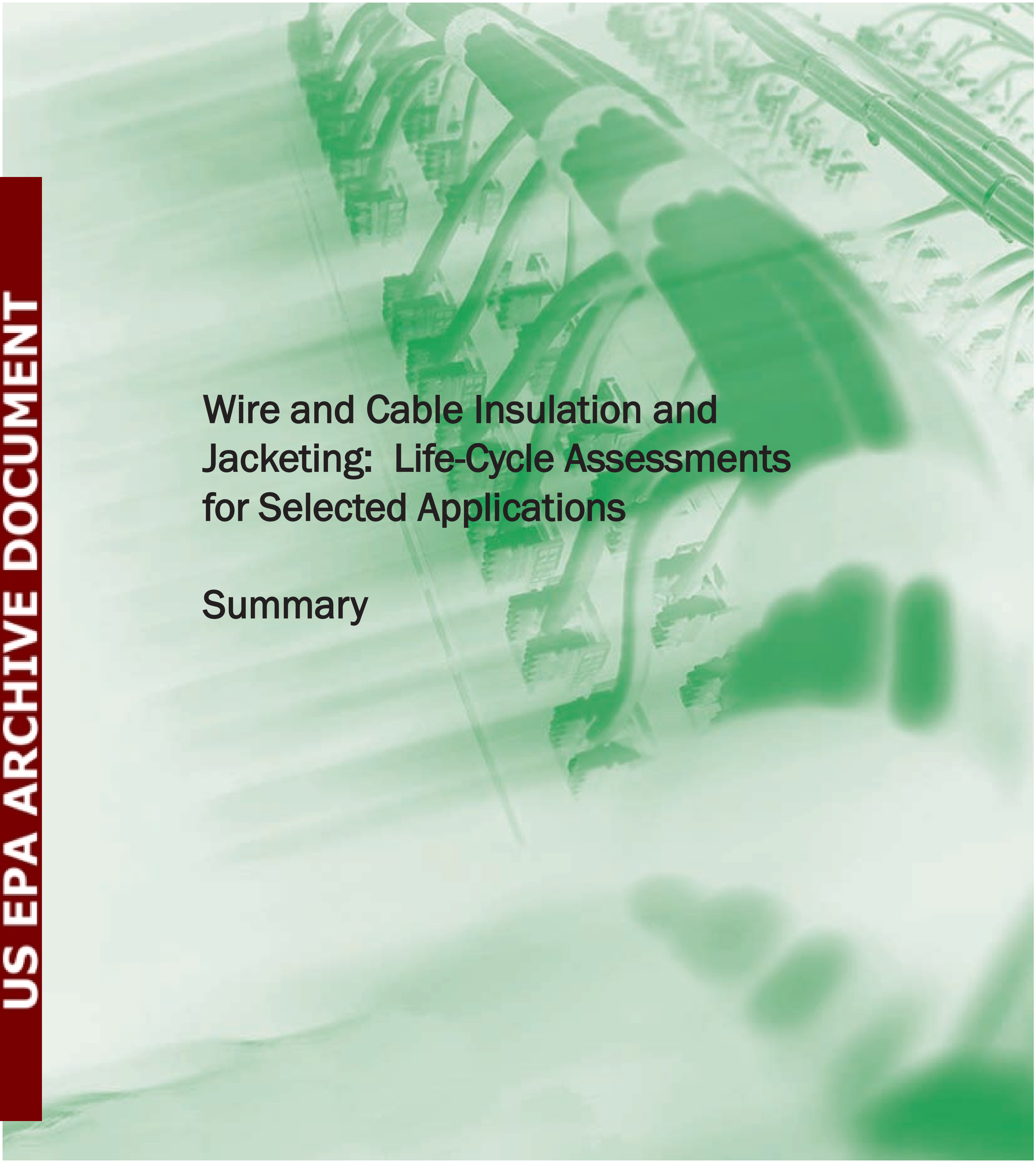

Wire and Cable Insulation and Jacketing: Life-Cycle Assessments for Selected Applications

Summary

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Summary

This summary document is based on information presented in the EPA Design for the Environment project report, *Wire and Cable Insulation and Jacketing: Life-Cycle Assessments for Selected Applications*. Some information in the life-cycle assessment report was provided by individual technology vendors and has not been independently corroborated by EPA. The identification of specific products or processes in this document is not intended to represent an endorsement by EPA or the U.S. Government. This summary document has not been through a formal external peer review process.

Design for the Environment
U.S. EPA

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This life-cycle assessment (LCA) summary was prepared for the U.S. Environmental Protection Agency's (EPA's) Design for the Environment (DfE) Wire and Cable Partnership by Abt Associates Inc., under contract #68-W02-077. This document is based primarily on the full project report, Wire and Cable Insulation and Jacketing: Life-Cycle Assessments for Selected Applications, prepared by Maria Leet Socolof, Jay Smith, David Cooper, and Shanika Amarakoon, under funding from the U.S. Environmental Protection Agency's DfE Program in the Economics, Exposure, and Technology Division (EETD) of the Office of Pollution Prevention and Toxics (OPPT).

This LCA study was conducted as part of the DfE Wire and Cable Partnership, under the direction of the project's Core Group members, including Kathy Hart, Project Co-Chair, U.S. EPA OPPT, DfE Branch; Liz Harriman, Project Co-Chair, Toxics Use Reduction Institute, University of Massachusetts Lowell; Maria Leet Socolof, David Cooper, Jay Smith, Shanika Amarakoon, Christopher Guyol, and Brian Segal, Abt Associates Inc.; Susan Landry, Albemarle Corporation; Dave Kiddoo, Gary Nedelman, and Troy Brantley, AlphaGary Corporation; Charlie Glew, Cable Components Group, LLC; Joe Daversa, Chemson, Inc.; Rob Wessels, CommScope; Ralph Werling and Gary Stanitis, Daikin America, Inc.; Stacy Cashin and James Hoover, DuPont; Fred Dawson, DuPont Canada; Brenda Hollo and Paul Kroushl, Ferro Corporation; Dr. Henry Harris, Georgia Gulf; Akshay Trivedi, Judd Wire; Richard Shine, Manitoba Corporation; Richard LaLumondier, National Electrical Manufacturers Association (NEMA); Tim Greiner, Pure Strategies, Inc.; J. Brian McDonald, SGS–US Testing–CTS; Melissa Hockstad, Society of the Plastics Industry (SPI); Paul Sims, Southwire Company; Stefan Richter, Sud-Chemie, Inc; Dr. Jim Tyler, Superior Essex; Mike Patel, Chuck Hoover, and David Yopak, Teknor Apex Company; Scott MacLeod and Steve Galan, Underwriters Laboratories; H.J. (Bud) Hall and Frank Borrelli, Vinyl Institute of the American Plastics Council.

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Contents

Introduction

Purpose and Scoe of the Study

The purpose of the Wire and Cable Partnership was to evaluate the life-cycle environmental impacts of standard (leaded) and alternative (lead-free and/or zero-halogen) cable insulation and jacketing formulations for three cable types (CMR, CMP, and NM-B) using the life-cycle assessment (LCA) approach. LCAs, which are generally global and non-site specific in scope, look at the full life cycle of the product being evaluated, from materials acquisition to manufacturing, use, and end-of-life (i.e., final disposition). The WCP LCA considers 14 impact categories, which are related to material consumption, energy use, air resources, water resources, landfills, and human and ecological toxicity.

Need for the Study

The wire and cable industry manufactures a wide range of products that support a multitude of applications. Many wire insulation and cable jacketing compositions contain materials, such as lead, halogenated compounds, and other ingredients, that impart electrical insulation and fire performance properties, but that have been identified as materials of potential environmental concern or as materials for which industry stakeholders have expressed a desire to identify and evaluate various alternatives. The DfE/TURI Partnership has generated information on the environmental impacts of leaded (baseline) and alternative cable constructions in order to help companies make environmentally sound product and material choices. Although some changes have been made in certain wire and cable sectors, the WCP believes that developing and providing sound environmental data using a life-cycle assessment approach could assist those and other sectors to pursue environmentally preferable cables. Because of the large quantity of cable put into commerce every year, choosing environmentally preferable materials could have a broad impact on public health and the environment. Quantitative environmental life-cycle analysis of the baseline and alternative cable formulations is needed, given the current interest in lead-free cables in the United States and halogen-free cable materials in certain overseas markets, the potential environmental concerns that lead- and halogen-containing additives pose, and the fact that the relative life-cycle environmental impacts of these cable formulations have not yet been determined. This project offers the opportunity to mitigate current and future risks by assisting the wire and cable industry in identifying cable jacketing and wire insulation formulations that are less toxic and that pose fewer risks over their life cycles, and identifying areas for environmental improvement.

About EPA's Design for the Environment Program

EPA's Office of Pollution Prevention and Toxics established the DfE Program in 1992 to encourage businesses to incorporate environmental concerns into their business decisions. DfE industry projects are cooperative, joint partnerships with trade associations, businesses, public-interest groups, and academia to assist businesses in specific industries to identify and evaluate more environmentally sound products, processes, technologies, and formulations. The DfE Wire and Cable Partnership consists of individual wire and cable manufacturers, supply chain members, trade association members, environmental researchers, a state funded research and assistance organization, and EPA.

Question 1:
What is a life-cycle assessment?

The DfE Wire and Cable Partnership (WCP) conducted this analysis of wire and cable products using a life-cycle assessment (LCA) approach, which allows for a comprehensive analysis of the environmental consequences of a product system over its entire life. LCA, which is increasingly being used by industry, contains four major steps:

1. **Goal Definition and Scoping** lays out why the LCA is being conducted, its intended use, and the system or data categories to be studied.

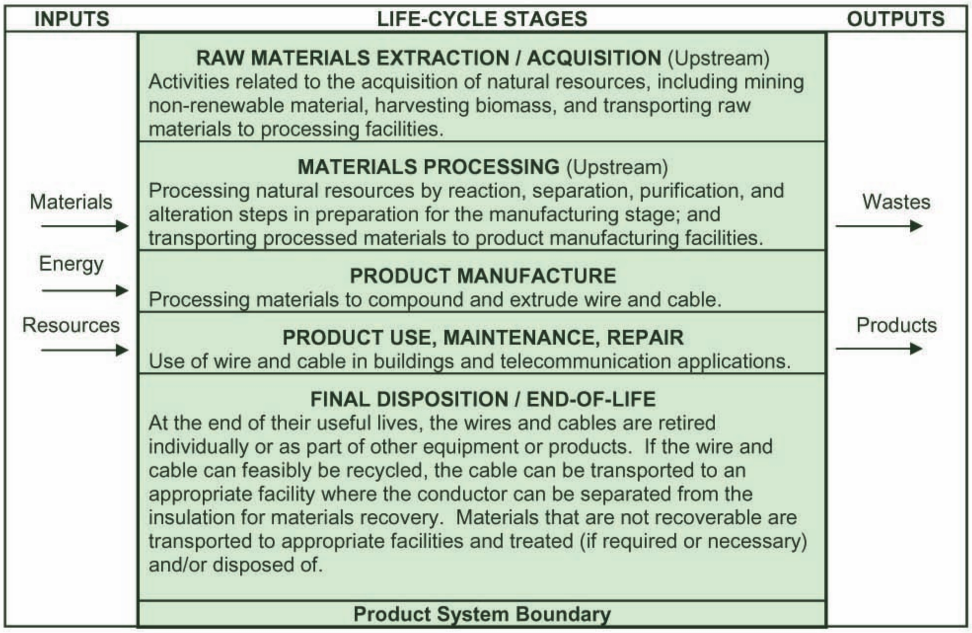
2. **Life-Cycle Inventory (LCI)** involves quantifying inputs (e.g., raw materials and fuel) and outputs (e.g., emissions, effluents, and products).

3. **Life-Cycle Impact Assessment (LCIA)** involves characterizing the effects of the inputs and outputs (as identified in the life-cycle inventory step) on the environment and human and ecological health.

4. **Life-Cycle Interpretation** analyzes major contributions, conducts sensitivity analysis and uncertainty analyses as warranted, and presents conclusions. This study presents results, but does not make recommendations as to preferred products or specific material choices, which is left to the wire and cable industry and others to complete. Using the results of this study; however, opportunities for improvement are introduced.

In the LCI and LCIA steps, the inputs and outputs, and environmental impacts associated with the product throughout its life are quantified and characterized for each life-cycle stage: raw material extraction, materials processing, product manufacturing, product use, and end-of-life. Each of these major stages of the product life cycle is described in Figure 1.1.

Figure 1.1 Life-Cycle Stages of Wire and Cable Evaluated in this Study



Question 2:
Which wire and cable products were investigated during the project?

This project investigated baseline and alternative cable formulations within three different types of wire and cable products: (1) Category 6 riser-rated communication cable (CMR); (2) Category 6 plenum-rated communication cable (CMP); and (3) non-metallic sheathed low-voltage power cable as used in building wire (NM-B). These products were chosen by the project partners 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. In particular, this report focuses on lead-stabilized and lead-free cable constructions within each product type. For CMR, a zero-halogen cable also was examined, though the limited available data only allowed for a partial cradle-to-gate assessment.

A typical cable product consists of a wire conductor (typically copper) covered by insulation, and a jacket that encases the insulated wire(s). The resins used for the insulation of NM-B and for the jacketing of CMR, CMP, and NM-B cables are compounded with other materials, such as heat stabilizers and flame retardants, in order to meet performance specifications.

The goal of the WCP was to evaluate as many lead-free and halogen-free cables as possible for each of the three cable types. Project partners assisted in identifying the baseline and alternative cable constructions for the three different cable products. Table 2.1 lists the general characteristics and makeup of each cable type.

Functional Unit

In an 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 cables. The product systems evaluated in this project are baseline (i.e., leaded) and alternative (i.e., lead-free and zero-halogen) cable wire insulation and cable jacketing formulations, as used in telecommunication and low-voltage power cable installations in the United States. Each of the three cable types was evaluated in separate analyses, as each type has a different functionality. 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 Underwriters Laboratories (UL) performance requirements and fire safety specifications for each product type.

Table 2.1

Insulation and Jacketing Resins for Each Cable Evaluated in the WCP

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

[a] CMR and CMP wire conductors are unshielded twisted pairs, 8 conductors in 4 pairs of equal gauge bare copper; NM-B wire conductors are 12-gauge, 2-conductor copper with ground wire.
[b] High-density polyethylene.
[c] Polyvinyl chloride (PVC) is compounded with various additives, including heat stabilizers and flame retardants.
[d] 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.
[e] Proprietary.

Question 3:

How were environmental and health impacts evaluated?

The life-cycle environmental and health impacts of wires and cables were evaluated through two sequential phases: (1) life-cycle inventory and (2) life-cycle impact assessment.

Life-Cycle Inventory (LCI)

The LCI tallies the material and energy inputs and the environmental releases (collectively referred to as "flows") throughout the products' life cycles. Given the enormous amount of data involved in creating an inventory of all of the input and output flows for a product system, decision rules were used to determine which cable materials would be included as entire upstream processes. The decision rule process began by assessing the materials used in cable production for the following attributes:

- *The mass contribution of each material.* With a greater mass of materials and resources consumed, the potential for a material to have a significant environmental impact increases.

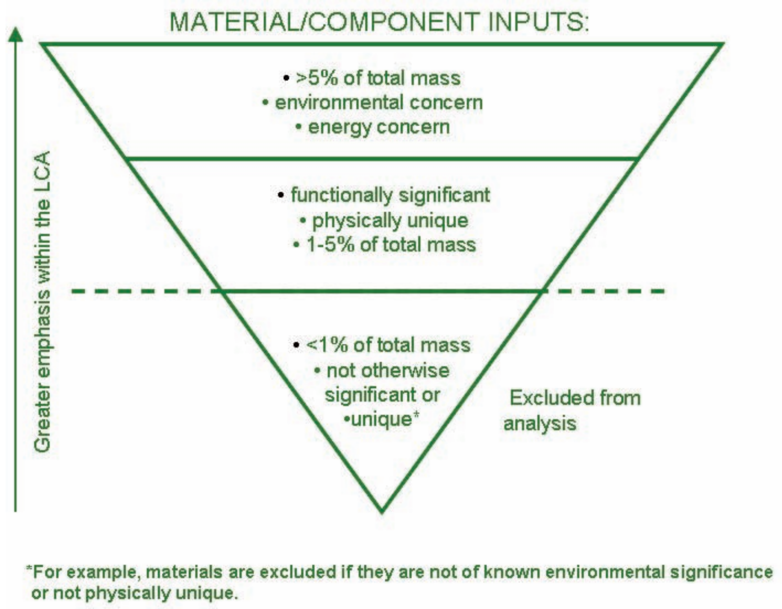
- *Materials that are of known or suspected environmental significance (e.g., toxic).* To the extent feasible, the process considers materials or components known or suspected to exhibit an environmental hazard.

- *Materials known or suspected to have a large contribution to the system's energy requirements.* Because many environmental impacts can be associated with energy consumption, priorities were given to including materials or processes that are known or suspected to consume large amounts of energy.

- *Materials which are physically or functionally unique to one cable formulation over another.* The physical or functional uniqueness of a material or component could be identified by chemical makeup or by size.

Attempts were made to include all materials greater than five percent by weight. Materials between one percent and five percent by mass were subject to inclusion based on other decision rules or data availability. Materials of known or suspected environmental or energy significance were also included, regardless of their mass contribution. Materials that are physically or functionally unique to a cable product compared to the baseline (leaded) construction, as determined by the Core Group,

Figure 3.1. Criteria for Selecting Inputs



are also considered if they would have been otherwise eliminated based on the mass cutoff. Figure 3.1 is a graphical representation of these decision rules.

In considering upstream materials, in addition to applying the decision rules, a combination of other factors was also considered, including availability of existing data and manufacturers' willingness to participate. When an inventory of a production process for a material identified by the decision rules could not be obtained, the material still remained in the inventory for the cable (what is not included are all the flows associated with producing that material).

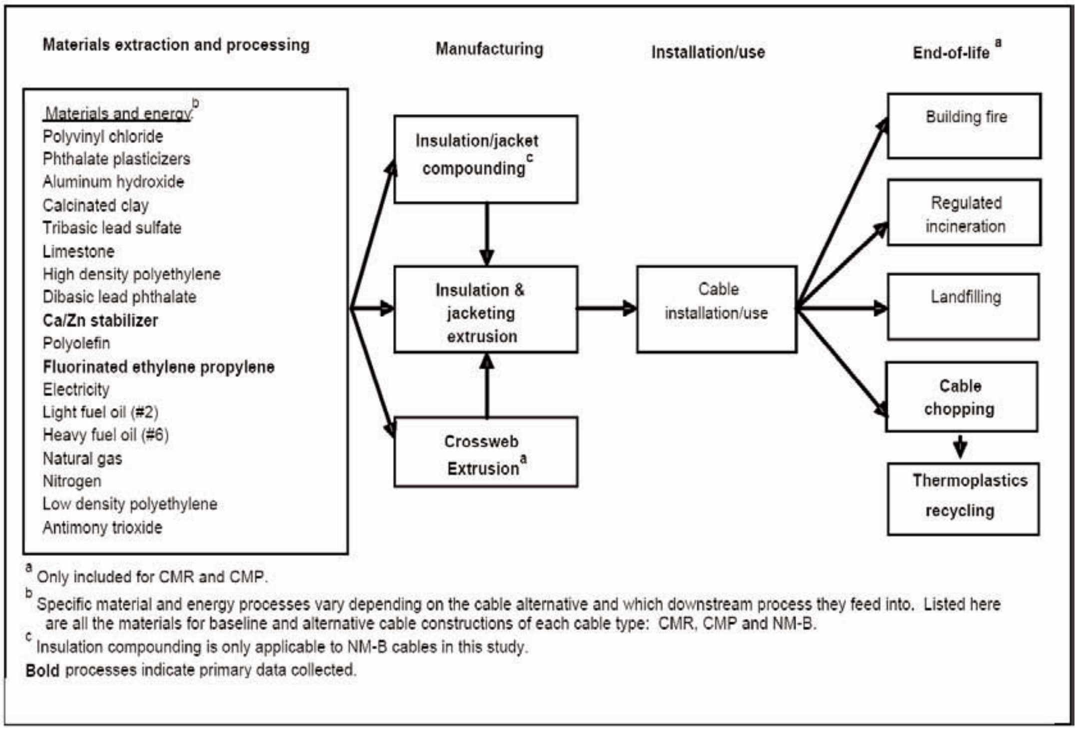
Based on the LCI data obtained for this study, 2 of the 4 analyses were based on the full life cycle: materials extraction ("upstream"), manufacturing, and end-of-life (EOL) stages. The remaining 2 analyses were based on only upstream and manufacturing stages:

- Full life cycle
  - Leaded and lead-free CMR Category 6 insulation and jacketing
  - Leaded and lead-free CMP Category 6 insulation and jacketing
- Partial life cycle
  - Leaded and lead-free vs. zero-halogen CMR Category 6 insulation and jacketing.
  - Leaded and lead-free NM-B power cable insulation and jacketing

The processes included in the full life-cycle analyses are presented in Figure 3.2. The processes in the partial life-cycle analyses are a subset of processes shown for the full life cycles.

Life-Cycle Impact Assessment (LCIA)

Figure 3.2 Generic Process Flows for All Cables Evaluated in the WCP



The LCIA is the process by which the environmental burdens identified in the LCI are translated into environmental impacts. It is important to note that direct comparisons cannot be made across impact categories, because impacts in different impact categories are generally calculated based on different scales. The WCP LCIA consisted of two steps: classification and characterization.

Classification – The process of assigning and aggregating data from inventory studies to impact categories. The WCP LCA places inventory data into one or more of 14 impact categories. These categories cover a range of effects that address natural resources impacts, abiotic ecosystem impacts, and human health and ecotoxicity.

Characterization – The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the WCP:

- Loading – An impact score is based on the inventory amount.
- Equivalency – An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical.
- Scoring of inherent properties – An impact score is based on the inventory

amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

Table 3.1 presents the 14 impact categories and a description of how each was calculated.

Table 3.1

Inventory Types and Properties for Classifying Inventory Items into Impact Categories

Impact Category	Inventory Properties		
	Input	Output	Chemical/Material Properties
Natural Resource Impacts			
Non-renewable resource use/depletion	Material, fuel	N/A	Non-renewable
Energy use	Electricity, fuel	N/A	Energy
Landfill space use (volume)	N/A	waste to landfill	Solid, hazardous, and radioactive waste
Abiotic Ecosystem Impacts			
Global warming	N/A	Air	Global warming gases
Stratospheric ozone depletion	N/A	Air	Ozone depleting substances
Photochemical smog	N/A	Air	Substances that can be photochemically oxidized
Acidification	N/A	Air	Substances that react to form hydrogen ions (H+)
Air particulates	N/A	Air	Air particulates (PM10, TSP)[a]
Water eutrophication (nutrient enrichment)	N/A	Water	Substances that contain available nitrogen or phosphorus
Human Health and Ecotoxicity			
Carcinogenic human health effects – occupational	Material	N/A	Toxic material (carcinogenic)
Carcinogenic human health effects – public	N/A	Air, soil, water	Toxic material (carcinogenic)
Chronic, non-carcinogenic human health effects – occupational	Material	N/A	Toxic material (non-carcinogenic)
Chronic, non-carcinogenic human health effects – public (and terrestrial ecotoxicity)	N/A	Air, soil, water	Toxic material (non-carcinogenic)
Aquatic ecotoxicity	N/A	Water	Toxic material

[a] Acronyms: particulate matter with average aerodynamic diameter less than 10 micrometers (PM10); total suspended particulates (TSP).
N/A=not applicable.

Question 4:

How was uncertainty in the wire and cable life cycle addressed?

Uncertainty Analysis

Four parameters within the life-cycle processes of the CMP and CMR cables were considered to be highly uncertain and were modeled as uniform distributions, using Monte Carlo statistical methods. These uncertainties only applied to the CMR and CMP analyses where the full life cycle was evaluated and where there was a large discrepancy in the extrusion energy data. The first three parameters below are from the EOL stage and the fourth is from the manufacturing stage.

- **Cable consumed in fire** – 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. The frequency of fires in buildings containing the cables of interest was well characterized, and the natural extreme bounds were that anywhere from 0% to 100% of the cable contained in these buildings would burn in the fire (equivalent to 0-1.1% of all cable installed). However, we chose 10% of cables that burn in a structure fire 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%.

- **Proportion of cable to recycling** – The percentage of cable insulation and jacketing resins going to recycling was another source of substantial uncertainty in the EOL stage. Using an upper estimate based on data from Europe (20% of recovered wire and cable resins are recycled), a range of 0% to 20% of the cable resins was modeled as being recycled.

- **Proportion of lead leached from landfills** – The parameter representing the percentage of lead leached into the ground assumed that 0-100% of the leachate would ultimately escape any landfill lining and leachate collection system (equivalent to 0-1.5% of total lead escaping for cable directly landfilled, or equivalent to 0-10% of total lead escaping for cable resins landfilled after chopping—a process that is used to recover the copper conductor).
- **Extrusion energy** – Inconsistent and highly divergent inter-company energy

values led to high uncertainty in the cable extrusion energy 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 baseline 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 baseline and lead-free cable extrusion inventories.

Sensitivity Analysis

The uncertainty of impact category results was a result of the concurrent variation of the four parameters. Therefore, a sensitivity analysis was necessary to assess the magnitude of each parameter's contribution. A built-in sensitivity analysis function from the GaBi4 LCA software was used to determine the amount of variance in each impact category attributable to each of the dynamic parameters.

Question 5:

What are the health and environmental impacts of baseline, lead-free, and zero-halogen CMR cables, and what drives the impacts?

This section presents the results for each impact category described in Question 3 for CMR cable. Although some LCAs assign importance ranks or weights to impact categories, this LCA does not, because ranking impact categories requires subjective choices that may not be appropriate for all stakeholders. The major focus was on the full life-cycle impacts of the baseline (lead-stabilized) cable and lead-free cable. A less comprehensive analysis was undertaken in the case of the partial life-cycle (or cradle-to-gate) impacts among the baseline, lead-free, and zero-halogen cables. Due to a lack of data, only the upstream energy use and resin production were modeled for the three cable types in the zero-halogen case.

Full Life Cycle: Baseline and Lead-Free

For each impact category, Table 5.1 presents life-cycle impact indicator scores for the baseline cable and the lead-free cable, the percent difference between the two cables, a data quality rating, and an indication of possible significance. Highlights from the results are as follows:

- The baseline cable had the greatest environmental burden (negative percent change) in 8 impact categories, 2 of which may be statistically significant.
- The lead-free cable had the greatest environmental burden (positive percent change) in 6 impact categories, 2 of which may be statistically significant.
- All 4 potentially significant differences were for toxicity impact categories.
- The 2 largest absolute percent changes (potential public non-cancer and potential aquatic ecotoxicity) are statistically significant, and showed a greater environmental burden for the baseline cable.

Figures 5.1 and 5.2 show the relative differences between baseline and lead-free

Table 5.1

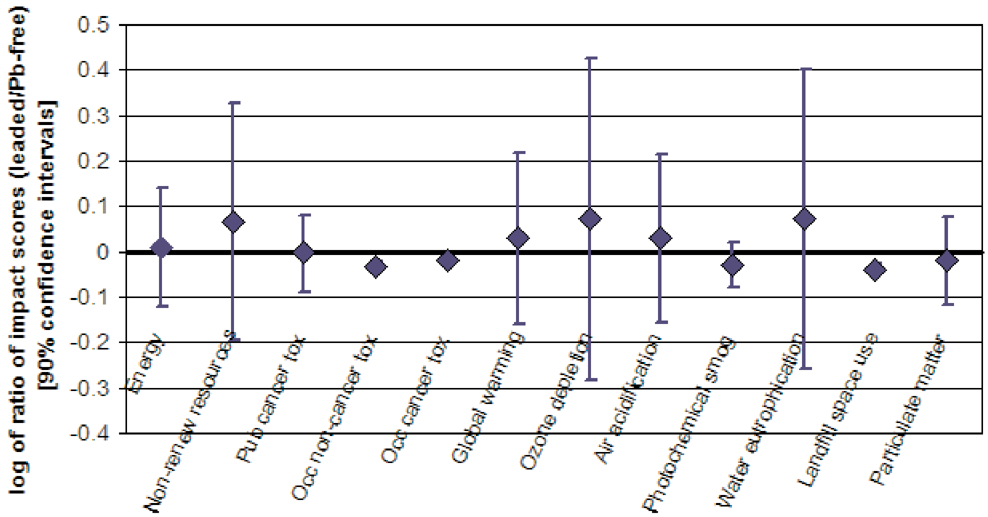
CMR LCIA Results – Full Life Cycle: Baseline and Lead-free.

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 cables were significantly different at 80% confidence (this confidence interval was used because it was part of a built-in program in GaBi4, the LCA software used for this project).
NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity.
NOTE: Bold indicates the cable with the greatest environmental burden within an impact category.

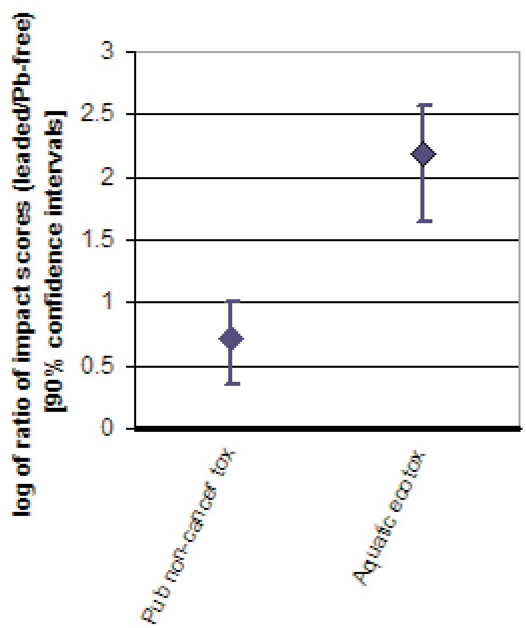
cables within the 14 environmental and human health impact categories presented in Table 5.1. The values in Figures 5.1 and 5.2 are the log of the ratio of the baseline cable impact score to that of the lead-free cable impact score. Positive log ratios indicate greater environmental burden for the baseline cable, and negative log ratios indicate greater environmental burden for the lead-free cable. Note that relative differences should only be examined within and not across impact categories because there is no association between relative differences in one category compared to that of another. Further, the relative differences depicted for each impact category are not normalized to indicate any significance of the impacts themselves; they only show the relative difference between the baseline and alternative cables.

Figure 5.1 Relative CMR Impacts: Baseline and Lead-free



NOTE: Log ratio > 0 indicates greater environmental burden for baseline cable; do not compare across impact categories.

Figure 5.2 Relative CMR Impacts: Baseline and Lead-free (Public Non-cancer and Ecotoxicity)



NOTE: Log ratio > 0 indicates greater environmental burden for baseline cable; do not compare across impact categories.

Which Processes Drive the Impact Scores?

A summary of the top contributing processes and material flows (i.e., input or output) for baseline and lead-free cables by impact category is presented in Table 5.2.

- For the baseline cable, electricity generation is the top contributing process for 6 of the 14 impact categories.
- For the lead-free cable, electricity generation is the top contributing process for 8 of the 14 impact categories.

Table 5.2

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

	Baseline		Pb-free	
Impact Category	**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)	Jacketing compounding	FR #2 (non-halogen)
Pot. occ. cancer	Jacketing compounding	Phthalates*	Jacketing compounding	Phthalates*
Pot. public noncancer	MSW landfill	Lead (water)	Electricity generation	Sulfur dioxide (air)
Pot. public cancer	Jacketing resin production	Nitrogen oxides (air)*	Jacketing resin production	Nitrogen oxides (air)*
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.
*Flows given default toxicity hazard values due to lack of toxicological data.

Natural Resource Impacts

Non-renewable resource use/depletion: Non-renewable natural resources are typically abiotic materials, such as mineral ore or fossil fuels. For both the baseline and lead-free cables, electricity generation contributes more than any other process to the non-renewable resource use impact category. Electricity generation contributes 74% of the total non-renewable resource use impact for the baseline cable and 71% for the lead-free cable. Inert rock is the top contributing material input flow for both cables, representing 60% of the impact for the baseline cable and 57% for the lead-free cable.

Energy use: Energy use impact scores are the sum of electrical and fuel energy inputs. The generation of electricity drives the impact for both baseline and lead-free cables, contributing 37% and 32% of the total energy use impact, respectively. Natural gas is the top contributing material flow for both cables, representing 29% of the impact for the baseline cable and 31% for the lead-free cable.

Landfill space use: Landfill space use impacts are calculated based on the volume of landfill space consumed by solid, hazardous, and/or radioactive waste. The municipal solid waste landfilling process dominates landfill space use impacts, contributing 76% of the total impact for both baseline and lead-free cables. PVC waste is the top contributing material flow for both cables, representing 46% of the impact for each cable.

Abiotic Ecosystem Impacts

Global warming: The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a global warming potential equivalency factor. The generation of electricity drives this impact category, contributing 56% of the total impact for the baseline cable, and 50% for the lead-free cable. Electricity generation produces considerable amounts of carbon dioxide, a global warming gas. Carbon dioxide is the top contributing material flow for both cables, representing 85% of the impact for the baseline cable and 83% for the lead-free cable.

Stratospheric ozone depletion: Ozone depletion impact scores are based on the identity and amount of ozone-depleting chemicals that are released to air. Electricity generation contributes 97% of the total impact for the baseline cable, and 95% for the lead-free cable. CFC-11 is the top contributing material flow for both cables, representing 44% of the impact for the baseline cable and 43% for the lead-free cable.

Photochemical smog: Photochemical smog refers to the release of chemicals that may react with sunlight in the atmosphere to produce photochemical oxidants, such as tropospheric ozone. The production of jacketing resin is the top contributor to the photochemical smog impact for both baseline and lead-free cables, contributing 45% and 50%, respectively, to the total impact. Unspecified volatile organic compounds (VOCs) are the top contributing material flow for both cables, representing 70% of the impact for the baseline cable and 74% for the lead-free cable.

Acidification: Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. The generation of electricity drives the acidification impact, contributing 56% and 49% of the total impact for baseline and lead-free cables, respectively. Sulfur dioxide is the top contributing material flow for both cables, representing 63% of the impact for the baseline cable and 60% for the lead-free cable.

Air particulates: Air particulate impacts are based on the amount of particulate matter with an average aerodynamic diameter less than 10 micrometers (PM10) that is released to the air. Jacketing resin production drives the air particulates impact, contributing 37% and 42% of the total impact for baseline and lead-free cables, respectively. Dust is the top contributing material flow for both cables, representing 99% of the impact for the baseline cable and 98% for the lead-free cable.

Water eutrophication (nutrient enrichment): Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. The generation of electricity drives the total impact, contributing 91% and 89% of the total impact for baseline and lead-free cables, respectively. Chemical oxygen demand is the top contributing material flow for both cables, representing 94% of the impact for the baseline cable and 93% for the lead-free cable.

Human Health and Ecotoxicity

Occupational health – potential non-cancer toxicity: Occupational impact scores are based on the potential toxicity of material *inputs* to each process. This characterization method does not necessarily indicate where actual exposure is occurring. Instead, it uses the inputs of potentially toxic materials as surrogates for exposure. The materials used during jacketing compounding drive potential non-cancer occupational health impacts, contributing 93% and 94% of the total impact for baseline and lead-free cables, respectively. A non-halogen flame retardant (proprietary) is the top contributing material flow for both cables, representing 89% of the impact for the baseline cable and 91% for the lead-free cable.

Occupational health – potential cancer toxicity: Materials used during jacketing compounding drive potential cancer occupational health impacts, contributing 95% and 84% to the total impact of baseline and lead-free cables, respectively. Unspecified phthalates are the top contributing material flow for both cables, representing 64% of the impact for the baseline cable and 62% for the lead-free cable. Unspecified phthalates, as a group, do not have specific toxicological data and therefore are characterized by a default toxicity hazard value, which assumes the toxicity is equivalent to the geometric mean of all chemicals used to determine the relative toxicity.

Public health – potential non-cancer toxicity: Impact scores are calculated based on the identity and amount of toxic chemical outputs with dispositions to air, soil, and water. Inventory items do not truly represent long-term exposure. Instead, impacts are relative toxicity weightings of the inventory. For the baseline cable, releases from landfilling municipal solid wastes are the greatest single contributor to potential non-cancer public health impacts, contributing 59% of the total impact. For the lead-free cable, emissions during electricity generation are the greatest single contributors to potential non-cancer public health impacts, contributing 58% of the total impact. Lead in water is the top contributing material flow for the baseline cable, representing 74% of the total impact. Sulfur dioxide is the top contributing material flow for the lead-free cable, representing 99% of the total impact.

Public health – potential cancer toxicity: Emissions from jacketing resin production drive the impact score for both baseline and lead-free cables. Jacketing resin production contributes 37% of the total impact for baseline cable, and 44% for lead-free cable. Nitrogen oxides (NOx) are the top contributing material flow for both cables, representing 41% of the impact for the baseline cable and 40% for the lead-free cable. NOx are characterized by a default toxicity hazard value.

Potential aquatic ecotoxicity: Potential aquatic ecotoxicity impacts refer to the effects of chemical outputs on non-human living organisms in freshwater aquatic ecosystems. Emissions from landfilling municipal solid wastes drive aquatic ecotoxicity impacts for baseline cables, contributing 79% of the total impact. Emissions from electricity generation drive potential aquatic ecotoxicity impacts for lead-free cables, contributing 77% of the total impact. Lead in water is the top contributing material flow for the baseline cable, representing 99% of the total impact. Dissolved chlorine is the top contributing material flow for the lead-free cable, representing 97% of the total impact.

Partial Life Cycle 3-Way Analysis: Baseline, Lead-Free, and Zero-Halogen
The 3-way CMR analysis (baseline versus lead-free versus zero-halogen) demonstrated that within the cradle-to-gate analysis, the zero-halogen cable used far more energy than the baseline or lead-free cable. This was a function of more energy required per mass of compounded resin produced, as well as the zero-halogen cable having a higher mass to length ratio. Thus, on a functional unit basis, the total energy requirement was much larger (quantities withheld for proprietary considerations). In the CMR 3-way results, the production of electricity drove most impact categories, except for landfill space use and potential occupational non-cancer and cancer toxicity, for which the jacketing process was the top contributor. For air particulate production, the lead and lead-free cables were driven by jacketing compounding, but the zero-halogen was driven by electricity production. Note that the robustness of these data is limited, as the zero-halogen data are only based on one company's data. Further, this analysis does not provide full life-cycle information and should not be construed to represent full life-cycle impacts.

These results also demonstrate that limiting the focus to a few manufacturing processes, even on a functionally equivalent basis, does not adequately estimate impacts over the full life cycle. This is evidenced by comparing the full CMR life-cycle analysis with the partial life-cycle analysis, which only takes into consideration jacketing compounding and associated energy. In the full life-cycle analysis, the lead-free cable had lower impact indicators than the baseline in 8 impact categories; however, for the partial analysis, only 1 category had lower impact indicators for the lead-free cable. Of the 5 categories in the full life-cycle analysis that had the greatest likelihood of statistically significant differences, 3 had results reversed in the partial life cycle (i.e., significantly less burden in the full life cycle versus more burden in the partial life cycle or vice versa): potential occupational cancer toxicity, potential public non-cancer toxicity, and potential aquatic ecotoxicity.

Question 6:

What are the health and environmental impacts of baseline and lead-free CMP cables, and what drives the impacts?

This section presents the results for each impact category described in Question 3 for CMP cable. Although some LCAs assign importance ranks or weights to impact categories, this LCA does not, because ranking impact categories requires subjective choices that might not be appropriate for all stakeholders.

For each impact category, Table 6.1 presents life-cycle impact indicator scores for the baseline and lead-free cables, the percent difference between the two cables, a data quality rating, and an indication of possible significance. Highlights from the results are as follows:

- The baseline cable had a greater environmental burden (negative percent change) for 12 impact categories, 4 of which may be statistically significant.

Table 6.1

CMP LCIA Results – Full Life Cycle: Baseline and Lead-free

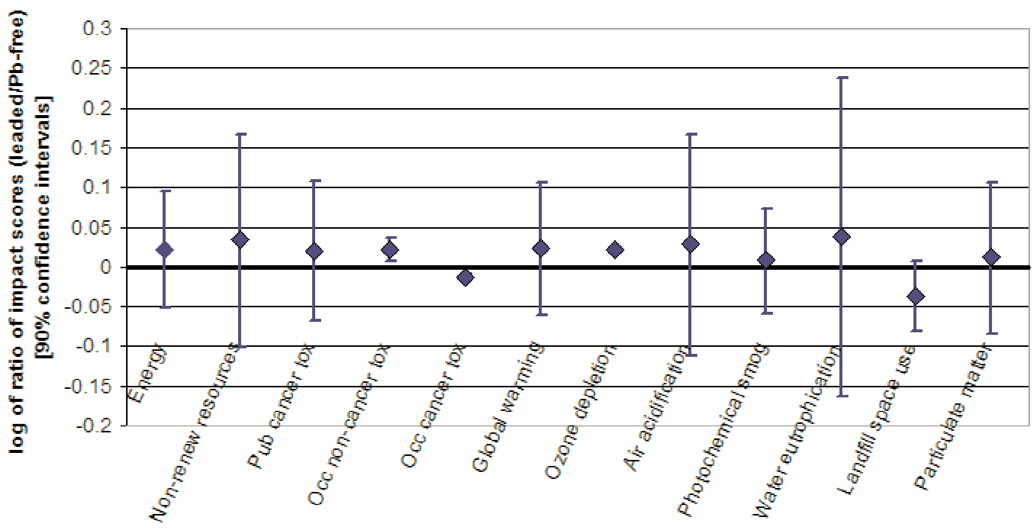
Impact Category	Units per km Cable	Baseline Impact Indicator	Pb-free Impact Indicator	Percent Change	Quality Rating	Possible Signif. Diff.[a]
NRR	Kg	**237**	219	-8%	M	
Energy	MJ	**3770**	3570	-5%	M	
Landfill space	m^3	0.0132	**0.0144**	9%	M	
Global warming	kg CO_2-equiv.	**181**	171	-5%	M	
Ozone depletion	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 cables were significantly different at 80% confidence (this confidence interval was used because it was part of a built-in program in GaBi4, the LCA software used for this project).
[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.
NOTE: Bold indicates the cable with the highest impact indicator score (i.e., greatest environmental burden) within an impact category.

- The lead-free cable had a greater environmental burden (positive percent change) for 2 impact category, one of which is statistically significant.
- Of the 5 impact categories with potential statistical significance, 4 were related to toxicity.
- The 2 largest absolute percent changes (potential public non-cancer and potential aquatic ecotoxicity) were statistically significant, and show a greater environmental burden for the baseline cable.

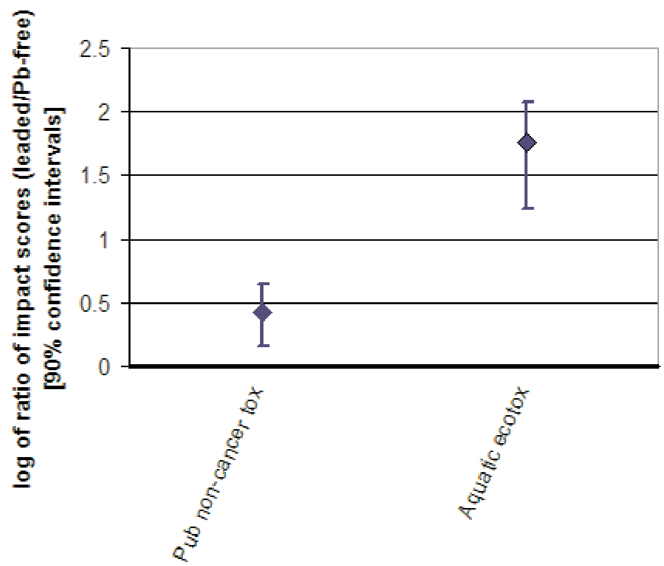
Figures 6.1 and 6.2 show the relative differences between baseline and lead-free cables within the 14 environmental and human health impact categories presented in Table 6.1. The values in Figures 6.1 and 6.2 are the log of the ratio of the baseline cable impact score to that of the lead-free cable impact score. Positive log ratios indicate greater environmental burden for the baseline cable, and negative log ratios indicate greater environmental burden for the lead-free cable. Note that relative differences should only be examined within and not across impact categories, because there is no association between relative differences in one category compared to that of another. Further, the relative differences depicted for each impact category are not normalized to indicate any significance of the impacts themselves; they only show the relative difference between the baseline and alternative cables.

Figure 6.1 Relative CMP Impacts: Baseline and Lead-free



NOTE: Log ratio > 0 indicates greater environmental burden for baseline cable; do not compare across impact categories.

Figure 6.2 Relative CMP Impacts: Baseline and Lead-free (Public Non-cancer and Ecotoxicity)



Which Processes Drive the Impact Scores?

A summary of the top contributing processes and material flows for baseline and lead-free cables by impact category is presented in Table 6.2.

- For the baseline cable, both insulation and jacketing resin production are the top contributing process for 3 of the 14 impact categories.

- For the lead-free cable, electricity generation is the top contributing processes for 5 of the 14 impact categories.

Natural Resource Impacts

Non-renewable resource use/depletion: Non-renewable natural resources are typically abiotic materials, such as mineral ore or fossil fuels. Electricity generation drives non-renewable resource use impacts, contributing 65% and 64% of the total impact for baseline and lead-free cables, respectively. Inert rock is the top contributing material flow for both cables, representing 52% of the total impact for each cable.

Energy use: Energy use impact scores are the sum of electrical and fuel energy inputs. Electricity generation drives energy use impacts, contributing 29% and 28% of the total impact for baseline and lead-free cables, respectively. Natural gas is the top contributing material flow for both cables, representing 60% of the total impact for each cable.

Table 6.2

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	Insulation resin production	Refrigerant #5
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	Natural gas production	Natural gas*	Natural gas production	Natural gas*
Pot. occ. cancer	Jacketing compounding	Flame retardant #3*	Jacketing compounding	Flame retardant #3*
Pot. public noncancer	MSW landfill	Lead (water)	Electricity generation	Sulfur dioxide (air)
Pot. public cancer	Jacketing resin production	Nitrogen oxides (air)*	Jacketing resin production	Nitrogen oxides (air)*
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.
*Flows given default toxicity hazard values due to lack of toxicological data.

Landfill space use: Landfill space use impacts are calculated based on the volume of landfill space consumed by solid, hazardous, and/or radioactive waste. The municipal solid waste landfilling process drives landfill space use impacts, contributing 66% and 69% of the total impact for baseline and lead-free cables, respectively. PVC waste is the top contributing material flow for both cables, representing 40% of the impact for the baseline cable and 42% for the lead-free cable.

Abiotic Ecosystem Impacts

Global warming: The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a global warming potential equivalency factor. For the baseline cable, electricity generation drives global warming impacts, contributing 74% of the total impact. For the lead-free cable, insulation resin production drives global warming impacts, contributing 68% of the total impact. Carbon dioxide is the top contributing material flow for both cables, representing 48% of the impact for the baseline cable and 47% for the lead-free cable.

Stratospheric ozone depletion: Ozone depletion impact scores are based on the identity and amount of ozone depleting chemicals that are released to air. Insulation resin production drives stratospheric ozone depletion impacts, contributing 88% and 87% of the total impact for baseline and lead-free cables, respectively. Refrigerant #5 is the top contributing material flow for both cables, representing 84% of the total impact for each cable.

Photochemical smog: Photochemical smog refers to the release of chemicals that may react with sunlight in the atmosphere to produce photochemical oxidants, such as tropospheric ozone. Jacketing resin production drives photochemical smog impacts, contributing 44% and 47% of the total impact for baseline and lead-free cables, respectively. Unspecified volatile organic compounds (VOCs) are the top contributing material flow for both cables, representing 43% of the impact for the baseline cable and 45% for the lead-free cable.

Acidification: Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Electricity generation drives acidification impacts, contributing 68% and 66% of the total impact for baseline and lead-free cables, respectively. Sulfur dioxide is the top contributing material flow for both cables, representing 65% of the impact for the baseline cable and 64% for the lead-free cable.

Air particulates: Air particulate impacts are based on the amount of particulate matter with an average aerodynamic diameter less than 10 micrometers (PM10) that is released to the air. Electricity generation drives air particulate impacts, contributing 47% and 44% of the total impact for baseline and lead-free cables, respectively. Dust is the top contributing material flow for both cables, representing 95% of the total impact for each cable.

Water eutrophication (nutrient enrichment): Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Electricity generation drives eutrophication impacts, contributing 96% of the total impact for both baseline and lead-free cables. Chemical oxygen demand is the top contributing material flow for both cables, representing 95% of the impact for the baseline cable and 94% for the lead-free cable.

Human Health and Ecotoxicity

Occupational health – potential non-cancer: Occupational impact scores are based on the potential toxicity of material inputs to each process. This characterization method does not necessarily indicate where actual exposure is occurring. Instead, it uses the inputs of potentially toxic materials as surrogates for exposure. Materials used during natural gas production drive potential non-cancer occupational health impacts, contributing 46% of the total impact for both baseline and lead-free cables. Natural gas is the top contributing material flow for both cables, representing 48% and 45% of the total impact for baseline and lead-free cables, respectively. Natural gas is characterized by a default toxicity hazard value.

Occupational health – potential cancer: Materials used during cable jacketing compounding drive potential cancer occupational health impacts, contributing 86% and 84% of the total impact for baseline and lead-free cables, respectively. Flame retardant #3, a proprietary material, is the top contributing material flow for both cables, representing 28% of the impact for the baseline cable and 29% for the lead-free cable. Flame retardant #3 is characterized by a default toxicity hazard value.

Public health – potential non-cancer: Impact scores are calculated based on the identity and amount of toxic chemical outputs with dispositions to air, soil, and water. Inventory items do not truly represent long-term exposure. Instead, impacts are relative toxicity weightings of the inventory. For the baseline cable, emissions from landfilling municipal solid waste drive potential non-cancer public health impacts, contributing 44% of the total impact. For lead-free cables, electricity generation drives potential non-cancer public health impacts, contributing 73% of the total impact. Lead in water is the top contributing material flow for the baseline cable, representing 56% of the total impact. Sulfur dioxide in air is the top contributing material flow for the lead-free cable, representing 98% of the total impact.

Public health – potential cancer: Electricity generation drives potential cancer public health impacts, contributing 44% and 42% of the total impact for baseline and lead-free cables, respectively. Nitrogen oxides (NOx) are the top contributing material flow for both cables, representing 44% of the total impact for each cable. Nitrogen oxides are characterized by a default toxicity hazard value.

Potential aquatic ecotoxicity: Potential aquatic ecotoxicity impacts refer to the effects of chemical outputs on non-human living organisms. For the baseline cable, emissions from landfilling municipal solid waste drives potential aquatic ecotoxicity impacts, contributing 78% of the total impact. For the lead-free cable, emissions from electricity generation drive potential aquatic ecotoxicity impacts, contributing 94% of the total impact. Lead in water is the top contributing material flow for the baseline cable, representing 98% of the total impact. Dissolved chlorine is the top contributing material flow for the lead-free cable, representing 81% of the total impact.

Question 7:

What are the health and environmental impacts of baseline and lead-free NM-B cables, and what drives the impacts?

This section presents the results for each impact category described in Question 3 for NM-B cable. The cradle-to-gate analysis examined only part of the cable life cycle, from material extraction to the compounding of the cable insulation and jacketing. Cable manufacturing (extrusion) was excluded as project researchers were unable to obtain a complete data set for this process. Subsequently, EOL could not be adequately modeled, because the output from cable manufacturing (extrusion) to EOL was not known. Although some LCAs assign importance ranks or weights to impact categories, this LCA does not, because ranking impact categories requires subjective choices that may not be appropriate for all stakeholders.

For each impact category, Table 7.1 presents life-cycle impact indicator scores for the baseline and lead-free cables, the percent difference between the two cables, and a data quality rating. Highlights from the results are as follows:

- The baseline cable has a greater environmental burden for 13 impact categories (negative percent change).
- The lead-free cable has a greater environmental burden for 1 impact category (positive percent change).

Table 7.1

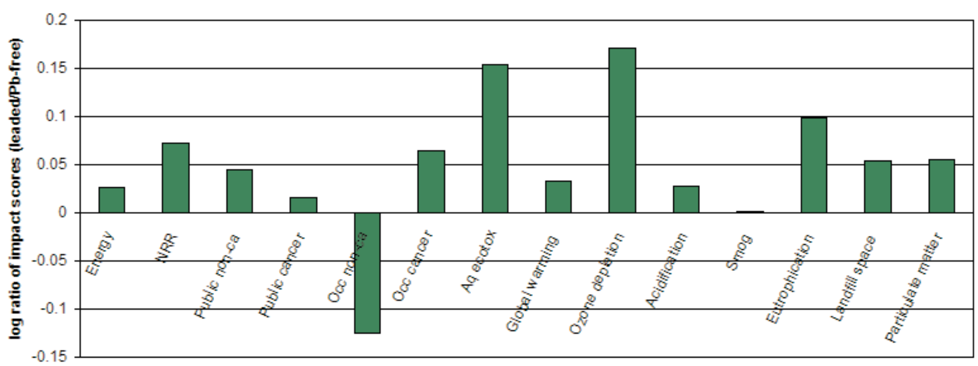
NM-B Results – Partial Life Cycle: Baseline and Lead-Free

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.
NOTE: Bold indicates the cable with the highest impact indicator score (i.e., greatest environmental burden) within an impact category.

Figure 7.1 displays the relative differences between baseline and lead-free cables within the 14 environmental and human health impact categories presented in Table 7.1. The values in Figure 7.1 are the log of the ratio of the baseline cable impact score to that of the lead-free cable impact score. Positive log ratios indicate greater environmental burden for the baseline cable, and negative log ratios indicate greater environmental burden for the lead-free cable. Note that relative differences should only be examined within and not across impact categories, because there is no association between relative differences in one category compared to that of another. Further, the relative differences depicted for each impact category are not normalized to indicate any significance of the impacts themselves; they only show the relative difference between the baseline and alternative cables.

Figure 7.1 Relative NM-B Impacts: Baseline and Lead-free (partial life cycle)



NOTE: Log ratio > 0 indicates greater environmental burden for baseline cable; do not compare across impact categories.

Which Processes Drive the Impact Scores?

A summary of the top contributing processes and material flows (i.e., input or output) for baseline and lead-free cables by impact category is presented in Table 7.2.

- For the baseline cable, jacketing resin production is the most frequent top contributor to impact categories (8 of 14 categories).
- the lead-free cable, jacketing resin production is the most frequent top contributor to impact categories (8 of 14 categories).

Table 7.2

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)	Insulation compounding	FR #2 (non-halogen)
Pot. Occ. cancer	Jacketing compounding	Plasticizer #2*	Jacketing compounding	Phthalate plasticizer #5*
Pot. Public noncancer	Jacketing resin production	Sulfur dioxide (air)	Jacketing resin production	Sulfur dioxide (air)
Pot. Public cancer	Jacketing resin production	Nitrogen oxides (air)*	Jacketing resin production	VOC (unspecified) (air)*
Pot. Aq. ecotox	Plasticizer production	Copper (+1, +2)	Plasticizer 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.
*Flows given default toxicity hazard values due to lack of toxicological data.

Natural Resource Impacts

Non-renewable resource use/depletion: Non-renewable natural resources are typically abiotic materials, such as mineral ore or fossil fuels. Jacketing resin production drives non-renewable resource use and depletion, contributing 39% and 47% of the total impact for baseline and lead-free cables, respectively. Inert rock is the top contributing material flow for the baseline cable, representing 22% of the total impact. Natural gas is the top contributing material flow for the lead-free cable, also representing 22% of the total impact.

Energy use: Energy use impact scores are the sum of electrical and fuel energy inputs. Jacketing resin production drives energy use impacts, contributing 56% and 60% of the total impact for baseline and lead-free cables, respectively. Natural gas is the top contributing material flow for both cables, representing 42% of the impact for the baseline cable and 43% of the impact for the lead-free cable.

Landfill space use: Landfill space use impacts are calculated based on the volume of landfill space consumed by solid, hazardous, and/or radioactive waste. Limestone production drives landfill space use impacts, contributing 64% of the total impact for both baseline and lead-free cables. Treatment residue is the top contributing material flow for both cables, representing 66% of the impact for the baseline cable and 64% of the impact for the lead-free cable.

Abiotic Ecosystem Impacts

Global warming: The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a global warming potential equivalency factor. Jacketing resin production drives global warming impacts, contributing 57% and 62% of the total impact for baseline and lead-free cables, respectively. Carbon dioxide is the top contributing material flow for both cables, representing 89% of the total impact for each cable.

Stratospheric ozone depletion: Ozone depletion impact scores are based on the identity and amount of ozone depleting chemicals that are released to air. Electricity generation drives stratospheric ozone depletion impacts, contributing 77% and 81% of the total impact for baseline and lead-free cables, respectively. CFC-11 is the top contributing material flow for both cables, representing 44% of the impact for the baseline cable and 45% of the impact for the lead-free cable.

Photochemical smog: Photochemical smog refers to the release of chemicals that may react with sunlight in the atmosphere to produce photochemical oxidants, such as tropospheric ozone. Jacketing resin production drives photochemical smog impacts, contributing 91% and 93% of the total impacts for baseline and lead-free cables, respectively. Unspecified volatile organic compounds (VOCs) are the top contributing material flow for both cables, representing 77% of the impact for the baseline cable and 79% of the impact for the lead-free cable.

Acidification: Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Jacketing resin production drives acidification impacts, contributing 71% and 77% of the total impacts for baseline and lead-free cables, respectively. Sulfur dioxide is the top contributing material flow for both cables, representing 58% of the impact for the baseline cable and 56% of the impact for the lead-free cable.

Air particulates: Air particulate impacts are based on the amount of particulate matter with an average aerodynamic diameter less than 10 micrometers (PM10) that is released to the air. Jacketing resin production drives air particulate impacts, contributing 65% and 75% of the total impacts for baseline and lead-free cables, respectively. Dust is the top contributing material flow for both cables, representing 93% of the impact for the baseline cable and >99% of the impact for the lead-free cable.

Water eutrophication (nutrient enrichment): Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Electricity generation drives water eutrophication impacts, contributing 64% and 57% of the total impacts for baseline and lead-free cables, respectively. Chemical oxygen demand is the top contributing material flow for both cables, representing 88% of the impact for the baseline cable and 86% of the impact for the lead-free cable.

Human Health and Ecotoxicity

Occupational health – potential non-cancer: Occupational impact scores are based on the potential toxicity of material inputs to each process. This characterization method does not necessarily indicate where actual exposure is occurring. Instead, it uses the inputs of potentially toxic materials as surrogates for exposure. Insulation compounding drives potential non-cancer occupational health impacts, contributing 64% and 54% of the total impacts for baseline and lead-free cables, respectively. Flame retardant #2 is the top contributing material flow for both cables, representing 58% of the impact for the baseline cable and 54% of the impact for the lead- free cable.

Occupational health – potential cancer: Jacketing compounding drives potential cancer occupational health impacts, contributing 85% and 94% of the total impacts for baseline and lead-free cables, respectively. Phthalate plasticizer #2 is the top contributing material flow for the baseline cable, representing 81% of the total impact. Phthalate plasticizer #5 is the top contributing material flow for the lead-free cable, representing 92% of the total impact. Both phthalate plasticizers are characterized by default toxicity hazard values.

Public health – potential non-cancer: Impact scores are calculated based on the identity and amount of toxic chemical outputs with dispositions to air, soil, and water. Inventory items do not truly represent long-term exposure. Instead, impacts are relative toxicity weightings of the inventory. Jacketing resin production drives potential non-cancer public health impacts, contributing 67% and 75% of the total impacts, respectively, for baseline and lead-free cables. Sulfur dioxide is the top contributing material flow for both cables, representing 98% of the impact for the baseline cable and 99% of the impact for the lead-free cable.

Public health – potential cancer: Jacketing resin production drives potential cancer public health impacts, contributing 64% and 57% of the total impacts, respectively, for baseline and lead-free cables. Nitrogen oxides (NOx) are the top contributing material flows for the baseline cable, representing 34% of the total impact. Unspecified volatile organic compounds (VOCs) are the top contributing material flows for the lead-free cable, representing 35% of the total impact. Both NOx and unspecified VOCs are characterized by default toxicity hazard values.

Potential aquatic ecotoxicity: Potential aquatic ecotoxicity impacts refer to the effects of chemical outputs on non-human living organisms. Plasticizer production drives potential aquatic ecotoxicity impacts, contributing 51% and 81% of the total impacts, respectively, for baseline and lead-free cables. Copper +1 and +2 ions are the top contributing material flow for both cables, representing 46% of the impact for the baseline cable and 62% of the impact for the lead-free cable.

Question 8:

Overall, where are the greatest potential health and environmental impacts?

CMR

The point estimate results from the CMR impact assessment showed mixed results for both baseline and lead-free cable types, though the disparities between the cable impact scores for most impact categories were minimal (Table 5.1). 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 impact uncertainty. In other words, overlap of the 10th and 90th percentiles eliminated the possibility of statistically significant differences. Two categories—potential public chronic non-cancer toxicity and potential aquatic ecotoxicity—had less environmental burden for the lead-free cable and did not have overlapping uncertainty ranges. Of the six categories that showed lower burdens for the baseline cable, only two did not have overlapping results due to uncertainty: potential occupational cancer and non-cancer toxicity. The following processes were the top contributors to a majority of the impact categories for the CMR cables evaluated in this study (see Table 8.1):

- Electricity Generation – Electricity generation was the top contributing process in the baseline cable life cycle for 6 impact categories: non-renewable resource use, energy use, global warming, ozone depletion, air acidification, and eutrophication. For the lead-free cable, the generation of electricity for cable extrusion was the top contributing process for the same 6 impact categories, in addition to being the top contributor to the potential public non-cancer toxicity and potential aquatic toxicity impact categories.

- Resin Production and Compounding – For both cables, jacketing resin production was the top contributing process for the photochemical smog formation, air particulates, and potential public cancer toxicity impact categories. The compounding of the jacketing was the top contributing process to the potential occupational non-cancer and cancer toxicity impact categories for both cables]

- Landfilling – Municipal solid waste landfilling was the top contributing process to the potential public non-cancer toxicity and potential aquatic ecotoxicity impact categories in the baseline case. Lead from landfilling was the top flow contributing to the potential public non-cancer toxicity and potential aquatic ecotoxicity impact categories. Landfilling was not a top contributor to any of the impact categories for the lead-free cable.

These results help to identify potential areas of environmental improvement. However, it must be noted that the results of this study are in the context of examining the relative differences of resin systems and their additives. Therefore, focusing solely on the top contributors identified here does not provide complete life-cycle impacts from the entire cable (e.g., impacts associated with the copper conductor were not examined in this study).

The point-estimate results from the cradle-to-gate analyses of the baseline, lead-free, and zero-halogen CMR cables showed that the zero-halogen cable had far greater environmental burden in all of the impact categories, except for potential occupational non-cancer toxicity. These results were not presented with the same level of detail as the other results, because the available upstream data for the halogen-free cable only allowed for the modeling of the upstream energy production and jacketing compounding processes. Since the cable manufacturing (extrusion) process was not included, this also precluded having data for downstream EOL processes.

CMP

The point estimates from the CMP cable analyses showed that all impact categories, except for potential occupational cancer toxicity and landfill space use, had fewer impacts (i.e., less environmental burden) for the lead-free cable than for the baseline cables. However, only four of these impact categories — potential occupational non-cancer toxicity, potential public chronic non-cancer toxicity, potential aquatic ecotoxicity, and ozone depletion — did not have overlapping 10th and 90th uncertainty ranges, suggesting greater confidence in these results. The following processes were the top contributors to a majority of the impact categories evaluated in this study (see Table 8.1):

- Resin Production – The production of jacketing (PVC) and insulation (FEP) resins were top contributors to 3 impact categories each. For both baseline and lead-free cables, the production of the jacketing resin, PVC, was the top contributing process for the photochemical smog formation, air particulates, and potential public cancer toxicity impact categories, for which unspecified VOCs were the top contributing flow. The production of FEP was the top contributing process to energy use, global warming, and ozone depletion.

- **Electricity Generation** – The generation of electricity for cable extrusion was another major contributing process to both cables. In the case of the baseline cable, electricity generation was the top contributing process for the non-renewable resources, air acidification, and eutrophication impact categories. In the case of the lead-free cable, electricity generation was the top contributor to the same impact categories, as well as to the potential public non-cancer toxicity and potential aquatic ecotoxicity impact categories.

- **Landfilling** – For the baseline CMP cable, the top contributing process to the potential public non-cancer toxicity and potential aquatic ecotoxicity impact categories was municipal solid waste landfilling. For both of these categories, the top contributor was lead, which was assumed to leach from the landfill into groundwater. For both cables, the landfill space use impact category was also dominated by the municipal solid waste landfilling process.

These results help to identify potential areas of environmental improvement. However, it must be noted that the results of this study are in the context of examining the relative differences of resin systems and their additives. Therefore, focusing solely on the top contributors identified here does not provide complete life-cycle impacts for the entire cable (e.g., impacts associated with the copper conductor were not examined in thisstudy).

NM-B

The point estimates from the NM-B cradle-to-gate cable comparisons showed that all categories, except for potential occupational non-cancer toxicity, had fewer impacts for the lead-free cables than for the baseline cables. No uncertainty or sensitivity analyses were run for this comparison because both cable extrusion and the end-of-life stages were excluded from the analyses due to lack of data, and those stages were the only ones in which there were large uncertainties.

In the NM-B analysis, which excludes the extrusion process and subsequent downstream processes, the production of the jacketing resin, PVC, is the top contributor to eight impact categories. It is followed by electricity generation from compounding (2 categories), then limestone production (1 category), insulation compounding (1 category), jacketing compounding (1 category), and phthalate production (1 category) (see Table 8-1). These results identify processes that could be the focus of environmental improvement opportunities for upstream and cable insulation compounding processes. However, it must be noted that these results are in the context of examining the relative differences of resin systems and their additives. Focusing solely on the top contributors identified here does not provide complete life-cycle impacts for the entire cable (e.g., impacts associated with the copper conductor were not examined in this study).

Table 8.1

Top Contributing Processes: CMR and CMP Full, and NM-B Partial Life Cycle[a]

Process	CMR		CMP		NM-B	
	Baseline	Lead-free	Baseline	Lead-free	Baseline	Lead-free
Electricity generation	6	8	3	5	2	2
Natural gas production	0	0	1	1	0	0
Jacketing/insulation[b]	5	5	7	7	10	10
Jacketing additive prod.	0	0	0	0	2[c]	2[c]
MSW landfilling[d]	3	1	3	1	N/A[e]	N/A[e]
Total impact categories	14	14	14	14	14	14

[a] Number of impact categories for which the specified process is the top contributor
[b] Includes jacketing and insulation resin production as well as jacketing and insulation compounding
[c] The two processes for jacketing additive production in the NM-B analysis were limestone production and phthalate production.
[d] MSW = municipal solid waste;
[e] Modeling of the NM-B cable did not include end-of-life disposition

Question 9:
What are the limitations of the study?

LCA Limitations and Data Uncertainties

LCI

Uncertainty in the inventory data depends on how the data are characterized by submitters, and other limitations identified during inventory data collection. These uncertainties are carried into the impact assessment. Uncertainties in the inventory data include, but are not limited to, the following:

- missing individual inventory items;
- missing processes or sets of data;
- estimation uncertainty;
- allocation uncertainty/working with aggregated data; and
- unspeciated chemical data.

In general, the number of primary data sets available for the upstream and manufacturing processes was quite limited. The greatest number of data sets collected for a particular process was three (e.g., CMR jacketing compounding). Where primary data could not be obtained, secondary data were used for some of the upstream processes. Further investigation into the proportion of the market modeled in this LCA is necessary in order to understand the potential magnitude of the uncertainty in the material and energy inputs derived from primary and secondary data used in this study.

Additionally, the full life cycle was not included in the NM-B analysis due to lack of available data. Lacking the full life-cycle inventory for the NM-B cable type, it is difficult to predict how the partial life-cycle impacts would compare to a full life cycle. The partial life-cycle results can, however, inform decisions about material and energy use during the cable insulation and jacketing compounding processes.

Sensitivity Analysis

The sensitivity analysis was used to probe the contributions to overall impact uncertainty from each of the stochastic parameters (see Question 4). Results of the analysis, shown in Table 9.1, give the largest contributing parameter along with the percent variance in the impact result attributable to this dominant parameter. It is evident that one parameter—the energy used for cable extrusion—is responsible for most of the variation in impacts for each cable type. However, for the CMR and CMP baseline cables, the uncertainty in the potential public chronic non-cancer toxicity and the potential aquatic ecotoxicity categories are dominated by the landfill leachate parameter. For all cables, thermoplastic recycling dominates the landfill space use indicators. The sensitivity analysis results showed that most categories were not greatly affected by the EOL assumptions, especially the proportion of cable destroyed in building fires.

Table 9.1

LCIA Sensitivity Analysis Results [a,b]

	Parameter that dominates the uncertainty (% contribution)			
	CMR		CMP	
Impact Category	Baseline	Lead-free	Baseline	Lead-free
NRR	Energy (98)	Energy (98)	Energy (98)	Energy (97)
Energy	Energy (>50)[c]	Energy (>50)[c]	Energy (>50)[c]	Energy (>50)[c]
Landfill space	Recycle (63)	Recycle (65)	Recycle (88)	Recycle (86)
Global warming	Energy (98)	Energy (97)	Energy (99)	Energy (98)
Ozone depletion	Energy (98)	Energy (98)	Energy (98)	Energy (98)
Smog	Energy (99)	Energy (99)	Energy (99)	Energy (99)
Acidification	Energy (94)	Energy (92)	Energy (92)	Energy (92)
Air particulates	Energy (98)	Energy (98)	Energy (98)	Energy (98)
Eutrophication	Energy (98)	Energy (98)	Energy (98)	Energy (98)
Pot. Occ. non-ca	Energy (97)	Energy (96)	Energy (96)	Energy (95)
Pot. Occ. cancer	Energy (98)	Energy (97)	Energy (97)	Energy (97)
Pot. Public non-ca	Landfill (83)	Energy (98)	Landfill (78)	Energy (97)
Pot. Public cancer	Energy (86)	Energy (96)	Energy (90)	Energy (96)
Pot. Aq. ecotox	Landfill (90)	Energy (98)	Landfill (90)	Energy (98)

[a] Results are reported as the dominant parameter (percentage of the overall impact result variance for which it is responsible).
[b] Energy = Variance of extrusion energy; Recycle = Percentage of cable going to thermoplastics recycling; Landfill = percentage of lead lost from landfill; NRR = non-renewable resource use; Pot. = potential; Occ. = occupational; Aq. ecotox = aquatic ecotoxicity.
[c] Actual percentage withheld to protect confidentiality.

LCIA

Some of the limitations and uncertainties in the LCIA derive from limitations and uncertainties in the inventory stage; however, many are unique to the LCIA. The limitations and uncertainties associated with the LCIA include but are not limited to

- **Lack of Spatial and Temporal Relationships** – The purpose of an LCIA is to evaluate the relative potential impacts of a product system for various impact categories. There is no intent to measure the actual impacts or to provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts.

- **Impact Score Parameter Uncertainty** – Uncertainties are inherent in the parameters used to calculate the various impact scores. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects), resulting in a high degree of uncertainty. Sources for each type of data should be consulted for more information on uncertainties specific to each parameter.

- **Chemical Ranking/Scoring System Uncertainty** – Uncertainties exist in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk.

- **Chronic Toxicity Endpoint Uncertainty** – Uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case.

- **Screening Level Tool for Chemical Risk** – The human health and ecotoxicity impact characterization methods presented in the WCP LCIA are screening tools that cannot substitute for more detailed risk characterization methods; however, the methodology is an attempt to consider chemical toxicity at a screening level for identifying potentially toxic materials in the inventory.

Due to the limitations in the LCI data, no category was given a "high" relative quality rating (see Tables 5.1, 6.1, and 7.1). In addition to LCI uncertainty, LCIA uncertainty contributes to the overall limitations. The categories with greater model and data uncertainty in the LCIA were given "medium" to "low" ratings. For example, the potential cancer impact category results were mostly based on materials that lack data on carcinogenicity rather than being based on known carcinogens. Also, as specific gaps in data contributing to stratospheric ozone depletion were identified, this category was given a "low" rating. This was due to the lack of information on the generation and emission of brominated organic byproducts during brominated phthalate production. Finally, the toxicity-based impact categories use inputs or outputs as surrogates for exposure and do not model fate and transport and actual exposure. This could be the subject of further analysis, such as a targeted risk assessment.

Question 10:
What can wire and cable suppliers, manufacturers, and waste managers do to reduce environmental impacts?

This section identifies selected opportunities for reducing the overall environmental and human health impacts of jacketing and insulation of communication cable products, based on the results of the full life-cycle LCA results (CMR and CMP lead and lead-free analyses). Opportunities for improvement are broken down into three categories: upstream material production and use, electricity generation, and end-of-life disposition.

Upstream Materials

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).

Lead Heat Stabilizers

Lead byproducts that originate in the baseline cable heat-stabilizers are responsible for much of the potential public non-cancer toxicity and potential aquatic ecotoxicity burdens for both CMR and CMP baseline cables. This is the most substantive difference between the baseline and lead-free cables with regards to any of the impact categories. While there was confidence in the observed difference between the leaded and lead-free cables, the absolute scores of each are dependent on parameters that have not been well studied, such as the proportion of lead that leaches out of landfilled resins and landfill failure rates. Attempting to understand the potential hazards inherent in the use of lead stabilizers is important for stakeholders; however, this study cannot provide definitive findings about actual risk or relative risk between baseline and alternative cables. Because the environmental impacts resulting from the use of lead heat stabilizers are seen primarily at the product EOL, they are discussed further in the EOL disposition section below.

Jacketing and Insulation Resins

The manufacture of jacketing and insulation resins contributes substantially to a number of impact categories in both CMR and CMP cables, including energy use and non-renewable resources, potential public cancer toxicity (NOx and VOC production), potential occupational non-cancer toxicity (potentially toxic chemicals used in jacketing/insulation resin production), air acidification, air particulate production, and photochemical smog production. Increasing the energy-efficiency of resin production, and reducing or capturing air emissions is likely to reduce the overall environmental burden. The use of alternative input materials during jacketing and insulation resin production might reduce overall environmental burden. However, in order to determine if this is the case, the life cycle analysis would have to be rerun, substituting the new, less toxic materials.

Phthalates

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. Due to phthalates' affinity for lipids, exposure in workers could potentially result in bioaccumulation over time. Though the issue of whether certain phthalates function as carcinogens has not been entirely resolved, the monitoring of worker cohorts for phthalate body burden and the minimization of direct contact with this suite of chemicals may be advantageous.

Elecricity Generation

Electricity generation throughout the wire and cable life cycle, particularly 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 cables, 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 cables, 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 9.1) revealed that the large impact uncertainty ranges for both the CMR and CMP cables 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, which were dominated by leachate uncertainty in the baseline cable, and landfill space use, where the percentage of resins recycled after chopping had a greater effect on the results for both cable types. The range of extrusion energy, modeled using a uniform uncertainty distribution, was quite large (>50% 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 many of the environmental and human health impact scores for wire and cable products.

EOL Disposition

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 kg noncancertox-equivalent; CMP: 952 versus 358 kg noncancertox-equivalent) and potential aquatic ecotoxicity impacts (CMR: 17.5 versus 0.113 kg aqtox-equivalent; CMP: 8.64 versus 0.151 kg aqtox-equivalent), with the lead-free cables displaying much lower impacts in these categories. The sensitivity analysis demonstrated 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 of exposure and risk of lead leachate from the landfill.

Beyond the issue of lead, 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 potential hazards beyond that of lead. 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 can be problematic from a public health standpoint. Thermoplastic recycling is energy-intensive and creates new waste streams, which must then be landfilled. 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 cables 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.