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

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## For More Information

To learn more about the Design for the Environment (DfE) Wire and Cable Partnership or the DfE Program, please visit the DfE Program web site at: www.epa.gov/dfe.

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# Acronyms and Abbreviations

| | |
|---|---|
| ACC | American Chemistry Council |
| AP | acidification potentials |
| APME | Association of Plastics Manufacturers in Europe (now PlasticsEurope) |
| ATH | Aluminum trihydrate |
| ATO | antimony trioxide |
| AWG | American Wire Gauge |
| BIR | Bureau of International Recycling |
| BOD | biological oxygen demand |
| BOM | bills of materials |
| BUWAL | Swiss Agency for the Environment, Forests and Landscape |
| C&D | construction and demolition |
| CAAA | Clean Air Act Amendments |
| CEREMAP | Center for Research into Plastic Materials |
| CFC | chlorofluorocarbon |
| CHAMP | Chain Management of Materials and Products |
| CHEMS-1 | Chemical Hazard Evaluation Management Strategies |
| CMP | plenum-rated communication wire |
| CMR | riser-rated communication wire |
| DEHP | di-2-ethylhexylphthalate |
| DfE | Design for the Environment |
| DHHS | Department of Health and Human Services |
| DIDP | diisodecyl phthalate |
| DINP | diisononyl phthalate |
| DOP | dioctylphthalate |
| DQI | data quality indicators |
| EOL | end-of-life |
| EP | eutrophication potential |
| EVA | ethylene vinyl acetate |
| FCM | Farrell Continuous Mixer |
| FEP | fluorinated ethylene propylene |
| FRPE | flame retardant polyethylene |
| GWP | global warming potential |
| HAZMAT | hazardous materials |
| HCFC | hydrochlorofluorocarbon |
| HDPE | high-density polyethylene |
| HEAST | Health Effects Assessment Summary Tables |
| HFP | hexafluoropropylene |
| HSDB | Hazardous Substances Data Bank |
| HV | hazard value |
| IARC | International Agency for Research on Cancer |
| ICEA | Insulated Cable Engineers Association |
| TIA/EIA | Telecommunications Industry Association/Electronics Industry Alliance |
| IRIS | Integrated Risk Information System |

| | |
|---|---|
| ISO | International Organization for Standardization |
| LC | limited combustible |
| LCA | life-cycle assessment |
| LCI | life-cycle inventory |
| LCIA | life-cycle impact analysis |
| LNG | liquefied natural gas |
| LOAEL | lowest-observed-adverse-effect level |
| LSF | low smoke and flame |
| ME&P | material extraction and processing |
| MITI | Ministry of International Trade and Industry |
| MJ | megajoule |
| MSW | municipal solid waste |
| NEC | National Electrical Code |
| NEMA | National Electrical Manufacturers Association |
| NFPA | National Fire Protection Association |
| NM-B | non-metallic sheathed low-voltage power cable |
| NOAEL | no-observed-adverse-effect level |
| NOEC | no-observed-effect concentration |
| NOEL | no-observed-effect level |
| NRR | non-renewable resource |
| OD | ozone depletion |
| ODP | ozone depletion potential |
| OEM | original equipment manufacturer |
| OPPT | Office of Pollution Prevention and Toxics |
| PAN | phthalic anhydride |
| PCB | printed circuit board |
| PE | polyethylene |
| PET | polyethylene terephthalate |
| PFOA | perfluorooctanoic acid |
| PFP | Perfluoropolymer |
| PM | particulate matter |
| POCP | Photochemical oxidant creation potential |
| POP | persistent organic pollutants |
| POTW | publicly-owned treatment works |
| Prop65 | California Proposition 65 |
| PTFE | polytetrafluoroethylene |
| PVC | polyvinyl chloride |
| PVDF | polyvinylidene fluoride |
| QSAR | quantitative structure-activity relationship |
| RAIS | Risk Assessment Information System |
| RCRA | Resource Conservation and Recovery Act |
| RoHS | Restriction of Hazardous Substances |
| RTECS | Registry of Toxic Effects of Chemical Substances |
| SAR | structure-activity relationship |
| SETAC | Society of Environmental Toxicology and Chemistry |
| SF | slope factor |

| | |
|---|---|
| TFE | tetrafluoroethylene |
| TRI | Toxics Release Inventory |
| TSP | total suspended particulates |
| TSS | total suspended solids |
| TURI | Toxics Use Reduction Institute |
| UL | Underwriters Laboratories Inc. |
| UTP | unshielded twisted pair |
| VOC | volatile organic compounds |
| WCP | Wire and Cable Project |
| WOE | weight of evidence |
| WTE | Waste-to-energy |

# Abstract

This report presents comparative environmental life-cycle assessment (LCA) results, pursuant to International Organization for Standardization (ISO) 14040, for resin systems with alternative heat stabilizer formulations used in Category 6, riser-rated communication cable (CMR); Category 6, plenum-rated communication cable (CMP); and non-metallic-sheathed low-voltage cable (NM-B). Based on primary and secondary data that span the wire and cable life-cycle stages from upstream material extraction and processing to the product end-of-life (EOL), this report presents impact results for 14 environmental and human health categories. Monte Carlo-based uncertainty analyses, which attempt to model the major sources of uncertainty in the wire and cable life cycle, are presented, along with sensitivity analyses that investigate the proportion of impact category uncertainty attributable to each source.

For all three classes of cable, upstream material production and use, generation of electricity, and the recycling or disposal of used cable at the EOL (the last only being applicable to CMR and CMP) play important roles in overall environmental burden. Energy use during cable manufacturing and the leaching of lead from landfills are the most important sources of uncertainty in impact results and, in combination with the production of insulation and jacketing resins, are the top contributors to nearly all of the impact categories. Though this analysis does not attempt to present comparative assertions per ISO 14040, opportunities for improvement of environmental performance in wire and cable products are discussed, focusing primarily on energy-efficiency and upstream material production.

Due to the presence of lead in the baseline communication cables, the potential public noncancer and aquatic ecotoxicity impact categories showed the greatest difference in environmental burden between the baseline and alternative cable constructions. These differences were driven by the EOL disposition of the cables, particularly landfilling, because a fraction of the lead was assumed to leach from the landfill into groundwater. Encouraging further recycling of chopped cable resin could potentially reduce the environmental burden of the baseline cable; however, there are other tradeoffs that would then need to be considered (e.g., the energy required for the cable chopping process). These conclusions only apply to communication cables (CMR and CMP), for which EOL was included in the full life-cycle analysis.

When identifying opportunities for improvement, particularly with respect to communication cable materials, conclusions must be understood in the context of the comparison defined within the boundaries of this analysis. For example, the same gauge copper was used in the baseline and alternatives within a cable type and was thus excluded from the analysis. As energy use is a driver for many of the impact results, increasing energy efficiency in all parts of the wire and cable life cycles could reduce many impacts. The sensitivity of impact results is primarily due to producing the energy needed for CMR and CMP cable extrusion, thus reducing energy inputs during extrusion could lessen the environmental impacts for all cable types substantially. Cable materials that tend to contribute largely to impacts (in decreasing order of environmental burden) include lead stabilizers, jacket and insulation resins, phthalates, and filler materials (e.g., calcined clay, limestone).

Opportunities for improvement also exist in the reduction of the quantities of lead entering the landfills (while recognizing potential tradeoffs if alternatives are needed to replace the reduced amounts of lead) or management of municipal solid waste and construction and demolition landfills, by ensuring that permeation of lead-containing landfill leachate is minimized. EOL disposition choices for wire and cable products are complicated by the trade-offs inherent in the processes themselves. As mentioned in

the preceding paragraph, the sequestration of wire and cable waste by landfilling is not without its source of hazards; and incineration, while advantageous from a landfill space use perspective, creates airborne lead emissions, which are problematic from a public health standpoint. Thermoplastic recycling is energy-intensive and creates new waste streams, which must be landfilled. Thus, the choices are not straightforward, and depend, among other things, on economic incentives and the value placed on different environmental burdens.

# 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.

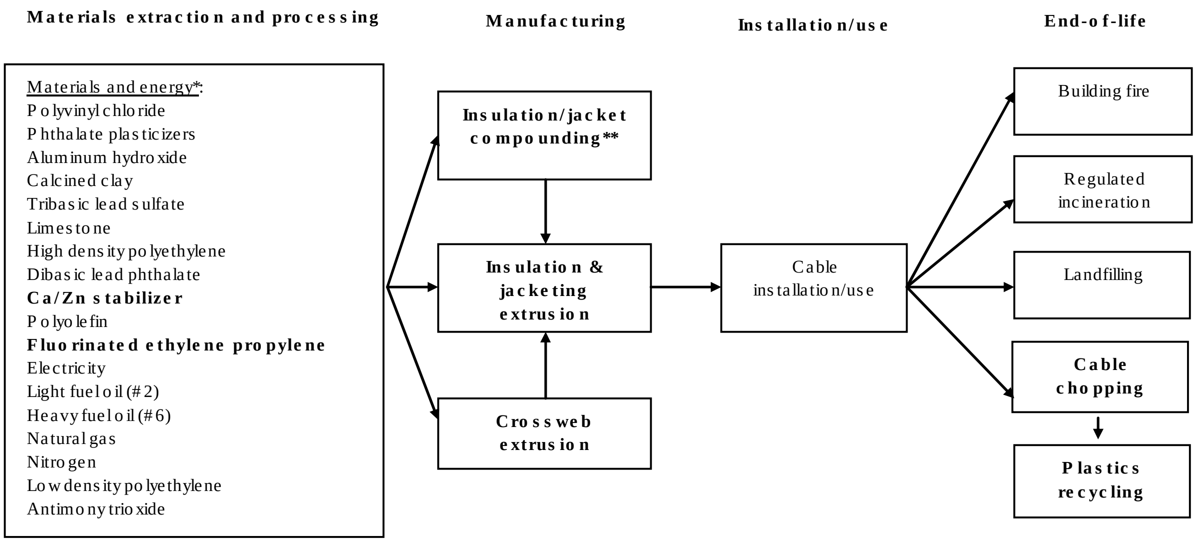
### 3.2.1 Upstream

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 10th-90th 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 $10^{th}$ and $90^{th}$ 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.

# CHAPTER 1. SCOPE AND BOUNDARIES

## 1.1 Purpose and Goals

### 1.1.1 Background

The Wire and Cable Project (WCP) is a voluntary, cooperative partnership among the following: the Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA's) Office of Pollution Prevention and Toxics (OPPT), the Toxics Use Reduction Institute (TURI) at the University of Massachusetts Lowell, individual wire and cable manufacturers, supply chain members (e.g., additive suppliers), and trade association members. OPPT established the DfE Program in 1992 to encourage businesses to incorporate environmental concerns into their business decisions. The EPA DfE Program promotes risk reduction, pollution prevention, energy efficiency, and other resource conserving measures through process choices at a facility level. DfE industry projects are cooperative, joint efforts that assist businesses in specific industries to identify and evaluate more environmentally sound products, processes, and technologies. The direction and focus of this project are determined by the project partners, while taking into consideration OPPT's goals.

The WCP partnership first developed partial life-cycle inventories (cradle-to-gate) of standard and alternative insulation and jacketing formulations for three selected cable products (Phase I):

1. Category 6, riser-rated communication wire (CMR)
2. Category 6, plenum-rated communication wire (CMP)
3. Non-metallic sheathed low-voltage power cable (NM-B)

These cable products have defined functionality and specifications, as described in Section 1.2.1.

The partnership then set out to objectively assess the complete environmental life-cycle impacts, including end-of-life (EOL) of the standard and alternative formulations for one or more of those three cable product types (Phase II).

The three product types were chosen because they 1) contain materials common to many cable applications; 2) contain materials of potential environmental concern, or materials for which stakeholders have expressed a desire to identify and evaluate alternatives; and 3) are believed to represent a significant amount of the wire and cable market. The project set out to evaluate alternative compositions that might meet, for example, lead-free, heavy metal-free, and/or zero-halogen specifications.[2,3] The goal is to determine whether the alternative products present environmentally preferable options.

The DfE WCP uses life-cycle assessment (LCA) as an environmental evaluation tool, which can be used to evaluate the environmental effects of a product, process, or activity. LCA is a comprehensive method for evaluating the full life cycle of the product system, from materials acquisition to manufacturing, use, and final disposition. As outlined in the ISO 14040 series, an LCA study has four major components: goal definition and scoping, life-cycle inventory (LCI), impact assessment, and

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[2] These terms are used generically to describe categories of alternative cable constructions. For example, they are not linked with specific definitions that may delineate trace quantities of the materials intended to be absent.

[3] The initial goal was also to include decabromodiphenyl ether (decaBDE) and decaBDE-free cables; however, the cable types selected did not use decaBDE in the standard formulation, and therefore this was not included in the scope.

interpretation of results. The remainder of Chapter 1 represents the goal definition and scope, which includes the purpose of the WCP, background information on the need for the project, descriptions of the product systems being evaluated, and the boundaries the study used. Chapter 1 incorporates scoping as it is recommended in the LCA process (e.g., ISO, 2006a; ISO, 2006b; Curran, 1996; Fava *et al*., 1991).

### 1.1.2 Purpose

The DfE/TURI Wire and Cable Partnership set out to select and analyze three types of cable products for which alternatives to lead and other substances of concern could be considered. The goal was to evaluate the standard and alternative cable insulation and jacketing formulations for three product types from a life-cycle perspective in order to understand their environmental impacts. Specifically, this project aimed to compare the life-cycle impacts of the alternative resins, heat stabilizers, flame retardants, and plasticizers used in the baseline and alternative cables. It was understood that the results may show any of the substances or their alternatives to be preferable from certain perspectives. The results primarily will be useful in identifying the materials that have significant environmental impacts when compared to those with the alternative constructions, so that industry can make informed, balanced formulation decisions based on fire safety, electrical performance, and environmental impact.

The purpose of Phase I of this study was to collect materials extraction and manufacturing data for the standard and alternative compositions for all three of the cable types. During this phase, the life-cycle inventory data associated with the extraction/processing and the manufacturing of these materials was compiled. Under Phase II, the life-cycle inventory was developed, as appropriate, for the use and EOL stages of a selected cable type or types, and a life-cycle impact assessment was conducted for all life-cycle stages. The purpose of Phase II was to evaluate the life-cycle environmental impacts of the selected traditional and alternative cable formulations using LCA methodologies.

### 1.1.3 Previous research

The major resins used in CMR, CMP, and NM-B cables include polyvinyl chloride (PVC), polyethylene (PE), and perfluoropolymers (PFPs). 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 phases. Williams *et al*., (2000) used the Chain Management of Materials and Products (CHAMP) methodology, which is based on life-cycle assessment, to compare the environmental impacts and options for recovery and recycling of Category 5 cables sheathed with PVC (assumed to be 100 percent pure) versus a low smoke zero halogen (LSZH) composition (50-67 percent aluminum trihydrate, 30-35 percent ethylene vinyl acetate copolymer, or EVA, 1 percent antioxidant). The study concluded that the copper conductor is the main contributor to the environmental impact of the systems studied. When the polymer sheaths alone are compared, PVC has slightly higher first-use environmental impacts, but it is slightly cheaper and has greater potential for recycling than the LSZH composition. This study, however, evaluated only cable formulations that meet European Category 5 standards, and did not account for additives in the PVC. It also did not evaluate the cable formulations that are required to meet the stricter U.S. standards for flame retardancy in plenum and riser applications. In addition, although information is available for the production of PE, no studies detailing its life cycle in wire and cable have been performed, and little to no life-cycle information is publicly available for PFPs, or fluorinated ethylene propylene (FEP), which is currently the most common PFP used in CMP cables. Monofluoroacetic acid (MFA), another PFP, can also be used as cable insulation. However, a current lack of adequate information regarding the production and use of MFA in the cable types examined prevents the WCP project from including it in this life-cycle assessment. EPA encourages further study of MFA so that it can be included in future assessments.

In a current study being done by DuPont (Krieger *et al*., 2007), plenum cable installations with either CMP cable or CMR cable in a steel conduit were compared. Based on their scope and assumptions, they found the required steel had the highest energy use and greenhouse gas emissions while the copper wire had the highest human toxicity impacts. The copper wire was shown to be a large contributor to most environmental impacts evaluated in their study. The study concludes that when comparing plenum space CMP and CMR/steel conduit alternatives, cabling material choices should be evaluated on whether they can reduce the use of copper or steel, thereby improving environmental performance of the cable installation. The Krieger study focused only on lead-free options for both CMP and CMR cables and did not focus on the comparisons of alternative constructions of similar cable installations (e.g., lead versus lead-free CMR in riser installations).

Aside from LCA studies, there is substantial information on PVC, which is inherently flame retardant, durable, tough, and relatively heat resistant, thus making it a suitable material for wire and cable insulation and jacketing (Vinyl Inst., 2003). However, vinyl chloride, the monomer that is polymerized to form PVC, is classified by the EPA and the International Agency for Research on Cancer (IARC) as a known human carcinogen. Acute exposure can occur in workers who make or use vinyl chloride and is linked to vascular disturbances and central nervous system effects, including dizziness, drowsiness, and headaches (SRC, 2006). Advances in the PVC industry have been reported to reduce worker exposure to the monomer, but PVC's life-cycle impacts in wire and cable applications still warrant further evaluation, because dioxin and hydrogen chloride can form when PVC is heated above 250º C (e.g., incineration or accidental fires). Hydrogen chloride is a corrosive, toxic gas that can cause skin burns and severe respiratory damage. Dioxin has received significant attention because of its carcinogenicity.

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 due to the known toxicity of lead. 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.

Plasticizers are also added to PVC in order to make it flexible enough for use as cable jacketing. Phthalate compounds are the most commonly used plasticizers for PVC. These compounds have come under scrutiny because their chemical composition mimics natural hormones in humans and other animals. They have been shown to cause fetal death, malformations, and reproductive toxicity in laboratory animals (Shea, 2003; Wilson, 2004).

High density PE (HDPE) is used in CMR cable and does not require additives. It is unclear whether HDPE presents health and safety concerns during its production and use, though it is approved for use in food containers such as milk cartons and water bottles. When burned, HDPE releases the toxic gas carbon monoxide. In addition, the inherent fuel value of HDPE may encourage fire spread.

Fluoropolymers (polymers with atoms of fluorine) are used to insulate individual conductors (such as copper wire). The three primary fluoropolymers used for wire and cable insulation are FEP, polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF). FEP is a common resin used to insulate wires in CMP cables because of its exceptional dielectric properties, flame and heat resistance, chemical inertness, durability, and flexibility. The polymer is also easily recycled at end of life. However, although FEP does not burn easily, it can emit toxic gases such as hydrogen fluoride (Wilson, 2004).

Perfluorooctanoic acid (PFOA), which is sometimes used as a polymerization aid in the production of FEP, also poses concerns. PFOA is a fully fluorinated organic compound produced synthetically or through the degradation or metabolism of other fluorochemical products. While PFOA may be used to manufacture FEP, it has not been detected in finished FEP products such as CMP cable (U.S. EPA, 2005a). Occupational exposure to PFOA as well as environmental release and fate, however, remain concerns. PFOA is present in low levels in the blood of the general U.S. population and in the environment, is highly persistent in the human body and in the environment, and has been found to cause developmental and other adverse effects in laboratory animals (U.S. EPA, 2005b). EPA released a preliminary risk assessment of potential developmental toxicity effects of PFOA in April 2003 and a draft risk assessment in January 2005 (U.S. EPA, 2005b). The draft risk assessment suggested that PFOA may be carcinogenic in male rats; however, EPA also identified uncertainty in the document and the need for further research.[4]

While EPA has obtained data on PFOA serum levels in workers and the general public, the pathways of human and environmental exposure to PFOA and the concentrations of PFOA in the environment are not well understood. Therefore, EPA has yet to determine whether PFOA poses an unreasonable risk to the public. Through its data gathering agreements with industry and other stakeholders, EPA continues to assess the potential risks posed by PFOA in order to determine what risk management steps may be appropriate, however, due to voluntary efforts on the part of industry stakeholders, it is less likely that further risk management steps will be necessary.[5]

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[4] Specifically, EPA stated in the 2005 draft risk assessment of PFOA (U.S. EPA, 2005b), "PFOA may be best described as 'suggestive evidence of carcinogenicity, but not sufficient to assess human carcinogenic potential' under the draft 1999 EPA Guidelines for Carcinogen Risk Assessment." In 2006, three quarters of a Scientific Advisory Board (SAB) panel, whose role was to comment on the draft risk assessment, "judged that the weight-of-evidence conclusion for the potential of PFOA to cause cancer in humans was more aligned and consistent with the hazard descriptor of 'likely to be carcinogenic' as described in the Agency's cancer guidelines (i.e., 2003 EPA Guidelines for Carcinogen Risk Assessment)."

[5] For example, in 2006 EPA created the 2010/15 PFOA Stewardship Program. The participants include 8 major manufacturers of flouropolymers and telomers, who have committed to reduce facility emissions and product content of PFOA and related chemicals by 95 percent by 2010, and to work toward eliminating PFOA emissions and product content by 2015. Companies participating in the Stewardship Program are 3M/Dyneon, Arkema, Inc., AGC Chemicals/Asahi Glass, Ciba Specialty Chemicals, Clariant Corporation, Daikin, E.I. DuPont de Nemours and Company, and Solvay Solexis. As noted on the PFOA Stewardship Program website

### 1.1.4 Market trends

Currently, the U.S. electronics industry is facing significant legislative and market pressures to phase out heavy metals and other hazardous materials from use in electrical and electronic equipment. This applies to some wire and cable products. These pressures include initiatives in Europe and Japan that mandate the elimination of lead from electronic products, or that request manufacturers to eliminate these voluntarily. In Europe, effective July 2006, the Restriction of Hazardous Substances (RoHS) Directive effectively banned the use of lead and other selected toxic chemicals in most electrical and electronic equipment.[6] In Japan, following take back (recycling) legislation effective as of 2001, the Japan EPA and MITI (Ministry of International Trade and Industry) currently suggest the reduced use of lead to take place along with increased recycling. California Proposition 65 (Prop65), the Safe Drinking Water and Toxic Enforcement Act of 1986, requires the governor to publish an annual list of chemicals known by the state of California to cause cancer, birth defects, or other reproductive harm. Businesses are then required to notify Californians about significant amounts of these chemicals found in products they purchase, in their homes or workplaces, or that are released to the environment. A 2002 settlement between the wire and cable industry, which was represented by the National Electrical Manufacturers Association (NEMA), and the state of California required only "frequently handled" electrical cords with a lead content by weight of 0.03 percent (300 ppm) to be labeled by September 2003. An exemption was made for cords that are infrequently handled, such as building cable, plenum cable, and telecom power cable (NEMA, 2002). Consumer demand for lead-free products may also increase as the general public becomes increasingly aware of lead issues, in part due to EPA's successful efforts to eliminate exposures to lead in gasoline, paint, and dust/soil. These drivers are all helping to move the U.S. market toward lead-free products.

A growing number of original equipment manufacturers (OEMs), particularly in the electronics and automobile industries, have introduced supplier materials declarations. These declarations, composed of lists of materials the OEMs want to restrict in their products, typically include materials found in wire and cable products, such as lead, cadmium, brominated flame retardants, and hexavalent chromium. Wire and cable components, however, have not been the initial target of materials declarations and restrictions by the OEMs. Several OEMs, including those in the High Packaging User Group (Dell, Hewlett-Packard, IBM, and Nokia), are even conducting tests to verify supplier compliance. In addition, Underwriters Laboratories Inc. (UL) and other testing houses have introduced compliance programs to assist all the channel partners with declarations. Because multinational OEMs want to make a class of products that can be sold anywhere in the world, rather than different products that comply with the requirements of various countries, they base their policies on the most restrictive worldwide standards. Many Japanese OEMs have been the most aggressive in restricting materials, in part to gain marketing advantage for the sale of their products (Harriman *et al*., 2003). A number of the leading electronics manufacturers in Japan–Sony-Europe, Sharp, Electrolux, and Ricoh of Japan–have PVC phaseout policies. Many auto manufacturers, including Toyota, Honda, and Nissan, also have goals to replace PVC with polyolefins[7] in order to increase the recyclability of plastic parts in vehicles at their end of life (Rossi *et al*., 2005).

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(http://www.epa.gov/oppt/pfoa/pubs/pfoastewardship.htm), many of these companies have already exceeded their 2010 goals and have moved on the 2015 goal of elimination of PFOA emissions and product content.

[6] RoHS does allow *de minimis* levels of lead (maximum concentrations of up to 0.1%.of lead in electrical and electronic equipment); however, lead stabilizers in the cables being analyzed are used in amounts greater than 0.1%.

[7] Polyolefins are a family of polymers such as polyethylene and polypropylene, which are made from olefin monomers. Olefin is the common name for the class of compounds known as alkenes, which contain double bonded carbons and include unsaturated aliphatic hydrocarbons, among which are ethylene, propylene, and butylene.

In addition to the OEM requirements, several European Eco-labels, such as the German Blue Angel and the Nordic Swan, act as market drivers. These labels prohibit the use of lead, hexavalent chromium, cadmium, and certain brominated flame retardants. In addition, some government and non-governmental organizations (e.g., Silicon Valley Toxics Coalition, Healthy Building Network) promote the purchase of products free of hazardous substances (Harriman *et al*., 2003).

Communications network cables in the U.S. have had to meet stringent NFPA (National Fire Protection Association) National Electrical Code® (NEC) fire performance requirements for the past 30 years. Network cables installed in vertical shafts (CMR) are highly flame retardant. Network cables installed in horizontal plenum spaces (CMP) must both be highly flame retardant and meet requirements for low smoke generation. An effort is also currently underway to further raise the standards for fire safety, requiring cables installed in concealed spaces to be "limited combustible" (LC). LC cables would be required to have higher flame retardancy and less smoke production than CMP cables. Fluoropolymer compounds would be one of the few jacketing materials currently available that would meet LC performance requirements. For the latest revision of the NEC in 2008, the decision was made not to include the LC designation.

Primarily as a consequence of distinct fire performance hierarchies, communication network cable markets differ considerably between the U.S. and Europe. Approximately 75 percent of the U.S. communications network cable market is CMP-rated cable (~6.0B ft/yr), and 15 percent is CMR-rated cable (~1.2B ft/yr). The U.S. market has changed substantially in recent years, as several cable manufacturers have introduced lead-free cables that meet Cat 6 CMR and Cat 6 CMP standards. In Europe, where cable fire performance standards are not as stringent as the U.S. NFPA NEC standards, 95 percent of the network cables (~5.0B ft/yr) currently meet the criteria for lower than CMR/Riser fire performance (CRU, 2002). (Typically, these European network cables are jacketed with either PVC or halogen-free compounds [e.g., polyolefins] and insulated with PE.)

The annual market for NM-B-rated cable is estimated at 800 million to 1 billion pounds (6.6 to 8.3 billion feet).[8] While some companies are converting to lead-free PVC insulation and jacketing, currently a relatively low percentage of the total annual market consists of alternative compositions, such as lead-free, heavy metal-free, and/or zero-halogen (Sims, 2007).

It should be noted that for many applications, alternatives do not always exist to the materials of potential concern that will satisfy performance requirements. For example, no commercial zero-halogen alternatives are available for CMP applications.

### 1.1.5 Need for the project

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 alternatives. In some applications, lead and other heavy metals have been removed from cable constructions, whereas other applications continue to use such materials. For example, European legislation has driven these changes for electronics and automotive applications; however, such changes have not been made for other

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[8] Using an average net weight of 83 lbs/1,000 ft (0.083 lbs per foot for 12-gauge 2-conductor copper NM-B with ground wire).

applications (e.g., low-voltage power cable) where such drivers are not present. Alternative constructions such as halogen-free jacketing (e.g., polyolefin-based polymer system) are available for some applications (i.e., subway systems and other locations where acid emissions from halogenated compounds are unacceptable). However, they have not been widely used, primarily due to their higher relative cost, the lack of market drivers, and their inability to meet all the requirements of the more demanding applications (Wilson, 2004).

Products that pose fewer environmental impacts are of interest to many wire and cable companies and their customers, if performance and cost requirements can be met. The DfE/TURI Partnership has generated information on the environmental impacts of traditional and alternative cable constructions in order to help companies make environmentally sound product and material choices. While 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 alternatives. 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 traditional and alternative 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 alternative 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.

### 1.1.6 Targeted audience and use of the study

The wire and cable industry is expected to be the primary user of the study results. The study is intended to provide the industry with an objective analysis that evaluates the life-cycle environmental impacts of selected cable products. Scientific verification of the relative environmental impacts will allow industry to consider environmental concerns along with traditionally evaluated parameters of safety, cost, and performance, and to potentially enhance efforts to manufacture products and design processes that reduce the environmental footprint, including energy consumption, releases of hazardous chemicals, and risks to health and the environment. Given the results, the industry can then evaluate material or process improvements based on the comparison of the alternative insulation and jacketing formulations. This study is designed to provide the wire and cable industry with information needed to identify the origin of impacts, throughout the life cycle, of both the traditional and alternative insulation and jacketing formulations. This information could lead to improvement in the cables' environmental attributes. The study results will also enable the wire and cable industry to make environmentally informed choices about alternatives when assessing and implementing improvements, such as changes in product, process, and activity design; raw material use; industrial processing; consumer use; and waste management.

Identification of impacts from the cables' life cycle can also encourage industry to implement pollution prevention options, such as development and demonstration projects, and technical assistance and training. The wire and cable industry can use the tools and data in this study to evaluate the health, environmental, and energy implications of the technologies. With this evaluation, the U.S. wire and cable industry may be more prepared to meet the demands of extended product responsibility that are growing in popularity in the global marketplace, to help guide public policy towards informed solutions that are environmentally preferable based on scientific study, and to be better able to meet the competitive challenges of the world market. In addition, the inventory data, results, and model in this study provide baseline data upon which other alternative cable formulations can potentially be evaluated. This allows for more expedited LCA studies, which are growing in popularity by industry and may be demanded by OEMs or international organizations.

We expect that the wire and cable industry will use the information generated in this study of the life-cycle environmental impacts of the standard insulation and jacketing formulations, and the alternative formulations, to select the formulations that meet the safety and transmission performance requirements of the end-use application, that pose fewer risks to public health, and that have the least impact on the environment.

## 1.2 Product Systems

### 1.2.1 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 alternatives. The product systems evaluated in Phase I of this project are standard and alternative (i.e., lead-free and zero-halogen) 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 is 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 one kilometer of linear length of cable, which would be used to transmit a signal that meets certain UL performance requirements and fire safety specifications for the product types listed in Table 1-1. Most telecommunications network cables are expected to achieve a minimum service life of 10 to 15 years. NM-B cables are generally replaced after 25 to 40 years of service, depending on the installation conditions. During remodeling, NM-B cables are typically replaced only if they are disturbed.

**Table 1-1**

**Wire & Cable Products Selected for Separate Analyses of Alternative Insulation and Jacketing Constructions**

| Wire and Cable Product | Application type | Specifications (standards)[b] |
|---|---|---|
| Riser communication cable (CMR) | Telecommunication (Category 6)[a] | UL-444, Article 800 NEC,<br>TIA-568-B.2-1, and ICEA S-80-576 |
| Plenum communication cable (CMP) | Telecommunication (Category 6)[a] | UL-444, Article 800 NEC,<br>TIA-568-B.2-1, and ICEA S-80-576 |
| Non-metallic-sheathed cable (NM-B) | Low-voltage power cable | UL-719, Article 334 NEC |

[a] Telecommunications Industry Association/Electronic Industries Alliance (TIA/EIA) (specifies data transmission performance category).

[b] UL=Underwriters Laboratories; NEC=National Electrical Code® (addresses flammability performance); ICEA = Insulated Cable Engineers Association (specifies physical, mechanical performance of insulation/jacket/finished product).

### 1.2.2 Cable systems and alternatives

A cable product generally consists of a wire conductor covered by insulation, and a jacket that encases the insulated wire(s). The insulation of NM-B and the jacketing of CMR, CMP, and NM-B cables are compounded with other materials, such as heat stabilizers and flame retardants, to meet performance specifications. Figure 1-1 shows the general process flow of manufacturing a cable.

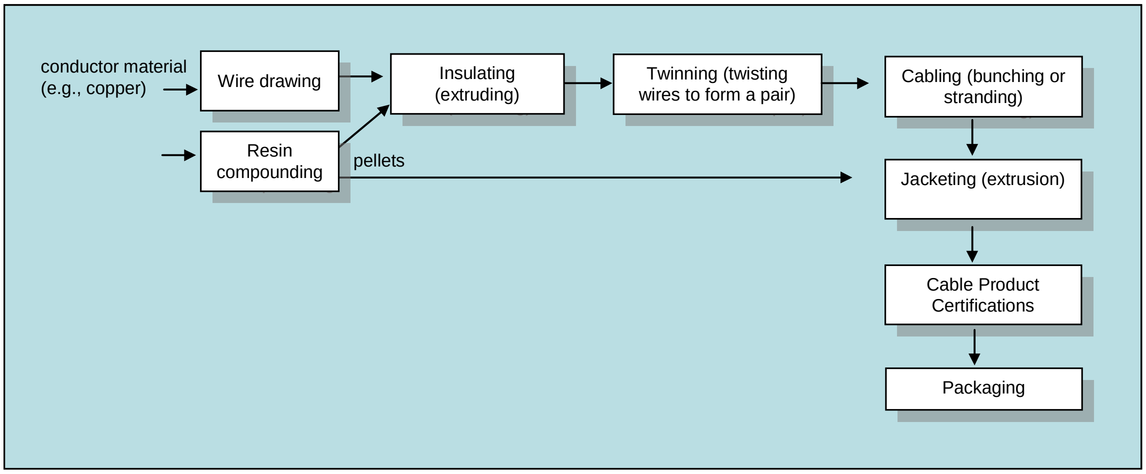


Figure 1-1. General Manufacturing Process Diagram for Cable

Project partners assisted in identifying alternative constructions to the cable products for inclusion in Phase I. We set out to evaluate as many lead-free and halogen-free alternatives for each cable type as possible. Given the data that were provided, Table 1-2 lists the general characteristics and makeup of each alternative included in Phase I this analysis.

The general makeup of each cable type is summarized in the pie charts in Figures 1-2, through 1-6. These constructions are from primary input data provided by the cable manufacturers and cable resin compounders that participated in this partnership. For CMR and CMP cable, the weight percentages for the baseline and lead-free constructions are only slightly different (Figures 1-2 through 1-5). Data received on the entire cable construction for the halogen-free CMR cables were not adequate to depict in a pie chart. Similarly, for NM-B cables, adequate data were not received for the lead-free cable to determine the component breakdown; however, industry partners of the WCP estimated the general makeup of baseline (Figure 1-6) and lead-free cables to be approximately the same. In each case, the cables were defined as having equivalent copper gauge wires, however, averaging primary copper input data from multiple companies resulted in the values being slightly different. This could be partially a function of different material efficiencies within different facilities. Thus, the cables as defined by the functional unit, are assumed to have the same amount of copper for each alternative within a cable type, and thus are excluded from the comparative analysis.

For all cable types, the conductor makes up between 52 and 70 percent of the weight of the cable for a given linear length of the cable. The percent mass that is insulation ranges from 10 to 21 percent of the cables, and jacketing ranges from 19 to 34 percent. Separators (also referred to as spacers or crosswebs) or other components constitute between 2 and 4 percent.

**Table 1-2**

**Wire & Cable Product Alternatives**

| Alternative | Insulation | Jacketing | Functional Unit (kg/km cable)[d] |
|---|---|---|---|
| CMR baseline[a] | HDPE | Compounded PVC (lead-based heat stabilizer) | 20.1 |
| CMR lead-free[a] | HDPE | Compounded PVC (non-lead heat stabilizer) | 21.8 |
| CMR zero-halogen[a] | HDPE | Non-PVC[b] (non-lead heat stabilizer) | 64.5 |
| CMP baseline[a] | FEP | Compounded PVC (lead-based heat stabilizer) | 22.8 |
| CMP lead-free[a] | FEP | Compounded PVC (non-lead heat stabilizer) | 22.9 |
| NM-B baseline[c] | Compounded PVC (lead-based heat stabilizer) | Compounded PVC (lead-based heat stabilizer) | e |
| NM-B lead-free[c] | Compounded PVC (non-lead heat stabilizer) | Compounded PVC (non-lead heat stabilizer) | e |

[a] Conductors are unshielded twisted pairs, 8 conductors in 4 pairs; 23-gauge bare copper.

[b] Proprietary.

[c] Conductors are 12-gauge, 2-conductor copper with ground wire.

[d] Functional unit conversions are based on primary data received for insulation and jacketing (see in Chapter 2).

[e] NM-B leaded and lead-free cables have approximately the same mass per length; the values are not reported to protect confidentiality.

Note: CMR = riser-rate communication cable; CMP = plenum-rated communication cable; HDPE = high density polyethylene; FEP = fluorinated ethylene propylene; PVC = polyvinyl chloride.

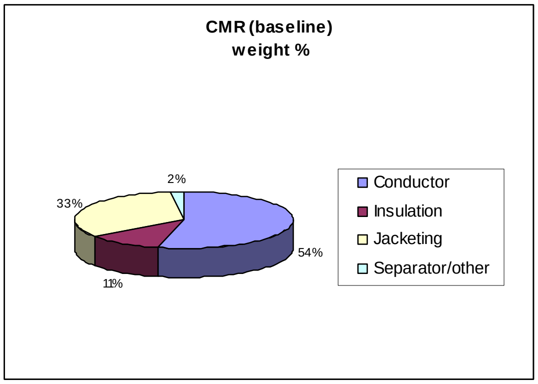


Figure 1-2. CMR Baseline Cable Component Breakdown

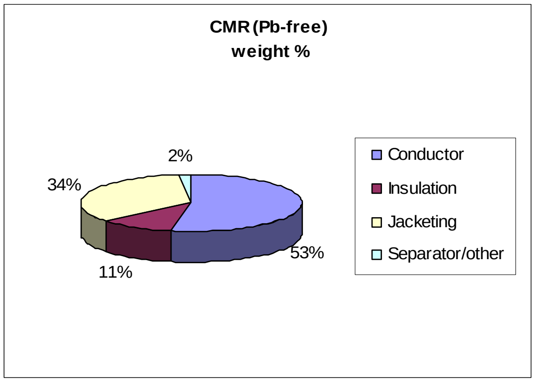


Figure 1-3. CMR Pb-free Cable Component Breakdown

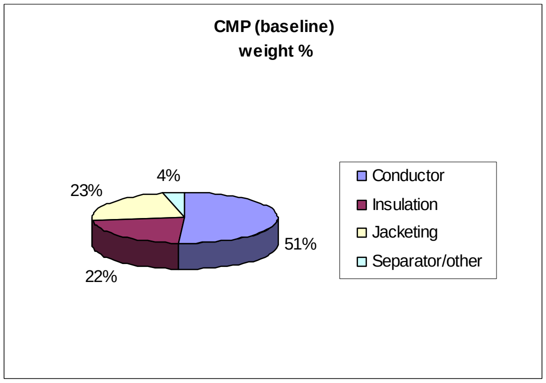


Figure 1-4. CMP Baseline Cable Component Breakdown

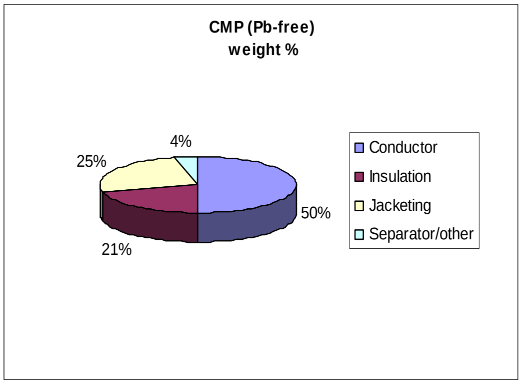


Fig 1-5. CMP lead-free Cable Component Breakdown

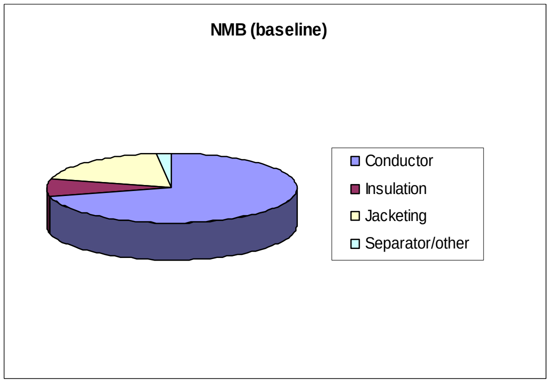


Figure 1-6. NM-B Cable Component Breakdown (percentages not shown; proprietary)

The focus of the comparative LCAs in this report is on the insulation, jacketing, and separator/ crossweb resins, as well as any compounded materials contained within the resins. Each cable type uses equivalent amounts of copper conductor per unit length of cable, and thus the conductor is excluded from the comparison of alternatives within each cable type.

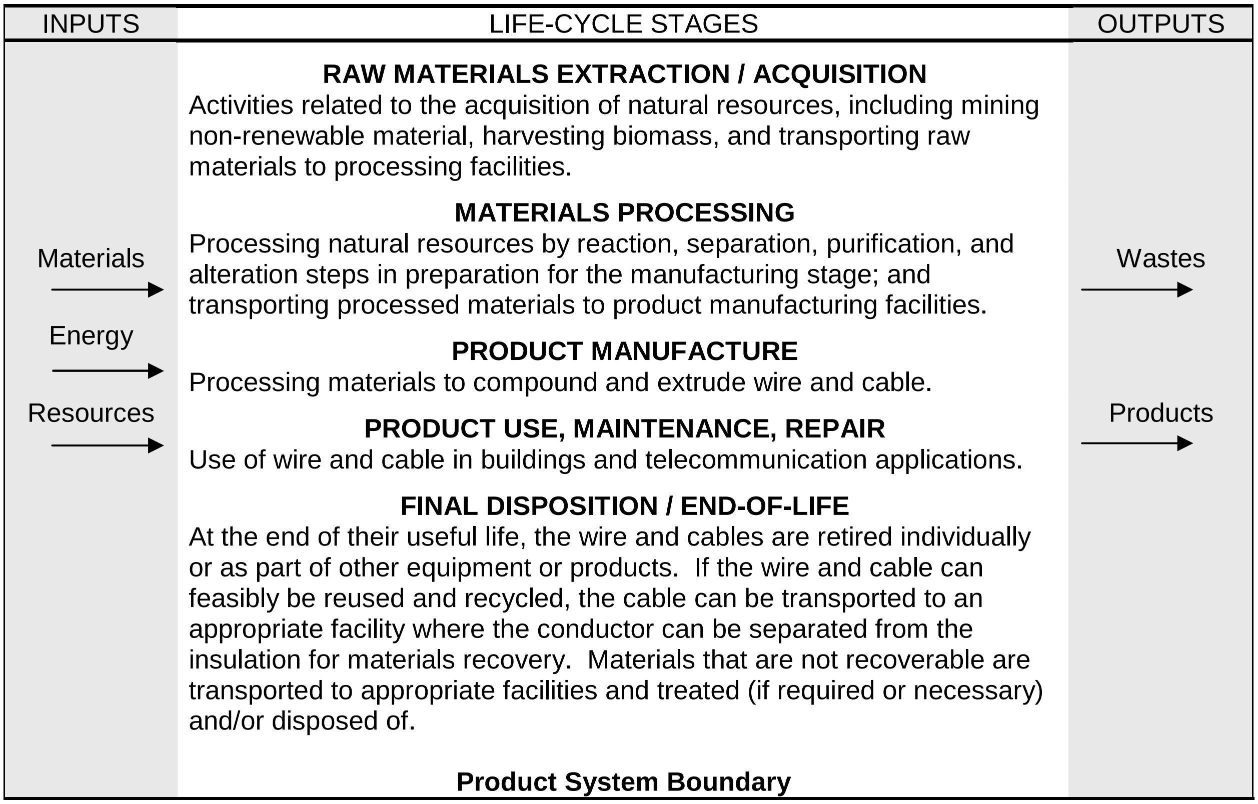
## 1.3 Assessment Boundaries

### 1.3.1 Life-cycle assessment (LCA)

LCAs evaluate the life-cycle environmental impacts from each of the following major life-cycle stages:

- Raw materials extraction/acquisition
- Materials processing
- Product manufacture
- Product use
- Final disposition/end-of-life

Figure 1-7 briefly describes each of these stages for a wire and cable product system. The inputs (e.g., resources and energy) and outputs (e.g., product and waste) within each life-cycle stage, as well as the interaction between each stage (e.g., transportation), are evaluated to determine the environmental impacts.



INPUTS

LIFE-CYCLE STAGES

OUTPUTS

Materials

Energy

Resources

**RAW MATERIALS EXTRACTION / ACQUISITION**

Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.

**MATERIALS PROCESSING**

Processing natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.

**PRODUCT MANUFACTURE**

Processing materials to compound and extrude wire and cable.

**PRODUCT USE, MAINTENANCE, REPAIR**

Use of wire and cable in buildings and telecommunication applications.

**FINAL DISPOSITION / END-OF-LIFE**

At the end of their useful life, the wire and cables are retired individually or as part of other equipment or products. If the wire and cable can feasibly be reused and recycled, the cable can be transported to an appropriate facility where the conductor can be separated from the insulation for materials recovery. Materials that are not recoverable are transported to appropriate facilities and treated (if required or necessary) and/or disposed of.

**Product System Boundary**

Wastes

Products

Figure 1-7. Life-cycle Stages of Wire and Cable Alternatives

As defined by the Society of Environmental Toxicology and Chemistry (SETAC), the four major components of an LCA are (1) goal definition and scoping, (2) inventory analysis, (3) impact assessment, and (4) improvement assessment. More recently, the international standard ISO 14040: Environmental Management—Lifecycle Assessment—Principles and Framework has defined the four major components of an LCA as (1) goal and scope, (2) inventory analysis, (3) impact assessment, and (4) interpretation of results. The SETAC and International Organization for Standardization (ISO) frameworks are essentially synonymous with respect to the first three components, but differ somewhat with respect to the fourth component: improvement assessment or life-cycle interpretation. Improvement assessment is the systematic evaluation of opportunities for reducing the environmental impacts of a product, process, or activity. Interpretation is the phase of LCA in which the findings from the inventory analyses and the impact assessment are combined, consistent with the defined goal and scope, in order to reach conclusions and recommendations.

The goals and scope of this LCA for wire and cable insulation and jacketing are the subject of Chapter 1. The inventory analysis and impact assessment are included in Chapters 2 and 3, respectively. Chapter 4 summarizes the results; however, much of the life-cycle interpretation, which is the last step of an LCA as recommended in ISO 14040, is left to the wire and cable industry. The life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) strategies are briefly described below.

The LCI involves quantifying raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents. The approach to the LCI in this study involved defining product materials, developing bills of materials (BOM) for the products, and obtaining inventory data for major processes within each life-cycle stage. Section 1.4 provides additional details of the LCI data-gathering activities.

The LCIA involves translating the environmental burdens identified in the LCI into environmental impacts. LCIA is typically a quantitative process involving characterizing burdens and assessing their effects on human and ecological health, as well as other effects, such as smog formation and global warming. Further details of the LCIA impact categories appear in Section 1.3.5. This project used an LCIA methodology that was used in the most recent DfE LCA, entitled *Lead-Free Solders: A Life-cycle Assessment* (Geibig and Socolof, 2005), which was based on the methodology used in DfE's Computer Display Project (Socolof *et al*., 2001).

### 1.3.2 Life-cycle stages and unit processes

In a comprehensive cradle-to-grave analysis, the product system includes five life-cycle stages: (1) raw materials extraction/acquisition; (2) materials processing; (3) product manufacture; (4) product use, maintenance, and repair; and (5) final disposition/end-of-life (EOL). Also included are the activities that are required to affect movement between the stages (e.g., transportation). The first two stages (materials extraction and materials processing) are represented as one "upstream" life-cycle stage throughout this report, as available data are aggregated as such.

Figure 1-8 depicts the major processes within the life cycles of the cables that are modeled in this study. Each of these unit processes has its own inventory of inputs and outputs. In the upstream stages, resins and additive materials for the insulation and jacketing are included. The extent to which additive materials are included depends on decision rules, which are discussed in Section 1.4.2. Because each cable alternative uses the same type and quantity of conductor material, this LCA does not include upstream stages of the copper conductors. The differences between the cable alternatives are in the insulation or jacketing, and thus those components of the wire and cable products are the focus of this comparative LCA.

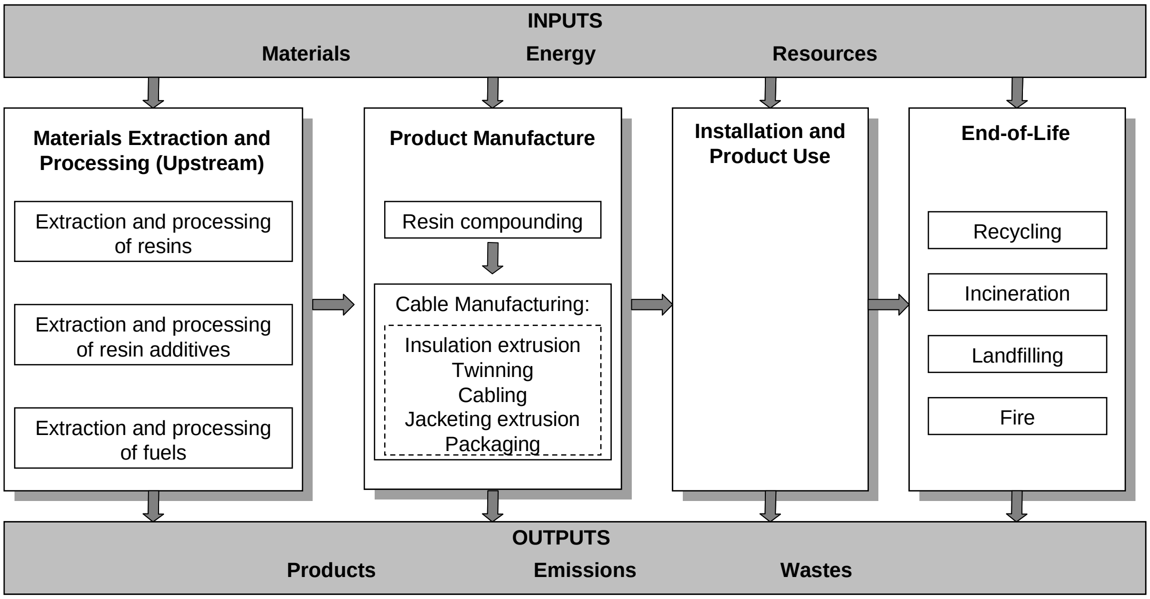


Figure 1-8. Wire and Cable Life-cycle Conceptual Model

The manufacturing stage includes compounding and extrusion processes, and any assembly processes associated with manufacturing a cable (see Figure 1-1). The installation and use of the cables is consistent between alternatives, and thus does not need to be included in a comparative analysis. If service lifetimes during use of the cables differ between alternatives, then the amount of cable produced would be scaled so that each alternative would have equivalent functional units. However, lifetimes for cables being compared were consistent.

Transportation of wire and cable materials for alternative constructions is expected to be the same for all plastic pellets and cables, and does not have any regional or global differences. Therefore, transportation was not included in this comparative analysis for transport between compounding facilities, cable manufacturing facilities, installation sites, and EOL disposition. Transportation is included when secondary data sets used for materials extraction and processing already have transportation aggregated into the data set.

### 1.3.3 Spatial and temporal boundaries

Geographic boundaries are used in an LCA to show where impacts are likely to occur for each life-cycle stage. This is important for assessing the impacts of things such as transportation impacts between life-cycle stages. Raw materials acquisition and material processing for materials used in the manufacture of the cables are conducted throughout the world. Product manufacturing also occurs worldwide. CMR-rated cable products are sold in numerous markets around the world, whereas the CMP-rated cable products and low-voltage power cables are more limited to the North American market. This study, however, focused on the use of these cables for telecommunications and low-voltage power cable applications in the United States. The EOL evaluation also focused on cables that reach the ends of their lives in the United States. However, due to limited data availability, data from other countries were used when available.

While the geographic boundaries show where impacts might occur for various life-cycle stages, traditional LCAs do not provide actual spatial relationships of impacts. That is, particular impacts cannot be attributed to a specific location. Rather, impacts are generally presented on a regional or global scale.

This study addresses impacts from cables that were manufactured between the years 2005 and 2006. Installation and use of the cables would occur shortly thereafter; however, EOL disposition would occur after the 10- to 15-year-service life for CMP and CMR cables, and after the 25- to 40- year NM-B service life. Given the lack of temporal specificity in an LCA, EOL impacts are assumed to be based on current EOL technologies and conditions, despite the potential changes that might occur during the product's service life. Thus, we assumed that any parameters that may change with time (e.g., availability of landfill space, recycling rates, recycling technologies) would be similar to current conditions, and would remain constant throughout the lifespan of the product system. Note that the inherent uncertainty in this assumption is greater when the product lifespan is longer.

### 1.3.4 General exclusions

Impacts from the infrastructure needed to support the manufacturing facilities are beyond the scope of this study (e.g., general maintenance of manufacturing plants). Given that the copper wire is equivalent, by definition, across alternatives, the mining and production of copper and the copper drawing process were not evaluated in the study.

### 1.3.5 Impact categories

In the LCIA phase of an LCA, several different impact categories can be evaluated among the alternatives. This study evaluates the following:

- Non-renewable materials use/depletion
- energy use
- landfill space use
- global warming (global climate change)
- stratospheric ozone depletion
- photochemical smog
- air acidification
- air particulates
- water eutrophication (nutrient enrichment)
- potential chronic non-cancer human toxicity – occupational
- potential cancer human toxicity – occupational
- potential chronic non-cancer toxicity – public
- potential cancer human toxicity – public
- potential aquatic ecotoxicity

The methodologies for each category are based on those used in previous DfE LCAs and are common to many LCAs. The toxicity-based categories use a methodology developed for DfE in a previous LCA (for computer displays), and has also been used in the DfE solder LCA. All the methodologies are detailed in Chapter 3.

## 1.4 Data Collection Scope

This section describes the data categories that were evaluated in the WCP LCI, the decision rules used to determine which materials would be eliminated from consideration, and data collection methods. It also describes procedures for allocating inputs and outputs from a process to the product of interest (i.e., a cable) when the process is used in the manufacture, recycle, or disposal of more than one product type at the same facility. Finally, it describes the data management and analysis software used for the project, and methods for maintaining overall data quality and critical review.

### 1.4.1 Data categories

Table 1-3 describes the data categories for which inventory data were collected, including material and energy inputs; and emissions, wastes, and product outputs. In general, inventory data are normalized to either (1) the mass of an input or output per functional unit, or (2) energy input (e.g., megajoules, MJ) per functional unit. As discussed in Section 1.2, the functional unit is a unit length of a particular cable for a given service life.

Data that reflect production for one year of continuous processes are scaled to one functional unit. Thus, excessive material or energy associated with startups, shutdowns, and changeovers are assumed to be distributed over time. Consequently, any environmental and exposure modeling associated with the impact assessment reflects continuous emissions such that equilibrium concentrations may be assumed. If the reporting year was given as less than one year for any inventory item, the analysis was adjusted as appropriate to the functional unit. Data were also collected on the final disposition of emissions outputs, such as whether outputs are recycled, treated, and/or disposed of. This information was used to help determine which impacts are calculated for a particular inventory item.

**Table 1-3**

**LCI Data Categories**

| Data Category | Description |
|---|---|
| Inputs: Material and resource flows (kg per functional unit) | |
| Primary material flows | *Actual materials that make up the final product for a particular process.* |
| Ancillary (process) material flows | *Materials that are used in the processing of a product for a particular process. May be renewable or non-renewable resources.* |
| Natural resource flows | *Materials extracted from the ground that are non-renewable (i.e., stock, resources such as coal), or renewable (i.e., flow resources such as water or limestone).* |
| Inputs: Energy flows (MJ per functional unit) | |
| Energy flows | *Process energy, pre-combustion energy (i.e., energy expended to extract, process, refine, and deliver a usable fuel for combustion), and when available, transportation energy are included. Energy can be renewable or non-renewable. The energy flows modeled in this analysis are generally from non-renewable sources.* |
| Outputs: Emissions, wastes (kg per functional unit) | |
| Emissions to air | *Mass of a product or material that is considered a pollutant within each life-cycle stage. Air outputs represent actual gaseous or particulate releases to the environment from a point or diffuse source, after passing through emission control devices, if applicable.* |
| Emissions to water | *Mass of a product or material that is considered a pollutant within each life-cycle stage. Water outputs represent actual discharges to either surface or groundwater from point or diffuse sources, after passing through any water treatment devices.* |
| Emissions to soil | *Mass of chemical constituents that are considered pollutants and emitted to soil within each life-cycle stage. Soil emissions represent actual or modeled discharges to soil from point or diffuse sources.* |
| Wastes/deposited goods | *Mass of a solid or hazardous waste landfill or deep well. Could include hazardous, non-hazardous, and radioactive wastes. Represents solid or liquid outputs that are deposited in a landfill or sent for treatment (e.g., incineration, composting), recovery, or recycling processes.* |
| Outputs: Products (kg or number of components per functional unit) | |
| Primary products | *Material or component outputs from a process that are received as inputs by a subsequent unit process within the product life cycle.* |
| Co-products | *Material outputs from a process that can be used, either with or without further processing, and that are not used as part of the final functional unit product.* |

### 1.4.2 Decision rules

Given the enormous amount of data involved in inventorying all of the input and output flows for a product system, LCA practitioners typically employ decision rules to make the data collection manageable and representative of the product system and its impacts.

In this project, decision rules were used to determine which upstream processes to include. In considering upstream materials, a combination of several factors were considered, including availability of existing data and manufacturers' willingness to participate. Decision rules are also used to determine whether material flows are excluded from a particular process. This was determined once all the inventory data were collected for each process in the product systems.

The decision rule process began by assessing the materials used in cable production for the following attributes:

1. *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.
2. *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.
3. *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.
4. *Materials that are physically or functionally unique to one alternative over another.* The physical or functional uniqueness of a material or component could be identified by chemical makeup or by size.

Materials that are greater than one percent of the total mass of material required to manufacture the product were considered for inclusion in the scope. 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 (as approved by the WCP Core Group, described in Section 1.4.7). 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 alternative over the baseline construction, as determined by the Core Group, are also considered if they would have otherwise been eliminated based on the mass cutoff.

### 1.4.3 Data collection and data sources

Data were collected from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand. Secondary data are from literature sources, LCI databases, or other LCAs, but may not be specific to the product of interest. Table 1-4 lists the types of data (primary or secondary) collected for each life-cycle stage in the WCP LCI. If both primary and secondary data are lacking, various assumptions and modeling serve as defaults.

**Table 1-4**

**Data Types by Life-cycle Stage**

| Life-cycle stage | Data types | Scope |
|---|---|---|
| Upstream (materials extraction and processing) | Secondary data; possibly primary data | Greater emphasis |
| Product manufacturing | Primary data or secondary data for industry averages | Greater emphasis |
| Installation and use | None | Excluded since it is equivalent among alternatives |
| Final disposition (recycling and/or disposal) | Primary and secondary data | Moderate emphasis |
| Packaging, transportation, distribution | None | Excluded because it is assumed to be equivalent among alternatives |

### 1.4.4 Allocation procedures

An allocation procedure is required when a process within a system shares a common management structure with other products produced. In the WCP LCI, allocation procedures may be required when processes or services associated with the functional unit are used in more than one product line at the same facility. Inputs and outputs are allocated among the product lines to avoid overestimating the environmental burdens associated with the product under evaluation.

The International Organization for Standardization (ISO) recommends that wherever possible, allocation should be avoided or minimized. This may be achieved by subdividing the unit process into two or more subprocesses, some of which can be excluded from the system under study. For example, if a manufacturer produces only one type of cable, no allocation would be necessary from that manufacturer. However, if the manufacturer produces multiple cables products, the flows would need to be allocated to the one cable of interest. As suggested by ISO, if sub-processes within the facility can be identified that distinguish between the cables being manufactured, the sub-processes manufacturing the cables that are not of interest can be eliminated from the analysis, thus reducing allocation procedures. Where disaggregation into subprocesses was not possible, inventory data for utilities and services common to several processes were allocated to reflect the relative use of the service. For example, fuel inputs and emission outputs from electric utility generation were allocated to a cable according to the actual or estimated electricity consumed during the applicable process.

### 1.4.5 Data management and analysis software

The data collected in this study were obtained either from data forms developed for this project, from existing databases, or from primary or secondary data collected by Abt Associates, Inc. All data were then transferred to spreadsheets, which were then imported into a commercially available LCA tool: GaBi4–The Software System for Life Cycle Engineering [PE Europe GmbH and IKP University of Stuttgart, 2003]. This software tool stores and organizes life-cycle inventory data and calculates life-cycle impacts for a product profile. It is designed to allow flexibility in conducting life-cycle design and life-cycle assessment functions, and provides the means to organize inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality. Impact methods developed by the University of

Tennessee under grants from DfE were also incorporated into the GaBi4 tool as appropriate for this project.

### 1.4.6 Data quality

LCI data quality can be evaluated based on the following data quality indicators (DQIs): (1) the source type (i.e., primary or secondary data sources), (2) the method in which the data were obtained (i.e., measured, calculated, estimated), and (3) the time period for which the data are representative. LCI DQIs are discussed further in Life-Cycle Assessment Data Quality: A Conceptual Framework (SETAC, 1994). Data quality for each life-cycle stage is summarized below.

For the primary data collected in this project, we asked participating companies to report the method in which their data were obtained and the time period for which the data are representative. Data from 2005-2006 were sought. The time period of secondary data and methods in which the data were originally obtained were also recorded, where available. Secondary data were expected to be from earlier time periods.

Anomalies and missing data are common hurdles in any data collecting exercise. Anomalies are extreme values within a given data set. Any anomaly identified during the course of this project that is germane to project results was highlighted for the project team and investigated to determine its source (e.g., mis-reported values). If the anomaly could be traced to an event inherently related to the process, it was left in the data set. If, however, the anomaly could not be accounted for, it was removed from the data set.

We attempted to account for missing data by replacing it hierarchically. That is, if specific primary data were missing, secondary data were used. Where neither primary nor secondary data were available, we made assumptions, and in cases where there was potentially large uncertainty with an assumption, we conducted an uncertainty analysis based on those assumptions. In the cases where no data were found or reasonable assumptions could be made, these deficiencies were reported. Any proprietary information required for the assessment is subject to confidentiality agreements between Abt Associates, Inc. and the participating company. Proprietary data are presented as aggregated data from a minimum of three companies to avoid revealing the source of the data.

### 1.4.7 Critical review

Critical review is a technique used to verify whether an LCA has met the requirements of the study for methodology, data, and reporting, as defined in the goal definition and scoping phase. A critical review process was maintained in the WCP LCA to help ensure that the following criteria were met:

- The methods used to carry out assessments are consistent with the EPA, SETAC, and ISO assessment guidelines.
- The methods used to carry out assessments are scientifically and technically valid within the LCA framework.
- The data used are appropriate and reasonable in relation to the goals of the study.
- The interpretations reflect the limitations identified and the goals of the study.
- The study results are transparent and consistent.

This review process conforms to the recommendations in ISO 14040.

A project Core Group of representatives from industry, academia, and government provided critical reviews of the project assessments.  The Core Group served as the project Steering Committee, and was responsible for approving all major scoping assumptions and decisions.  It provided technical guidance and reviews of all major project deliverables including the final LCA report.  In addition to Core Group review, the report was also reviewed by several EPA staff, including those with LCA and risk assessment expertise.

Comments on the review drafts were collected, logged into a comment-response log, and shared with all reviewers.  Meetings to discuss and/or resolve comments were conducted and the final responses and actions taken were entered into the comment-response long and provided to the reviewers with the final report.  An independent LCA expert was identified within EPA, who was tasked with conducting a review of the methods and findings of this study.  Supplied with this document, in accordance with Section 7.3.2 of ISO 14040, is a review statement from the authors of the study, comments of the expert LCA practitioner, and responses to the recommendations made by this practitioner.

# CHAPTER 2 LIFE-CYCLE INVENTORY

The process of quantifying the inputs (e.g., materials, utilities) and outputs (e.g., emissions, wastes) of a product system is the life-cycle inventory (LCI) phase of a life-cycle assessment (LCA). A product system is made up of the multiple processes that help produce, use, or dispose of the product. Each process has an inventory that consists of input and output flows for that process, and an LCI of a product system consists of several inventories for processes throughout the life cycle of the product. This chapter presents the data collection methodology for each life-cycle stage, in Sections 2.1 through 2.4, followed by the LCI results in Section 2.5.

## 2.1 Upstream Materials Extraction & Processing Life-Cycle Stages

This section addresses the LCIs related to two major life-cycle stages—materials extraction and materials processing (ME&P)—which together will be referred to as the life-cycle stages that are "upstream" of the product manufacturing (i.e., compounding and extruding) stage.

The purpose of this section is to present the approach used to obtain process-specific inventory data, from primary and secondary sources, related to extraction and processing of the materials needed to produce wire and cable insulation and jacketing compounds. Numerous materials and upstream processes are used to produce wire and cable insulation and jacketing compounds. Therefore, decision rules were used to limit which materials to include in the scope of the LCA. Existing data from secondary sources were used where available. For inventories related to materials extraction and materials processing, various databases with input and output LCI data exist for materials commonly used in the wire and cable industry (i.e., PVC, HDPE, and certain fillers). However, data do not exist for most of the flame retardants, heat stabilizers, plasticizers, and other resins (e.g., FEP) used in the insulation and jacketing compounds. Because of the lack of available secondary LCI data, the WCP sought to collect primary data for these materials.

This section of the report first identifies materials considered for inclusion in the ME&P life-cycle stage. The remainder of the section presents the methodology for collecting upstream data, including data sources, and the limitations to using the upstream data for the WCP.

### 2.1.1 Materials selection

This section describes the decision process for including materials in the WCP upstream LCI data. The first step in collecting upstream data was to identify those materials that are used in producing the cables, both primary materials and ancillary materials (i.e., fuels and process materials). Bills of materials for the cables in this study are presented in Tables 2-1, 2-2, and 2-3, respectively. (Note that the WCP excluded the conductor from the analysis because the same gauge copper and number of conductors are used in each of the cable alternatives within a given cable type.) The tables present the mass per unit length of each component material in each of the cable alternatives, and their percent mass contribution of the cable with and without the copper conductor. The quantities are based on primary data collected from compounders and manufacturers under confidentiality agreements. The tables show the averages from a total of six different companies.

For each of the three cable types in this study, the bills of materials of lead-stabilized cable (baseline) and the non-leaded alternatives are presented in Tables 2-1, 2-2, and 2-3. A complete bill of materials for CMR zero-halogen cables was not obtained; thus, only limited analyses with these cables are possible. Upstream data selection for the CMR zero-halogen cable alternative is based on general descriptions of the cables provided by participating companies and limited data provided under confidentiality agreements (Table 2-4).

**Table 2-1**

**Average CMR Cable Construction Bills of Materials[a]**

| Material Name [CASRN][b] | Function | Baseline Construction | | | Pb-free Alternative Construction | | |
|---|---|---|---|---|---|---|---|
| | | **Mass (kg/km)[c]** | **Weight % of cable with Cu** | **Weight % of cable without Cu** | **Mass (kg/km)[c]** | **Weight % of cable with Cu** | **Weight % of cable without Cu** |
| Copper (Cu) [7440-50-8] | Conductor[d] | 23.3 | 54% | N/A | 24.2 | 53% | N/A |
| Polyvinyl chloride (PVC) [9002-86-2] | Jacket resin | 7.47 | 17% | **37%** | 8.92 | 19% | **37%** |
| High density polyethylene (HDPE) [9002-88-4] | Insulation resin | 4.55 | 11% | **23%** | proprietary | >5% | **>5%** |
| Phthalate-based plasticizer | Jacket plasticizer | 2.25 | 5.2% | **11%** | proprietary | 1-5% | **>5%** |
| *Non-halogenated flame retardant #1* | Jacket flame retardant | proprietary | 1-5% | **>5%** | proprietary | 1-5% | **>5%** |
| Polyolefin | Separator | proprietary | 1-5% | **1-5%** | proprietary | <1 | **1-5%** |
| Trimellitate plasticizer | Jacket plasticizer | proprietary | 1-5% | **1-5%** | proprietary | 1-5% | **>5%** |
| Brominated phthalate | Jacket flame retardant | proprietary | 1-5% | **1-5%** | N/A | | |
| *Non-halogen FR#2* | Jacket flame retardant | 0.466 | 1-5% | **1-5%** | proprietary | 1-5% | **1-5%** |
| Calcined clay [66402-68-4] | Jacket filler | proprietary | <1% | **1-5%** | proprietary | <1% | **1-5%** |
| Tribasic lead sulfate [12202-17-4] | Jacket heat stabilizer | 0.351 | 0.81 % | **1.8 %** | N/A | | |
| Dibasic lead phthalate [17976-43-1] | Jacket heat stabilizer | proprietary | <1 % | <1 % | N/A | | |
| Calcium-Zinc-based stabilizers [various] | Jacket heat stabilizer | N/A | | | proprietary | 1-5% | **1-5%** |
| Unspecified colorants [various] | Insulation colorant | proprietary | <1% | **1-5%** | proprietary | <1% | <1% |
| Calcium carbonate (CaCO3) [471-34-1] | Jacket filler | proprietary | <1% | <1% | proprietary | 1-5% | **1-5%** |
| Polyethylene terephthalate (PET) | Ripcord | proprietary | <1% | <1 % | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Jacket lubricant | 0.0538 | 0.12% | 0.27% | proprietary | <1% | <1% |
| *Proprietary light stabilizer #1* | Light stabilizer | proprietary | <1% | <1% | proprietary | <1% | <1% |
| *Proprietary lubricant #2* | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Printing Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary material #1 | Other | N/A | | | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 43.3 [e] | | | 46.0 [f] | | |

[a] Zero-halogen not included as complete cable construction data were not provided.

[b] Chemical Abstract Services Registry Number.

[c] Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

[d] Conductor is unshielded twisted pair, 8 conductors in 4 pairs; 23-gauge bare copper. The mass of copper is slightly different due to averaging data from different companies, all of whom did not provide data for both alternatives. Thus, although within a company, the amount of copper was consistent across alternatives, averaging a different number of data sets for each alternative resulted in slightly different mass averages of copper.

[e] 94 wt% of the total CMR baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

[f] 90 wt% of the total CMR lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

**Table 2-2**

**Average CMP Cable Construction Bills of Materials**

| Material Name [CASRN][a] | Function | Baseline Construction | | | Pb-free Alternative Construction | | |
|---|---|---|---|---|---|---|---|
| | | **Mass (kg/km)[b]** | **Weight % of cable with Cu** | **Weight % of cable without Cu** | **Mass (kg/km)[b]** | **Weight % of cable with Cu** | **Weight % of cable without Cu** |
| Copper (Cu) [7440-50-8] | Conductor[c] | 23.7 | 51% | N/A | 22.5 | 50% | N/A |
| Fluorinated ethylene propylene (FEP) [25067-11-2] | Resin (insulation / separator / filler) | proprietary | >5% | **>5%** | proprietary | >5% | **>5%** |
| Polyvinyl chloride (PVC) [9002-86-2] | Jacket resin | proprietary | >5% | **>5%** | proprietary | >5% | **>5%** |
| Aluminum trihydrate (ATH) [21645-51-2] | Jacket flame retardant | proprietary | >5% | **>5%** | proprietary | >5% | **>5%** |
| Fluoropolymer | Separator | proprietary | 1-5% | **>5%** | proprietary | 1-5% | **1-5%** |
| Proprietary FR#3 | Jacket flame retardant and/or plasticizer | proprietary | 1-5% | **1-5%** | proprietary | 1-5% | **1-5%** |
| Ammonium octamolybdate [12411-64-2] | Jacket flame retardant and/or plasticizer | proprietary | 1-5% | **1-5%** | proprietary | 1-5% | **1-5%** |
| Calcined clay [66402-68-4] | Jacket filler | proprietary | <1% | **1-5%** | proprietary | 1-5% | **1-5%** |
| Brominated phthalate [various] | Jacket flame retardant and/or plasticizer | proprietary | <1% | **1-5%** | proprietary | 1-5% | **1-5%** |
| Calcium carbonate (CaCO3) [471-34-1] | Jacket filler | proprietary | <1% | **1-5%** | proprietary | <1% | **1-5%** |
| Proprietary plasticizer #1 | Jacket plasticizer | proprietary | <1% | <1% | proprietary | <1% | **1-5%** |
| Lead-based stabilizer #1 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Lead-based stabilizer #2 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Calcium-Zinc-based stabilizers [various] | Jacket heat stabilizer | N/A | | | proprietary | <1% | **1-5%** |
| Unspecified colorant | Insulation colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Unspecified colorant | Jacketing colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary FR#4 | Jacket flame retardant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Polyethylene terephthalate (PET) | Ripcord | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Lead-based stabilizer #3 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Zinc borate | Jacket flame retardant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary light stabilizer #1 | Light stabilizer | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary material #2 | Unknown | N/A | | | proprietary | <1% | <1% |
| Barium stearate [6865-35-6] | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Printing Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 46.5[e] | | | 45.4[f] | | |

[a] Chemical Abstract Services Registry Number.

[b] Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

[c] Conductor is unshielded twisted pair, 8 conductors in 4 pairs; 23-gauge bare copper. The mass of copper is slightly different due to averaging data from different companies, all of which did not provide data for both alternatives. Thus, although within a company, the amount of copper was consistent across alternatives, averaging a different number of

data sets for each alternative resulted in slightly different mass averages of copper.

[e] 92 wt% of the total CMP baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

[f] 92 wt% of the total CMP lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

**Table 2-3**

**Average NM-B Cable Construction Bills of Materials**

| Material Name [CASRN][a] | Function | Baseline Construction | | | Pb-free Alternative Construction[b] | | |
|---|---|---|---|---|---|---|---|
| | | **Mass (kg/km)[c]** | **Weight % of cable with Cu** | **Weight % of cable without Cu** | **Mass (kg/km)** | **Weight % of cable with Cu** | **Weight % of cable without Cu** |
| Copper (Cu) [7440-50-8] | Conductor[d] | proprietary | >5% | N/A | proprietary | >5% | N/A |
| Polyvinyl chloride (PVC) [9002-86-2] | Resin | 14.4 | 12% | **39%** | proprietary | >5% | **>5%** |
| Proprietary plasticizer #2 | Plasticizer | proprietary | >5% | **>5%** | N/A | | |
| Paper/bind | Filler | proprietary | 1-5% | **>5%** | proprietary | 1-5% | **>5%** |
| Calcium carbonate (CaCO3) [1317-65-3] | Filler | 7.2 | 5.8% | **20%** | proprietary | 1-5% | **>5%** |
| Nylon [63428-83-1] | Conductor jacketing resin | proprietary | 1-5% | **>5%** | proprietary | 1-5% | **>5%** |
| Non-phthalate plasticizer #1 | Plasticizer | proprietary | <1 % | **1-5%** | proprietary | 1-5% | **>5%** |
| Proprietary plasticizer #3 | Plasticizer | proprietary | <1% | **1-5%** | N/A | | |
| Calcined clay [66402-68-4] | Filler | 0.600 | 0.48% | **1.7%** | proprietary | <1% | **1-5%** |
| Ca/Zn based stabilizer | Stabilizer | N/A | | | proprietary | <1% | **1-5%** |
| Omyacarb F Bags | Unknown | N/A | | | proprietary | <1% | <1% |
| Unspecified lubricants | Lubricant | N/A | | | proprietary | <1% | <1% |
| Lead-based heat stabilizer #2 | Heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Unspecified colorants [various] | Colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Phthalate plasticizer #4 | Plasticizer | proprietary | <1% | <1% | N/A | | |
| Phthalate plasticizer #5 | Plasticizer | N/A | | | proprietary | >5% | >5% |
| Lead-based heat stabilizer #1 | Heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Antimony trioxide [1309-64-4] | Flame retardant | 0.085 | 0.07% | 0.23% | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Lubricant | 0.070 | 0.06% | 0.19% | N/A | | |
| Lubricant #2 | Lubricant | N/A | | | proprietary | <1% | <1% |
| Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 124[e] | | | 124[f] | | |

[a] Chemical Abstract Services Registry Number.

[b] Data for the extrusion of the NM-B Pb-free alternative was not provided. The bill of materials was generated assuming the same relative inputs of jacketing, insulation, and other materials as in the baseline.

[c] Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

[d] Conductor is 12-gauge 2-conductor copper with ground wire.

[e] 88 wt% of the total NM-B baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

[f] 85 wt% of the total NM-B lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

**Table 2-4**

**CMR Zero-Halogen Material Breakdown**

| Material Name | Weight % of Cable Without Copper[a] |
|---|---|
| Resins<br>FR # 1 | > 5 % |
| FR # 2, 3 | 1 – 5 % |
| Heat stabilizer<br>Lubricants<br>Other | < 1 % |

[a] Materials modeled in this analysis constitute 7 wt% of cable insulation and jacketing.

Decision rules were then applied to the bills of materials in order to determine which materials to focus on during the upstream data collection process. In considering the inclusion of production processes for upstream materials, several factors were considered, including availability of existing data and manufacturers' willingness to participate. Including all of the upstream processes in the scope of the project can unnecessarily lengthen the project period and expend project resources on materials that are unlikely to influence the impact results. The upstream processes included in this analysis were limited to materials contained within the materials found in the final cable constructions. Production processes for materials contained within those cable materials were not included (e.g., production of fluorspar used in FEP production was not considered for inclusion).

The decision criteria provided in Section 1.4.2 were used to assess which upstream processes the scope should include. As per the decision rules, those materials constituting more than 5 percent were given priority, and materials comprising between 1 and 5 percent were evaluated for whether or not upstream inventories were required. Inclusion of materials falling into the 1 to 5 percent range was based on the other decision rule criteria, as well as data availability. Materials of known or suspected environmental or energy significance were included, regardless of their mass contribution. Additionally, materials that were physically unique or functionally significant to a cable alternative (e.g., a Ca/Zn-based stabilizer), as determined by the Core Group, were included to the extent possible if they would have been otherwise eliminated based on the mass cutoff. Because the LCA is comparative in nature, greater emphasis was placed on materials that are physically unique to a cable formulation. In cases where we set out to collect data for a material that met our decision rules and were unsuccessful, in Section 2.1.3 we explain the limitations.

Table 2-5 shows the specific materials for which upstream LCI data were sought, the rationale for their inclusion, and the type of inventory data included in the LCIs. Resins and plasticizers were included because they comprise more than 5 percent of the cable insulation and jacketing compounds by mass. The weight percent of flame retardants ranged from less than 1 percent to greater than 5 percent for the different cable types and alternatives. Any flame retardant comprising greater than 5 percent was included for upstream process data (i.e., ATH), those between 1 and 5 percent were included if secondary data were readily available, and those less than 1 percent were included only if they were greater than 1 percent for a different cable alternative. The lead-based heat stabilizers, which comprise either less than 1 percent or 1 to 5 percent of the insulation and jacketing by mass were included because they are of potential environmental significance. The Ca/Zn-based heat stabilizers were included because they are between 1 and 5 percent and they are physically unique to the alternative formulations compared to the

Pb-based baseline. The fillers and separators were included based on mass. Details about the data are contained in the following sections.

As shown in Table 2-5, primary or secondary data were collected for most of the materials identified using the decision rules. However, data for a few materials, such as some of the flame retardants and other fillers in the compounded jacketing resin (PVC) were not obtained. For the CMR cables, 94 percent of the cable mass is accounted for in the upstream processes for the baseline cable and 90 percent for the lead-free alternative. The zero-halogen CMR cable only accounted for 7 percent of the cable mass. For the CMP cables, 92 percent of the mass is accounted for in both the CMP baseline and lead-free alternative. Finally, 88 percent of cable mass of the NM-B baseline cable is accounted for, and 85 percent of the lead-free NM-B cable. Details of what was and was not included are provided in Section 2.1.2.

**Table 2-5**

**Upstream Materials Selected for Inclusion in LCIs**

| Component | Material name | Decision criteria meta | Upstream process data included |
|---|---|---|---|
| Insulation and jacketing resin | Fluorinated ethylene propylene (FEP)[a] | Mass cutoff | Primary data |
| | High density polyethylene (HDPE) | Mass cutoff | Secondary data |
| | Polyvinyl chloride (PVC) | Mass cutoff | Secondary data |
| | Nylon | Mass cutoff | Secondary data |
| Plasticizer | Phthalate-based | Mass cutoff | Secondary data combined for multiple phthalates |
| | Non-phthalate-based | Mass cutoff | No data obtained |
| Flame retardant | Aluminum trihydrate (ATH) | Mass cutoff | Secondary data |
| | Ammonium octamolybdate (AOM) | Mass cutoff | No data obtained |
| | Antimony trioxide | Mass cutoff | No data obtained |
| | Brominated phthalate | Mass cutoff | No data obtained |
| Heat stabilizer | Pb-based | Environmental significance | Secondary data |
| | Ca/Zn-based | Physical uniqueness | Primary data |
| Filler | Calcined clay | Mass cutoff | Secondary data |
| | Calcium carbonate | Mass cutoff | Secondary data |
| Separator | Polypropylene | Mass cutoff | Secondary data |
| | Polyethylene | Mass cutoff | Secondary data |
| | Fluoropolymer | Mass cutoff | Used primary data of FEP |

[a] FEP production, which came from primary datasets, was modeled with 2 industrial precursor chemicals functioning as inputs; PVC and HDPE, both of which came from secondary datasets, were 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.

Fuels and electricity are used in various processes in each life-cycle stage. All fuels and electricity contributing greater than 1 percent of total energy sources for each process are included in the LCI. Production inventory data were collected for the following:

- natural gas,
- light or distillate fuel oil (fuel oil #2),
- heavy fuel oil (fuel oil #6), and
- electricity generation.

No ancillary (process) materials meeting the decision rules outlined in Section 1.4.2 were identified for the compounding or extruding processes; therefore, no upstream data were collected for ancillary materials. For materials that do not meet the decision rules for inclusion as upstream production processes, the materials themselves are still included in the LCI for a cable alternative and are used to calculate impacts as appropriate for each impact category (see Chapter 3).

### 2.1.2 Data collection

Upstream LCI data were collected from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand. Secondary data are from literature sources or other LCAs, but are specific to a product, material, or process used in the manufacture of the product of interest. Where both primary and secondary data were lacking, modeled data or assumptions served as defaults.

Based on input from the Core Group members, a number of companies (many of which participated in the Core Group) were identified as potential sources of primary data for the production of FEP, plasticizers, flame retardants, and heat stabilizers. These included three manufacturers of FEP, five plasticizer manufacturers, two flame retardant manufacturers, and four manufacturers of heat stabilizers. Only a subset of these companies provided data. Primary data for upstream processes were ultimately obtained for FEP resin and Ca/Zn stabilizer production. Any proprietary information collected from primary sources was subject to confidentiality agreements between Abt Associates, Inc. and the participating company. When multiple data sets were collected from the companies for a single process, data were aggregated to generate a single value for each inventory flow. If aggregation was insufficient to protect the confidentiality of the data, then the data were not reported at a process-specific level.

Where primary data for upstream materials were lacking, secondary data were pursued. In addition, data for the fuels and electricity used in the life-cycle processes were obtained from secondary data sources.

Secondary data were collected for manufacturing PVC, HDPE, phthalate plasticizers, selected flame retardants, and filler material. Neither primary nor secondary data were available for lead-based stabilizer manufacturing, but secondary data were collected for lead manufacturing. The following sections detail the primary and secondary data collected for these materials.

#### 2.1.2.1 Resin manufacturing

The resin is the principal component of cable insulation and jacketing. PVC, FEP, and HDPE are the three main resins used in the cables of interest to the WCP. Secondary data were collected for PVC and HDPE, as well as nylon, another resin used in NM-B cables.

Two databases were identified as potential sources of secondary LCI data for PVC, HDPE, and nylon manufacturing:

- PlasticsEurope (formerly the Association of Plastics Manufacturers in Europe, APME) is an industry body that has published inventory data on HDPE and PVC resin (PlasticsEurope, 2007). These data sets are European-based, of moderate quality, and available free.
- BUWAL is the Swiss Agency for the Environment, Forests and Landscape (PRé, 2004). This agency has several published reports on LCA. BUWAL 250 is an English version of the agency's LCI database of several common industrial materials. It is a relatively inexpensive database that uses European data collected from secondary sources; therefore, the data quality is marginal.

Secondary LCI data from PlasticsEurope (formerly APME) for the production of suspension-polymerized PVC were used in this study. Originally collected by APME in 1992-1993, this LCI data set was last updated in March 2005 (Boustead, 2005b). Ten separate European PVC plants, which produced a combined 1,730,000 metric tons of PVC in 1993, supplied data for the APME study. The PVC data set begins with the raw materials (i.e., crude oil, natural gas, rock salt, and brine) and includes all operations up to the production of the PVC resin; it does not include the compounding process. For detailed information about PVC manufacturing, see Boustead (2005b).

The WCP chose to use the PlasticsEurope secondary data because the data are publicly available and the data collection process is well documented.[9] A major shortfall of the PlasticsEurope PVC data is the fact that it ignores the generation of intermediate products such as ethylene dichloride and vinyl chloride. This gap in the data is expected to potentially understate the occupational health impacts inherent in the production of these chlorinated organics. Secondary LCI data from PlasticsEurope also were used for HDPE production. PlasticsEurope collected production data, representing 1999 production, from 24 plants in Western Europe, which produced a total of 3.87 million metric tons (accounting for 89.7 percent of Western European production) of HDPE in 1999 (Boustead, 2005a). The HDPE data set begins with the raw materials (i.e., crude oil and natural gas) and includes all process steps through to the production of HDPE by polymerizing ethylene. For detailed information about HDPE manufacturing, see Boustead (2005).

Primary LCI data for FEP manufacturing were collected for the WCP. Primary data, representing 2005 production, were collected from two of three major manufacturers contacted.

FEP is synthesized from hexafluoropropylene (HFP) and tetrafluoroethylene (TFE) via emulsion polymerization. A 68:32 molar percent HFP:TFE vapor mixture is fed to a heated reactor containing a surfactant, a perfluoropolyether, and deionized water. A free radical initiator solution starts the polymerization, and additional HFP, TFE, and initiator solution are added as the polymerization proceeds. LCI data included in the WCP cover the synthesis of FEP from fluorspar, sulfuric acid, methane, and chlorine. Figure 2-1 shows the steps in the synthesis of TFE, HFP, and FEP (Ring *et al*., 2002):

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[9] A report prepared for the Plastics Division of the American Chemistry Council (ACC) includes newly developed LCI data for several plastics, including HDPE, PVC and polypropylene (Franklin and Associates, 2007). The report, however, was not available in time for this study. The ACC study described differences between their data and the PlasticsEurope database. They found that the energy impacts of HDPE, PVC and polypropylene based on the ACC database were 9%, 10%, and 13% less than the PlasticsEurope data, respectively. The differences were due to the differences between the North American and European means of forming, transporting, and disposing materials. Thus, the use of PlasticsEurope data could overestimate energy impacts by the percentages noted; and could potentially overestimate other impact categories by unknown amounts. Note: another data source (EcoInvent) was not available for review.

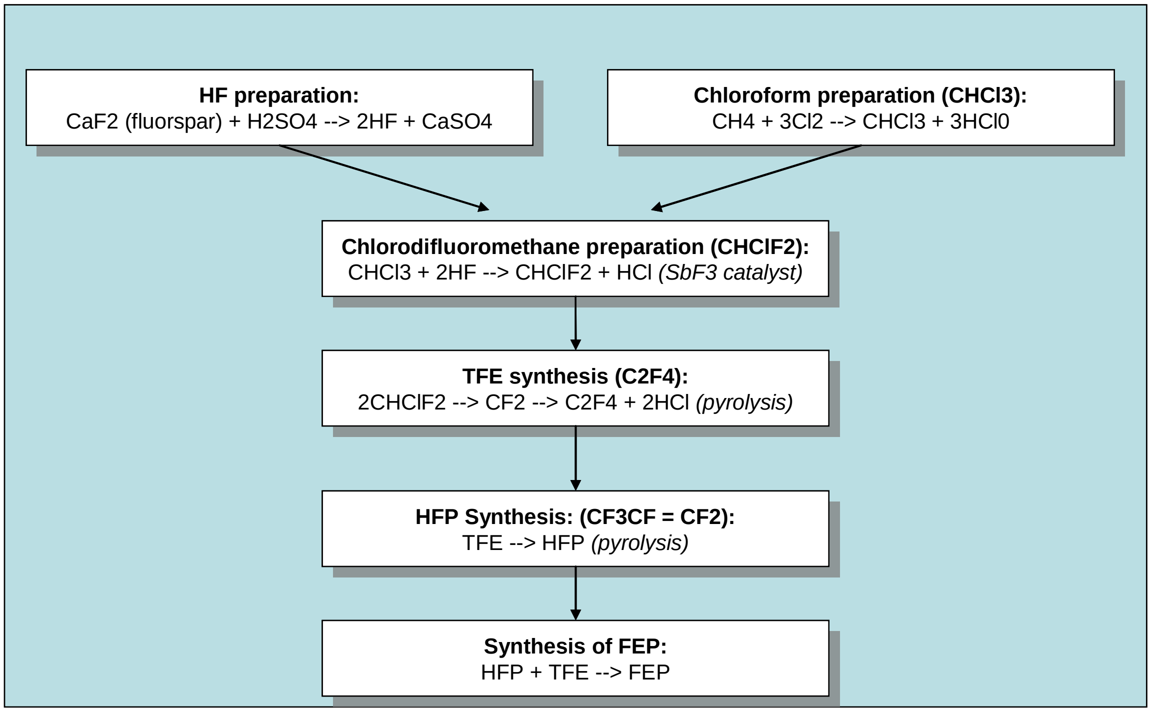

Figure 2-1. Fluorinated Ethylene-Propylene Synthesis

This study included upstream production of major materials in the cables (e.g., FEP) as defined by decision rules described earlier; however, it did not include in its scope upstream production of major materials used to produce the upstream materials (e.g., production of fluorspar, which is used in FEP production, is not included as an upstream process; however, these materials are included in the cable inventories and any impacts associated with those flows are included). However, as a result of secondary dataset boundaries, PVC and HDPE were modeled as coming from ground (i.e., all inputs were mined, bulk precursors). This discrepancy limits the utility of comparisons between FEP and the other resins, especially in impact categories that utilize inputs rather than outputs.

Polypropylene and polyethylene are two resins used in the CMR separators (crosswebs) that meet the mass cutoff decision rules. Secondary data for HDPE described above is used, as well as secondary data available in GaBi 4 for polypropylene. The polypropylene data within GaBi was secondary LCI data derived from the Eco Inventories of the European Polymer Industry (PlasticsEurope). The GaBi 4 documentation does not note the sample size, location, and total mass output of the representative plants. Polypropylene constitutes less than 5 percent of the mass of the cables without copper.

#### 2.1.2.2 Plasticizer manufacturing

The wire and cable industry incorporates plasticizers into PVC in order to make it flexible and workable. The wire and cable industry uses many different plasticizers, most commonly, phthalate esters and trimellitates. For CMR cables, plasticizers represent between 12 and 16 percent by weight of the cable without the copper; for NM-B, between 10 and 40 percent; and for CMP, less than 7 percent. Phthalate esters are the most commonly used type of plasticizers. The wire and cable industry uses many different phthalate esters in PVC compounds. This report does not list the specific phthalate esters that the study partners use, because the compounds' formulations are proprietary. The WCP was unable to collect primary data for plasticizer manufacturing; therefore, secondary LCI data from *Ecobilan* for the production of the three major phthalate esters—dioctylphthalate or di-2-ethylhexyl phthalate (DOP or DEHP), diisononyl phthalate (DINP), and diisodecyl phthalate (DIDP)—were used as a surrogates in this study (*Ecobilan*, 2001). Eight companies, representing 15 European production plants, provided data for the *Ecobilan* study, which refer to 1998 phthalate ester production, with the exception of some 1999 data.

Phthalate esters are manufactured by reacting phthalic anhydride (PA) with two moles of oxo alcohols to produce the ester (Kattas *et al*., 2000; *Ecobilan*, 2001). The length and nature of the oxo alcohols (C1 to C13) used to make the esters affects their properties. DEHP is produced from 2-ethylhexanol, DINP is produced from isononyl alcohol, and DIDP is produced from isodecyl alcohol (*Ecobilan*, 2001). The *Ecobilan* study collected primary data for the production of DEHP, DINP, and DIDP; and the main intermediates: phthalate anhydride (PAN), C8 and C9 olefins, synthesis gas, n-butyraldehyde, 2-ethylhexanol, isononyl alcohol, and isodecyl alcohol.

Since the *Ecobilan* data are general to three major phthalate esters, they are used to represent all the phthalate plasticizers in this project. This approach was chosen over excluding upstream data for the plasticizers, which are greater than 10 percent by mass of CMR and NM-B cables.

Trimellitate esters are used as plasticizers in wire and cable compounds in conjunction with phthalate esters. The WCP was unsuccessful in its attempts to collect primary data for the manufacture of trimellitate esters, and no sources of secondary data were identified; therefore, this LCA does not include an LCI dataset for the manufacture of trimellitate esters. However, trimellitate plasticizers represent less than 5 weight percent of the insulation and jacketing for the CMR baseline and less than 7 weight percent for the CMR lead-free alternative. This omission will therefore have a greater effect on the lead-free alternative results than the baseline.

### 2.1.2.3 Flame-retardant manufacturing

Flame retardants are added to PVC in order to slow the spread of fire, reduce the amount of heat and smoke emitted during a fire, and cause a fire to self-extinguish. Aluminum trihydrate (ATH, aluminum hydroxide) is the most commonly used flame retardant in U.S. wire and cable, comprising 73 percent of the market in 1998 (TURI, 2002). Antimony trioxide/oxide (ATO), ammonium octamolybdate, and brominated phthalates are also used as flame retardants in the cables that the WCP is evaluating.

The WCP was unsuccessful in its attempts to collect primary data for the manufacture of these four flame retardants. Secondary LCI data were available for ATH production, while no secondary data sets were available for ATO, ammonium octamolybdate, or brominated phthalates. ATH represents the majority (by weight) of all flame retardants used in the CMR and CMP alternatives this study is evaluating. The flame retardant in NM-B cables comprises less than 1 percent by weight, and therefore no upstream flame retardant data are included.

A secondary data set for the production of ATH was used in this study, from the SP Swedish National Testing and Research Institute (Andersson *et al*., 2005). ATH is a heat-absorbing flame retardant that removes heat by using it to evaporate water from its structure (Kattas *et al*., 2000). It is typically used in flexible PVC formulations in the 20 to 50 phr (parts per hundred parts resin) range (Kroushl, 2004). ATH is typically manufactured from the mineral bauxite, which contains 40 to 60 percent alumina, silica (silicon oxide), iron oxide, and titanium dioxide. In the Bayer process for alumina production, the alumina is dissolved in hot sodium hydroxide solution, and the iron oxide and other oxides are removed as insoluble “red mud.” The solution is then purified, and aluminum trihydrate is precipitated by cooling the purified solution and seeding with aluminum trihydrate crystals (Beck, 2001).

Antimony trioxide (ATO) is a flame retardant synergist that acts to enhance the flame retarding properties of bromine- or chlorine-based flame retardants (Kattas *et al*., 2000). It is used in PVC-based compounds in the 2 to 3 phr range (Kroushl, 2004). ATO is produced from stibnite ores (antimony trisulfide) or as a by-product of lead smelting and production (IARC, 1989). The manufacture of ATO involves a sublimation reaction of antimony metal with oxygen. Commercial ATO generally contains a maximum up to 0.25 percent of lead and up to 0.1 percent of arsenic contaminants on a weight basis (EFRA, 2006). In cables (in this study) that use ATO, the ATO is less than 3 percent by mass of a length of cable.

### 2.1.2.4 Heat stabilizer manufacturing

Heat stabilizers are added to PVC in order to prevent its thermal degradation during periods of exposure to elevated temperatures, such as during processing (i.e., extrusion) and during the useful life of the cable (Kattas *et al*., 2000). The cables the WCP is studying use either lead-based heat stabilizers or mixed metal-based heat stabilizers. Lead-based heat stabilizers have been the predominant heat stabilizers used in wire and cable applications because they have provided cost-effective stabilization while offering excellent electrical insulation properties. However, lead-based heat stabilizers are being replaced by mixed metal-based heat stabilizers because of concerns about the toxicity of lead (Kattas *et al*., 2000).

The WCP was unsuccessful in its attempts to collect primary data for the manufacture of lead-based heat stabilizers, but a secondary data set for lead manufacturing was available (Primary lead mix, 1997). Because lead-based heat stabilizers are predominantly composed of lead, the lead data set was used as a surrogate for lead-based heat stabilizer manufacturing, by applying the percentage of lead in the lead-based heat stabilizer to the lead data set. Lead sulfates (e.g., tribasic lead sulfate) are inorganic-based stabilizers that are manufactured by reacting lead oxides with sulfuric acid or a sulfate solution (Baitz *et al*., 2004). Dibasic lead phthalate, an organic-based heat stabilizer, contains 76 percent lead; tribasic lead sulfate contains 83.5 percent lead (Associated Additives, 2007). Since the lead-based stabilizers are included for the potential environmental significance of lead, and comprise only small percentages of the non-copper portion of the cables, the remaining non-lead portion of the heat stabilizers, which constitute even smaller percentages of the cables, are not included as upstream data.

Primary data for calcium/zinc-based heat stabilizer manufacturing were provided by two different companies. Calcium/zinc-based heat stabilizers are simple physical blends; no chemical reactions occur. The stabilizers are manufactured by mixing the components in an electrically powered ribbon blender. Table 2-6 shows a typical formulation for a Ca/Zn based stabilizer.

**Table 2-6**
**Ca/Zn-Based Heat Stabilizer Formulation**

| Material | Weight |
|---|---|
| hydrotalcite/zeolite | 0.56 kg/kg |
| calcium stearate | 0.18 kg/kg |
| zinc stearate | 0.17 kg/kg |
| proprietary additives | 0.09 kg/kg |

#### 2.1.2.5 Fillers

The primary fillers used in the manufacture of wire and cable are limestone ($CaCO_3$) and calcined clay. The inventory for the production of both minerals was obtained from secondary data contained within GaBi. The inventory for limestone was based on studies from 1995, 1997, and 1999 documented in German. The source of the inventory for calcined clay, or kaolin, was from 1995 data.

#### 2.1.2.6 Fuels and process materials

The fuel and power inventories were obtained from secondary data sources. The GaBi database inventories of natural gas, fuel oils, and electricity generation were used, and they contain the following processes:

- Electricity generation - Assumes a grid of 52.3 percent hard coal, 22.7 percent nuclear power, 12.4 percent natural gas, 4.2 percent crude oil, 3.5 percent lignite, 3.4 percent hydro, and 1.5 percent other. This process includes the extraction of individual fuels from the ground (e.g., coal, lignite, uranium) and the energy required to extract those fuels. Steam and cogenerated electricity were not modeled as products of the grid, but rather as a burden-less byproduct of using natural gas to generate heat during other processes.
- Natural gas - Exploration, extraction, processing, and distribution (via pipeline or liquefied natural gas [LNG] tanker) to the end customer.
- Light fuel oil (#2) - Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, desulphurization (i.e., medium distillates to hydrofiner), medium distillates mix plant that produces light fuel oil.
- Heavy fuel oil (#6) - Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, residue to fuel mix plant that produces heavy fuel oil.

Table 2-7 summarizes the data sources and data quality information for the secondary fuel and power source inventories used in this study.

### 2.1.3 Limitations and uncertainties

Upstream data for the primary materials used in wire and cable compounds are not readily available. Primary and/or secondary data sets were collected for 12 of the 16 materials identified for inclusion in the upstream data collection process. Primary data were collected for two of the materials: FEP and Ca/Zn-based heat stabilizers. Secondary data were collected for the remainder (see Table 2-5). For the lead-based stabilizers, while data was unavailable on the compounds themselves, the majority of the compounds are lead, and thus the production process of lead was included and scaled to the amount of lead in the stabilizer compounds. Secondary data sets were also collected for all of the fuels and electricity used in the compounding and extruding processes that met the decision rules.

The limitations and uncertainties associated with the ME&P stage inventories are primarily due to the fact that some of these inventories were unobtainable and others were derived from secondary sources and are not tailored to the specific goals and boundaries of the WCP. Because the secondary data may be based on a limited number of facilities and have different geographic and temporal boundaries, they do not necessarily represent current industry practices in the geographic and temporal boundaries defined for the WCP (see Chapter 1). These limitations and uncertainties are common to LCA, which strives to evaluate the life-cycle environmental impacts of entire product systems and is, therefore, limited by resource constraints that do not allow the collection of original, measured data for every unit process within a product life cycle.

**Table 2-7**

**Data Sources and Data Quality for Fuel and Power Inventories Used In Various Life-Cycle Stages**

| Materials | Year of data | Geographic boundaries | | Primary data sources[a] | Data quality description |
|---|---|---|---|---|---|
| | | *Extraction* | *Processing* | | |
| Natural gas | 1995 | Canada, Mexico, United States, Algeria | United States | b, c | GaBi4 states the data quality is "...good. The important flows are considered. Natural gas supply is representative." |
| Light fuel oil (#2) | 1994 | Unclear (various country-based data sources cited) | Germany | d, e | GaBi4 describes the data quality as "good." It is average industrial data from 1994. |
| Heavy fuel oil (#6) | 1994 | Unclear (various country-based data sources cited) | Germany | d, e | GaBi4 describes the data quality as "good." It is average industrial data from 1994. |
| Electricity generation | 1995 | Multiple countries, fuel dependent | United States | Not available | GaBi describes the data quality as "good," claiming to use consistent statistics and a comparable information basis for every state. |

[a] All primary data sources are available within the GaBi4 database (PE&IKP, 2003).

[b] ETH Zuerich. oekoinventare Energiesysteme. Schweiz, 1996 (in PE&IKP, 2003).

[c] U. Fritsche *et al.* Gesamt- Emissions- Modell Integrierter Systeme (GEMIS) Version2. Darmstadt, 1992 (in PE&IKP, 2003).

[d] ETH Zuerich. oekoinventare Energiesysteme. Schweiz, 1996 (in PE&IKP, 2003).

[e] K. Weissermehl; H.J. Arpe. Industrielle Organische Chemie. 5. vollst. ueberarb. Auflage. Weinheim, 1998 (in PE&IKP, 2003).

Specific to the secondary PVC and HDPE inventories, a major assumption is that European-based data for production of these resins is similar to U.S.-based process data. For PVC, chlorinated intermediate materials such as ethylene dichloride and vinyl chloride were not provided in the inventory, which will affect occupational inputs (see Chapter 3). For the lead-based heat stabilizer inventory, a major assumption is that the production of lead adequately represents the upstream impacts associated with lead-based stabilizer manufacturing. Specific to the electric grid inventory, uncertainties exist in the weighting values applied to the various fuel sources from which the power is generated for the U.S. electric grid. The factors were based on a reference year of 1995, and, thus, may vary given the volatility of the oil supply and the current U.S. energy policy.

Other, specific limitations include the following:

- For the primary data sets (i.e., FEP and Ca/Zn production), 2 companies provided data for each process. While a greater number of companies would have been preferred, those providing data likely represent a large market share of the products.
- Data for phthalate esters were not directly available; thus the *Ecobilan* data, which combines the production of several phthalate esters into one data set, was used to represent all phthalate plasticizers identified for the cables being studied in this project. It is unknown what the

implications of this limitation would be on the results; however, those alternatives using a smaller amount of plasticizers will have less uncertainty associated with this limitation.

- Upstream process data for trimellitate plasticizers (used for CMR and NM-B cables) were not included in the LCIs for this study; however, these plasticizers are used in lower amounts than the phthalate plasticizers.
- Upstream data for some flame retardants were not available; however, those for which data were lacking only constitute small amounts of the cable insulation and jacketing by mass.
- FEP production data does not include extraction and processing of fluorspar and many other post-mining precursors, in contrast to PVC and HDPE. However, this only affects the results to the extent there are differences in the amount of FEP used in the lead versus the lead-free alternatives (the baseline uses under 10 percent more FEP by weight).
- Secondary data are not all US-specific; however, it is unknown how this affects the results, except that it contributes to uncertainty.

In general, although some upstream data have been excluded from the LCIs despite meeting the mass cutoff, what is most important about how they affect the results is how different the quantities are for the alternatives being compared. For example, if CMP, lead-stabilized cables use nearly the same amount of a certain material, there will be less impact on the results.

## 2.2 Manufacturing Life-Cycle Stage

This section addresses the LCIs related to the product manufacturing life-cycle stage of cables. The cable manufacturing life-cycle stage includes two distinct processes: the compounding of the insulation and jacketing resins, where applicable, and cable manufacturing, which includes extrusion of insulation and jacketing.

The purpose of this section is to present the approach for obtaining process-specific inventory data related to the manufacturing stage (i.e., compounding, crossweb manufacturing, and extruding) of three cable types: Category 6 CMR- and CMP-rated telecommunications cables, and low-voltage power (i.e., NM-B) cables. LCI inputs for the manufacturing stage of the WCP include primary materials used in the insulation and jacketing compounds and in the cable extrusion process, ancillary materials used to manufacture the compounds and extrude the cables, and energy and other resources consumed in the manufacturing of the compounds and extrusion of the cables. LCI process output flows include primary products; co-products; and releases to air, water, and land.

### 2.2.1 Data collection

Primary data were collected through site visits or through the distribution of data collection forms for all of the processes associated with the manufacturing life-cycle stage. Site visits were conducted at four facilities, representing two compounders, two extruders, and one crossweb manufacturer (one facility performs both compounding and extruding).

Data collection forms were developed by the Abt Associates, Inc. research team and approved by the Core Group to most efficiently collect and organize inventory data needed for the LCA (Appendix A). Data forms were completed during site visits or directly by companies when site visits were not possible. Collected data included brief process descriptions; primary and ancillary material inputs; utility inputs (e.g., electricity, fuels, water); air, water, and waste outputs; and product outputs. Quantities of inputs and outputs provided by companies were converted to mass per unit of product produced, which was later scaled to the mass per one kilometer of cable length to conduct the analyses on a common functional unit basis. Transport of materials to and from the manufacturing facility was excluded from the data collection process for this study, because it was assumed that impacts from transportation would be similar for all alternatives within each product type.

During each site visit, Abt Associates, Inc. researchers and company personnel completed a data collection form similar to those completed by facilities that were not visited. Each site visit took approximately half a day and included an extensive tour of the processes, interviews with process personnel, and a period of time spent completing and reviewing the data on the collection form for accuracy. Data either had been previously measured or collected by the facility, or were estimated with the assistance of process personnel with appropriate experience and process knowledge. Data were collected, when possible, on a per mass of compound or cable produced basis.

Data collected from the processes were then scaled to represent the mass of the material required per functional unit, which for the WCP is one kilometer (3,281 feet) of cable. Process data collected based on volume were converted to mass using the product’s density. In cases where data collected covered the processing of more than one type of compound or cable (e.g., monthly energy consumption for a process producing multiple compounds or cable types), data were allocated to the various compound or cable types based on the mass of product produced. Other data were allocated to the compounds or cables using appropriate conversions, where applicable. Multiple data sets collected for a single process were aggregated before being used for analyses in the study. Data were aggregated to generate a single value for each inventory item, to represent an industry average and to protect the confidentiality of individual data points. The one variation to this approach (for CMR/CMP extrusion energy data) is described in Section 2.2.4.

### 2.2.2 Telecommunications cables

The WCP is evaluating two types of telecommunications cables: Category 6 riser-rated cable (CMR) and Category 6 plenum-rated cable (CMP). These cables consist of four pairs of insulated copper conductors that are separated by a crossweb and encased in a plastic jacket. Primary data for the manufacturing life-cycle stage were collected from compounders, crossweb manufacturers, and extruders through a series of facility site visits and through the distribution of data collection forms. Data were collected for the standard (i.e., baseline) and alternative formulations for both cable types (see Section 2.1.1). Although these processes vary slightly by manufacturer and cable type, the overall process for manufacturing telecom cables follows a similar series of process steps. Figure 2-2 displays a flow diagram for both CMR and CMP cable manufacturing. The diagram depicts the primary process steps for which manufacturing LCI data were collected. (Note that the wire drawing process was excluded from this study.)

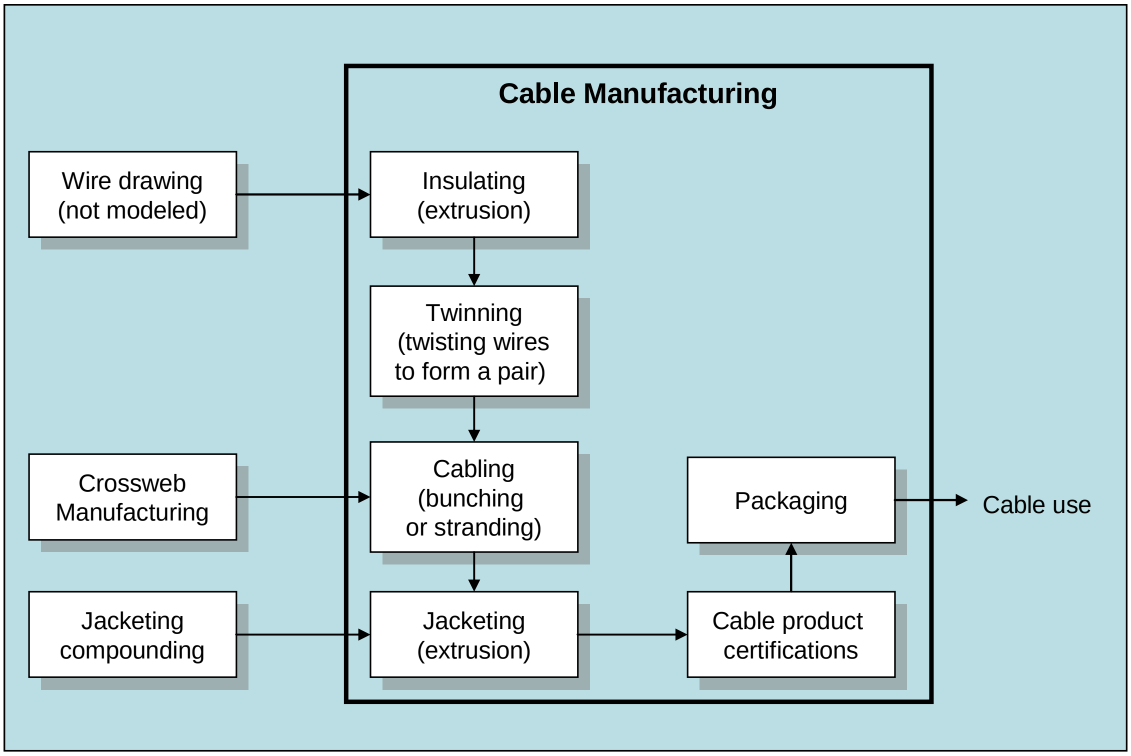

Figure 2-2. Manufacturing Process Diagram for CMR- and CMP-rated Telecommunications Cables

Compounding, a preliminary step in the manufacturing stage, involves the blending of the base jacketing resin (PVC) with various additives in order to impart desired characteristics (e.g., flame retardancy, flexibility) in the resin. Within the wire and cable industry, compounding is conducted either by custom compounders or by the cable manufacturers themselves. Crosswebs, which typically consist of only the base insulation resin (i.e., HDPE or FEP), are manufactured by extrusion. Cable manufacturing is a multi-step process that involves extruding insulation onto the conductors, twinning two insulated conductors to form a pair, bunching or stranding multiple twisted pairs (cabling), extruding a jacket over the bunched pairs, and packaging the cable for sale.

Primary data were collected for the three processes—compounding, crossweb manufacturing, and extruding—that comprise the manufacturing life-cycle stage for telecom cables. The following subsections describe these processes and the associated data collected for them.

#### 2.2.2.1 Compounding

PVC, which is used as a jacketing for CMR and CMP cables, is given its desired properties (e.g., flexibility, resistance to thermal degradation, flame retardancy) by compounding the base PVC resin with a variety of additives—plasticizers, heat stabilizers, and flame retardants—at an elevated temperature. Although each individual PVC compounder uses its own proprietary mix of additives, they all employ a similar PVC compounding process.

PVC compounds are prepared in a batch process using blenders that allow precise temperature control. The compounding process involves high-intensity blending of resin and additives to form a dry blend powder, which is then compounded using compounding equipment, such as a Farrell Continuous Mixer (FCM), a Buss Kneader, or twin screw and other machines. The compounded mixture is then pelletized. The pellets are spherical or cylindrical, with diameters averaging 1 to 5 mm (Barry and Orroth, 2000).

Electricity is the main energy source used in the compounding process; it is used to power the blenders and roll mills. The compounding process also uses fuel oil or natural gas to produce steam, which provides heat to the blenders.

Primary data for manufacturing the baseline and alternative CMR and CMP jacketing compounds of interest to the WCP were collected directly from the compounders participating in the project. A total of six primary datasets were received for compounding CMR jackets: three for lead-stabilized compounding, two for Ca/Zn-stabilized compounding, and one for halogen-free CMR jacket compounding. Four primary datasets were received for compounding CMP jackets: two for lead-stabilized compounding and two for Ca/Zn-stabilized compounding.

#### 2.2.2.2 Crossweb manufacturing

The Category 6-rated CMR and CMP unshielded twisted pair (UTP) telecom cables of interest to this study contain a crossweb or pair separator. Crosswebs provide physical and electrical separation of the twisted conductor pairs, which improves the cable's crosstalk performance. (Crosstalk is the unwanted interference signal that comes from coupling between one conductor pair and another; see d'Allmen, 2000.) Although the specific design of the crossweb varies by manufacturer, the material used in the crossweb is typically chosen so that it mimics the insulation material used in the cable as closely as possible. The crosswebs used in the cables of interest to this study generally consist of virgin or postindustrial recycled PE (for CMR cables) or FEP (for CMP cables). Postindustrial sources of FRPE and FEP include resin that does not meet specification, and bleeder scrap (i.e., the plastic that cable manufacturers generate during the start-up of their extrusion lines). Postconsumer cable scrap (i.e., plastic collected from cable chopping operations) is currently not usable as a feedstock for crosswebs because the plastic contains an unacceptable level of copper fines.

Crosswebs are manufactured by a basic extrusion process. The extruder line consists of a hopper to hold the resin, a screw extruder, a cooling bath, a puller (to pull the crossweb through the process), and a reel for winding the final product. Electricity, which is used to heat the extruder, is the main energy source used during the crossweb manufacturing process. FEP-based crosswebs require more energy to extrude than PE-based crosswebs because FEP has a higher melting temperature than PE; therefore, a higher temperature is required in the extruder.

Primary data for CMR and CMP crossweb manufacturing were collected directly by one crossweb manufacturer participating in the project.

#### 2.2.2.3 Cable manufacturing

Cable manufacturing is a multistep process. The conductor material (e.g., copper wire) is first drawn to the specified diameter. The bare wire is then transferred to the wire coating line, where electrical insulation material (HDPE for CMR cables, FEP for CMP cables) is extruded onto the conductor using a single-screw extruder. The wire coating line typically consists of an unwinding roll for the wire followed by a tension controlled input capstan, possibly a wire straightener, and a wire preheater, which improves the adhesion of the plastic to the conductor. The wire proceeds from the preheater to the extruder's crosshead die, where the melted plastic insulation is applied. Processing temperatures in the die average 400° F (204° C) for HDPE and 650 to 700° F (343 – 371° C) for FEP. The coated wire continues through a water bath and/or air-cooling system, spark tester, gauge controller, tension output capstan, and tension controller, and is then wound onto a bobbin or reel.  Output rates for extruding the wire insulation average approximately 550 m/min (1,800 ft/min) for FEP and 1,500 m/min (5,000 ft/min) for HDPE (Tyler, 2007).

After the insulation has been applied, two conductors are twisted together (paired) in a process called twinning.  The number of twists per foot is precisely controlled during the twinning process, and each of the four pairs is twisted differently (i.e., different number of twists per foot) in order to limit crosstalk between pairs in the final cable.  Twinning lines use two motors:  one to feed insulated wire to the process and one to take up the twisted conductor pairs.  The next step is cabling, in which four of the twisted pairs are bunched or stranded together with a crossweb separating the twisted pairs.  A jacket, which protects the conductors from mechanical damage and provides fire retardancy, is then extruded over the core using a process similar to the one used to apply the wire insulation.  Any markings are printed onto the cable jacketing during this step.  Jacketing proceeds at an average speed of 400 to 500 feet per minute (120-150 m/min); temperatures in the die average 320 to 350° F (160 – 177° C).  Both the CMR and CMP cables use compounded PVC for the jacketing.  The final cable product is tested for adherence to electrical parameters and then packaged into customer-desired lengths.

The primary wastes from the cable manufacturing process (excluding waste from the copper drawing process) are scrap cable, and insulation and jacketing resins.  Any insulation or jacketing that is bled from the extruding lines during start-up or shut-down is collected and recycled to the process.  Preconsumer PVC waste is relatively easy for PVC compounders and cable extruders to recycle and reuse as an equivalent for virgin PVC, because the composition is known.  Scrap cable from the process is sent to cable chopping operations for recycling (see Section 2.4).

One dataset was collected for CMR Pb-stabilized cable manufacturing, two datasets were received for CMR Ca/Zn-based cable manufacturing, and no datasets were received for halogen-free CMR cable manufacturing.  For CMP cable manufacturing, one dataset was received for Pb-stabilized CMP cables and two datasets were received for Ca/Zn-stabilized CMP cables.

### 2.2.3 Low-voltage power cables

The WCP is evaluating one type of low-voltage power cable—nonmetallic-sheathed cable (NM-B)—that is primarily used in residential wiring as branch circuits for outlets, switches, and other loads.  There are numerous types of NM-B cables available because both the conductor gauge and number of conductors can be varied.  The WCP chose to focus on 12-2 NM-B cables because they are the most commonly used NM-B cables.  12-2 NM-B cables consist of two insulated copper conductors and a paper-wrapped ground wire, all of which have a diameter of 12 AWG (American Wire Gauge).  The entire assembly is wrapped with a paper filler, then encased in a plastic jacket.

Primary data for the manufacturing life-cycle stage were collected from compounders and extruders through facility site visits and through the distribution of data collection forms.  Data were collected for baseline and alternative formulations for 12-2 NM-B cables.  Although the compounding and extruding processes vary slightly by manufacturer, the overall process for manufacturing low-voltage power cables follows a similar series of process steps.  Figure 2-3 displays a flow diagram for the manufacture of NM-B cables.  The diagram depicts the primary process steps for which manufacturing LCI data were collected.  (Note that the wire drawing process was excluded from this study.)

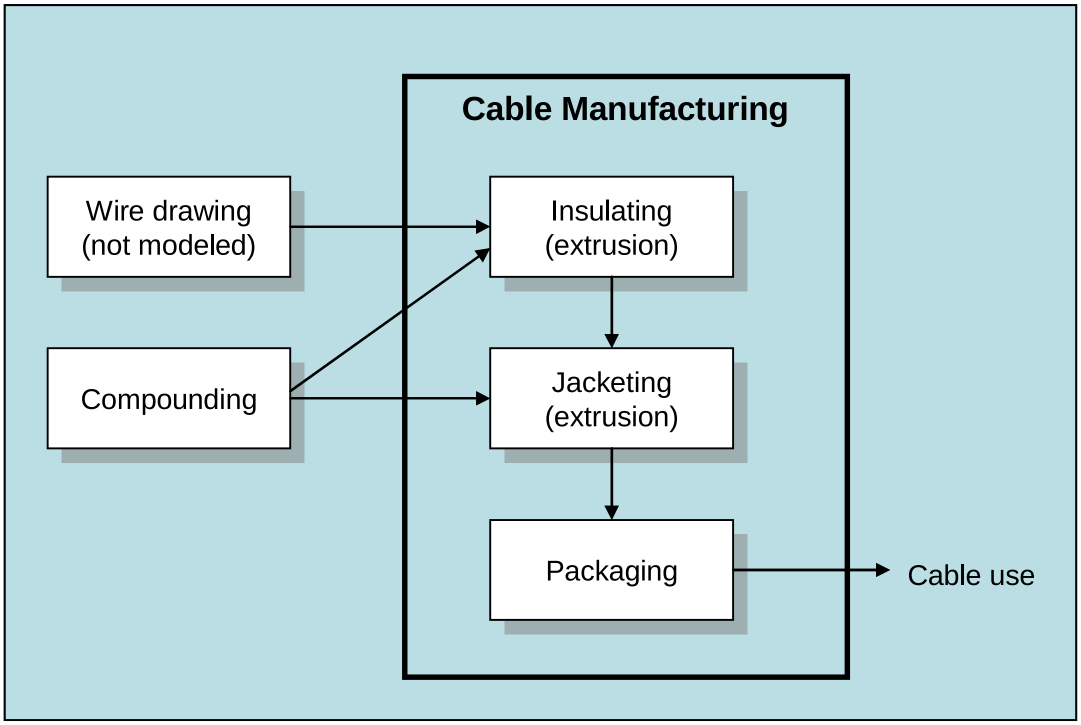

Figure 2-3. Manufacturing Process Diagram for Nonmetallic-sheathed Low-voltage Power Cable

Similar to the communication cables, compounding is the first step in the manufacturing life-cycle stage. Compounding involves the blending of a base resin (i.e., PVC) with various additives in order to impart desired characteristics (e.g., flame retardancy, flexibility) to the resin. Within the wire and cable industry, compounding is conducted either by custom compounders or by the cable manufacturers themselves. Cable manufacturing (primarily involving extruding) is a multi-step process that involves extruding insulation onto the conductors, applying the paper filler to the ground wire, wrapping the entire construction with a paper filler, extruding a jacket over the three wire assembly, and then packaging the cable for sale.

Primary data were collected for compounding and extruding of low-voltage power cables, which are described in the following subsections.

### 2.2.3.1 Compounding

PVC is used as insulation and jacketing for NM-B cables, is given its desired properties (e.g., flexibility, resistance to thermal degradation, flame retardancy) by compounding the base PVC resin with a variety of additives—plasticizers, heat stabilizers, and flame retardants—at an elevated temperature. Although each individual PVC compounder uses its own proprietary mix of additives, all employ a similar PVC compounding process.

As described above in Section 2.2.2.1, which discusses CMR and CMP cables, PVC compounds are prepared in a batch process using blenders that allow precise temperature control. The compounding process involves high-intensity blending of resin and additives to form a dry blend powder, which is then compounded using compounding equipment, such as a Farrell Continuous Mixer (FCM), a Buss Kneader, or Werner-Pfleiderer PK-400 machines. The compounded mixture is then pelletized using a twin-screw extruder. The pellets are spherical or cylindrical with diameters averaging 1 to 5 mm (Barry and Orroth, 2000).

Electricity is the main energy source used in the compounding process; it is used to power the blenders and compounders. The compounding process uses fuel oil, natural gas, and propane to produce steam, which provides heat to the blenders.

Three primary datasets were received for NM-B Pb-stabilized insulation compounding; only one dataset was received for compounding the Pb-stabilized jacket. For the Ca/Zn-stabilized compounds, two datasets were received for the insulation and one was received for the jacketing.

#### 2.2.3.2 Cable manufacturing

Cable manufacturing (primarily involving extruding) is a multistep process. The copper conductors and ground wire are first drawn to the specified diameter. The conductors are then transferred to the wire coating line, where the electrical insulation is extruded onto the conductors using a tandem extruder. The tandem extruder first extrudes the PVC-based electrical insulation compound onto the bare wire and then immediately extrudes a nylon jacket onto the PVC. Color concentrates are added to the PVC in the extruder. The wire coating line typically consists of an unwinding roll for the wire followed by a tension-controlled input capstan, possibly a wire straightener, and a wire preheater, which improves the adhesion of the plastic to the conductor. The wire proceeds from the preheater to the extruder's crosshead die, where the melted plastic insulation is applied. Processing temperatures in the die average 320 to 350 °F (160 – 177 °C). If required by the customer, the specifications are then printed on the conductor. The coated wire continues through a water bath and/or air-cooling system, spark tester, gauge controller, tension output capstan, and tension controller, and is then wound onto a roll. Output rates for extruding the wire insulation average 4,000 feet per minute (1,300 m/min) (Barry and Oroth, 2000; Rosato, 1998).

Spools of the insulated conductors and uncoated ground wire are mounted at the beginning of the jacketing line. Two spools of paper, which are approximately one to two inches wide, are also mounted at the beginning of the jacketing line. The ground wire is first wrapped with paper, rather than being insulated with plastic, because paper is less expensive than plastic. The insulated conductors and paper-wrapped ground wire are then laid parallel, with the ground wire between the conductors, and the entire assembly is wrapped with a paper filler. A PVC-based jacket, which protects the conductors from mechanical damage and provides fire retardancy, is then extruded onto the cable using a process similar to the one used to apply the wire insulation. Jacketing proceeds at an average speed of 400 to 500 feet per minute (120-150 m/min); temperatures in the die average 320 to 350 °F (160 – 177 °C). An inkjet printer prints the specifications onto the jacketing before the cable is cooled in a water bath. The finished cable is then coiled, spooled, or reeled, depending upon the customers' needs, and packaged for delivery.

Electricity is the main energy source used during the cable manufacturing process. It is used for wire drawing, to melt the plastic in the extruder, and to drive machinery that moves the wire around the facility.

The primary wastes from the cable manufacturing process (excluding waste from the copper drawing process) are PVC and nylon. These materials are primarily generated as bleeder scrap (i.e., insulation and jacketing that is bled from the extruding lines during startup). A majority of the bleeder scrap is repelletized and reused in the process, but that which is not recyclable is sent to landfills. Scrap cable is sent to cable chopping operations for recycling. (See Section 2.4 for more information about the cable chopping process.)

One primary dataset was received for NM-B Pb-stabilized cable manufacturing; no datasets were received for Ca/Zn-stabilized cable manufacturing.

### 2.2.4 Data collection summary

Table 2-9 shows the number of primary datasets received for the major processes associated with the cable manufacturing life-cycle stage. Primary data were collected for the major processes associated with the manufacturing life-cycle stage for telecom and low-voltage power cables. These data were collected directly from eight cable compounders and manufacturers through site visits and through the distribution of data collection forms. These data represent a total of 30 data sets for the manufacturing life-cycle stage of the three cable types.

**Table 2-9**

**Total Primary Datasets Received for the Cable Manufacturing Life-cycle Stage**

| Cable type/alternative | Crossweb manufacturing | Compounding | | Cable manufacturing | Total |
|---|---|---|---|---|---|
| | | Insulation | Jacketing | | |
| CMR Pb-stabilized | 1 | n/a | 3 | 1 | 5 |
| CMR Ca/Zn-stabilized | 1 | n/a | 2 | 2 | 5 |
| CMR halogen-free | 0 | n/a | 1 | 0 | 1 |
| CMP Pb-stabilized | 1 | n/a | 2 | 1 | 4 |
| CMP Ca/Zn-stabilized | 1 | n/a | 2 | 2 | 5 |
| NM-B Pb-stabilized | n/a | 3 | 2 | 1 | 6 |
| NM-B Ca/Zn stabilized | n/a | 2 | 2 | 0 | 4 |

Multiple data sets for a process were averaged to represent the industry average. In one case, a large discrepancy existed, and the simple averaging approach was modified as necessary. That is, for CMR and CMP cables, electricity is the main energy source used during the cable manufacturing process. It is used for wire drawing, to melt the plastic in the extruder, and to drive machinery that moves the wire around the facility. The modeling of the extrusion of *lead-free* CMR/CMP cable drew upon data sets from two companies. Utilities information from these data sets suggested that the use of electricity during the extrusion process varies highly from company to company. The modeling of the extrusion of the *baseline* CMR/CMP cable drew on data from only one of these companies. Consequently, the aggregated lead-free value from the two companies was divergent from what would be expected as an aggregated value for the baseline (as verified by the companies supplying the data). In light of this, a proxy energy value for the baseline CMR/CMP cable was created. The proxy value was generated by applying the ratio of the extrusion energy of the lead-free extrusion energy data points to the leaded case. Thus,

$$\text{Proxy}_{\text{base},2} = (E_{\text{Pb-free},2} / E_{\text{Pb-free},1}) \cdot E_{\text{base},1}$$

### 2.2.5 Limitations and uncertainties

Limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (i.e., those companies that are more advanced in terms of environmental protection might be more willing to supply data than those that are less progressive). Companies providing data also may have a vested interest in the project outcome, which could result in biased data being provided. Where possible, multiple sets of data were obtained for this project to develop life-cycle processes. The peer review process and employment of the Core Group as reviewers in this project is intended to help identify and reduce any such bias. Additional limitations to the manufacturing stage inventory are related to the data themselves. Specific data with the greatest uncertainty include the utility data for multiple processes that were scaled to the specific process or processes of interest to the WCP. The greatest source of variability in the data was the CMR/CMP cable extrusion energy, described in the preceding section.

## 2.3 Use Life-Cycle Stage

The use stage encompasses installation, use, maintenance, repair, and reuse of the standard and alternative cables. During these activities any input flows such as materials, fuels, and electricity are assumed to be the same for each alternative within a cable type, and therefore do not affect the comparative analyses in this study. Further, no direct outputs would be anticipated. While installers could be exposed to dust recirculated within an existing installation site from aging cable insulation and jacketing, these exposures are expected to be the same regardless of the alternative and therefore also would not affect the study’s comparative analyses.

### 2.3.1 Installation

For installation during new construction, CMP communications cable is placed within the plenum space, typically using a J-hook or a tray to secure it. The cable is mechanically connected and left in place for use. The ceiling acoustic tiles are then secured. When additional cable is installed, a few ceiling tiles are removed and new cable is added (Dawson, 2007). CMR communications cable is placed in conduits or secured to existing structures with ties during installation. The cable is left in place for use after being mechanically connected.

NM-B cable is used primarily in residential wiring as branch circuits for outlets, switches, and other loads. The cable is typically installed during residential construction through holes drilled into studs where the cable is pulled through. If additional cable is added, holes are drilled in the wall and the cable inserted (Sims, 2007).

Within each cable type, installation procedures are the same for each cable alternative, which supports the scoping decision to exclude the use stage from the LCI.

Although concern has been raised about the existence of lead dust during installation of new cables (Wilson, 2004), any existing dust would be the same for any alternative, provided installation occurs at the same time for each alternative. For example, if lead-free CMP cable is compared to lead-stabilized CMP cable, installation would occur at the same time and installers would have the same exposure to existing dust, regardless of the resin cable being installed. Differences would occur at EOL when cables are removed and dust is generated from either the leaded or lead-free alternative.

### 2.3.2 Use, maintenance, and repair

Communications cable and electrical cable are used in temperature-controlled environments where the temperatures are well below those known to release chemicals of concerns from cable insulation or jackets under normal conditions. (Catastrophic events such as fires are addressed in the end-of-life, Section 2.4). Communications cable has built-in redundancy; therefore, there is no planned maintenance and repair during cable life, and the cable's technical obsolescence is the usual driver for replacement (Dawson, 2007). NM-B electrical cable has a 25 to 40 year useful life with typically no maintenance or repair. The cable installed at construction is usually used throughout the building life (Sims, 2007). For this analysis, there is no difference among the standard and alternative cable types for use, maintenance, and repair.

### 2.3.3 Reuse

Communications cable is typically replaced when it is obsolete (Dawson, 2007) and there is little domestic market for reuse. Any reuse in developing world markets is outside the scope of this analysis. Electrical cable, with a life span of 25 to 40 years, is not reused either, often due to electrical codes (Sims, 2007). However, the copper conductor in both types of cable is likely to be recovered (as discussed in Section 2.4).

### 2.3.4 Limitations and uncertainties

The use stage has not been included in the WCP LCIs. Since the focus of the analyses in this project is comparing functionally equivalent alternatives, and no differences among alternatives are anticipated during the use stage, no limitations are foreseen. Potential exposure to workers removing cables is discussed in Section 2.4, although the WCP does not quantify such exposures. Because this life-cycle stage is excluded, care must be taken not to interpret results as the full life cycle of an individual alternative, but rather as a comparison of differences among alternatives.

## 2.4 End-Of-Life

EOL issues are of growing interest to cable manufacturers, building owners, and building tenants, due to the National Electrical Code's requirement that all accessible abandoned copper and fiber optic cabling be removed from buildings. It is important to note that although the copper conductor material is an essential component of cable wire and contributes to life-cycle impacts, this project focuses on the insulation and jacketing resins, and follows disposition of these materials through the end of life.

This section describes the issues associated with EOL cables (i.e., cables that have been used for their initial, intended purpose and are no longer intended to be used), and the approach used to evaluate the EOL life-cycle stages of CMR, CMP, and NM-B cables for the WCP. This approach includes developing scenarios to represent reasonable EOL alternatives, and collecting LCI data for the EOL alternatives.

### 2.4.1 Background

Based on 2002 data, U.S. sales of CMR-rated cables average approximately 1.2 billion ft/yr and account for 15 percent of the total U.S. communications network cable market. CMP-rated cable sales total approximately 6.0 billion ft/yr, accounting for approximately 75 percent of the U.S. communications network cable market (CRU, 2002). Category 6 cables held approximately a 45 percent share of the unshielded twisted pair (UTP) market in 2005, with rapidly increasing growth (Glew, 2005). An estimated 2.7 billion ft/yr of Cat 6 CMP-rated cable, and 0.54 billion ft/yr of Cat 6 CMR-rated cable, is installed annually in the U.S.[10]

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[10] This assumes that the breakdown of CMP- and CMR-rated cables (75% and 15%, respectively) holds true for Cat 6 cables: 6.0B ft/yr*0.45 = 2.7B ft/yr of Cat 6 CMP cable, and 1.2B ft/yr*0.45 = 0.54B ft/yr of Cat 6 CMR cable.

In 2005, the annual U.S. market for NM-B rated cable was estimated at 800 million to 1 billion pounds (7.3 to 9.2 billion feet)[11] (Sims, 2005). Information on projected sales of communications and low-voltage power cables or on amount of cable installed (current and projected) was not available.

Cables are long-life products; therefore, there is a considerable time lag between when the cables are manufactured and installed and when they reach end-of-life. For example, communications cables have an expected lifetime of 10 to 15 years, due to obsolescence resulting from technological advancements. In addition, low-voltage power cables have a useful life of approximately 25 to 40 years. As a result of this time lag, current EOL generation patterns of cables are not correlated with their contemporary production (Mersiowsky, 2002). A large quantity of PVC waste is not expected to hit the market until 2010 because PVC did not achieve significant market shares until the 1970s (Plinke *et al*., 2000).

The removal of abandoned cabling is expected to generate in excess of 300 million pounds of plastic waste over the "next several years" (Realcomm Advisory, 2006). EOL cables are generated in small quantities from disperse sources. This may change over time as more EOL cable becomes available due to stricter regulations, such as the Abandoned Cable Provision of the National Electrical Code (Realcomm Advisory, 2006).

Projected amounts of EOL cable in the U.S. were not found (e.g., the amount of communications EOL cable in 10 and 15 years; and the amount of low-voltage power EOL cable in 25 and 40 years).

### 2.4.2 Materials Recovery

#### 2.4.2.1 Copper

End-of-life communications and low-voltage power cables are valuable because they consist of approximately 50 percent copper by weight, which sold for $4,800 to $7,400/ton in the last year (June 2006 to June 2007) (COMEX, 2007). According to the Bureau of International Recycling (BIR), this historically high price of copper ensures that an estimated 95 percent of EOL cable and wire is recycled (Bartley, 2006). EOL cables are highly sought after by copper consumers in North America and overseas, and overseas competition, especially from China, is often cited as a source for changes that have greatly affected the wire and cable recycling sector in recent years. Foremost among the changes has been a willingness among export brokers representing consuming companies in China to pay more for copper-bearing wire and cable scrap than many North American consumers will pay (Taylor, 2005). China's seemingly insatiable demand resulted in a shortage of copper cable for U.S. scrap cable processors in 2003 (Taylor and Toto, 2003); however, in 2004, customs, trade, and environmental regulations in China slowed down the pace of EOL cable sales to China and helped to re-establish the U.S. wire chopping market (Taylor, 2004).

#### 2.4.2.2 Polymer fraction

Traditionally the polymer fraction (i.e., insulation, jacketing, and crossweb) of EOL cables has been landfilled because it is regarded as a waste product with little value; however, it does have value and can be recycled (Hagström *et al*., 2006). The types of products the polymer fraction can be used for are typically limited because it consists of a mix of plastics (i.e., compounded PVC, HDPE, and FEP), whereas plastics extruders typically require a pure feedstock. Because these polymers are all

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[11] Using an average net weight of 109 lbs/1,000 ft (0.109 lbs per foot for 12-gauge 3-conductor copper NM-B with ground wire, i.e., typical Romex building wire).

thermoplastics, they can be remelted during recycling and used as a substitute for virgin materials in general plastic products (e.g., industrial flooring, car floor mats and mud flaps, shoe soles, sound barriers, and garden hoses), concrete products (e.g., parking blocks, speed bumps, and large planters), and/or wood products (Plinke *et al.*, 2000).

The potential to collect and recycle installation wastes (i.e., cut-offs from installing cables) also exists; however, this cable waste is often mixed with other construction waste and would have to be separated prior to recycling (Plinke *et al.*, 2000).

### *Fluorinated ethylene propylene*

While the high cost of virgin fluoropolymers provides a greater incentive to recycle the FEP from EOL cables, the small volumes that are available and the difficulty of separation make the recycling of FEP from EOL cables problematic (Ring *et al.*, 2002). However, several companies are developing technologies to effectively recycle fluoropolymer cable. For example, DuPont, Inc. has implemented a copper cable recycling program to develop new cable products containing recycled plastics. The program recycles the plastics from EOL communications cables into separate streams for each plastic material. DuPont notes that an average Category 6 enhanced plenum cable could contain over 3 lbs per 1,000 foot-box of recycled fluoropolymer (DuPont, 2006). In addition, some manufacturers of cable recover 100 percent of their waste FEP to manufacture pair separators used in Category 6 plenum cables (Uniprise, 2006).

### *Polyvinyl chloride*

The amount of EOL PVC insulation and jacketing that is recycled is limited due to technical, economic, and logistical constraints (UNEP, 2002). Plinke *et al*. (2000) identify two primary technical constraints:

- PVC is a compounded material; an average cable jacket consists of a mixture of 50 percent plasticizers, heat stabilizers (often lead-based), flame retardants, and other additives, and 50 percent PVC resin.
- Different cable applications (i.e., CMR, CMP, and NM-B) use different PVC-based compounds, including different plasticizers, stabilizers, and flame retardants. Furthermore, different cable manufactures use their own unique compounds, so even within the same cable type, the compounds differ. These formulations also change over time, which can cause additional problems for a long-life product such as cable.

Because the overall PVC industry is large, many potential markets exist for the recovery of PVC materials. If the recycled PVC is to be used to produce new PVC products, its composition must meet the specifications of the new product, which may be achieved through additives to gain or enhance the needed properties (Bennett, 1990). However, the technical constraints noted above make it difficult to identify the composition of the post-consumer EOL PVC insulation and jacketing, and, for post-consumer PVC waste, to make a one-to-one substitution of recycled PVC for virgin PVC (Plinke *et al.*, 2000).

Based on a European source (Plinke *et al.*, 2000), EOL cables are collected primarily to recover the valuable copper conductor. Therefore, from an economic standpoint, the recycling of the PVC fraction starts at the cable recycler and does not include the collection and treatment of the cables. As with other waste streams, the decision to recycle the plastic fraction is based on whether the cost to transport and recycle the material, minus any revenue for the recovered plastic, is less than the costs of landfilling or incineration. In addition, the profitability and demand of PVC recycling depends on the fluctuating cost of virgin PVC (Plinke *et al.*, 2000). As of 2000, PVC recovered from EOL cables was considered the only post-consumer PVC waste for which recycling is profitable (Plinke *et al.*, 2000).

Logistical constraints are largely related to the fact that EOL cables are generated in small quantities from dispersed sources, making collection less efficient. This may change over time as more EOL cable becomes available due to stricter regulations, such as the Abandoned Cable Provision of the National Electrical Code.

The presence of heavy metals, such as lead, and other potentially toxic substances in PVC is of potential concern because these materials will be dispersed into the variety of products that are made from the recycled PVC. However, because these toxic materials are fixed in the PVC matrix, the risk of exposure to humans and the environment is often considered low (Plinke *et al.*, 2000). According to Wilson (2004), there is, however, some concern that removing abandoned cables could result in lead exposure because, as the plasticizer leaches out of the compound over time, the PVC becomes brittle and the lead could potentially migrate to the surface, leaving behind dust with a high lead content. Lead dust in the plenum space, for example, could reach building occupants or workers removing the abandoned cables. However, studies have shown that the aged PVC cables perform extremely well in regards to physical properties, precluding embrittlement from occurring (Dini, Fabian, and Chaplin, 2006).

In 1997, 0.2 million kilograms (0.5 million pounds) of PVC were recovered from EOL wire and cable and recycled (Principia Partners, 1999). However, we do not have the breakdown of how much is pre- and post-consumer waste.

***Polyethylene***

Polyethylene (PE), when used as the insulation for CMR cables, is typically not compounded (i.e., the insulation consists of 100 percent PE). Therefore, PE could potentially be recovered and reused. In many mechanical recycling operations, however, it is difficult to obtain the clean streams of recycled PE that are required for it to replace virgin PE (Hagström, *et al*., 2006). BASF, on a pilot scale, has tested a thermolysis process (in which PE is decomposed into ethylene using heat) for chemically recycling PE; however, the cost of the recovered ethylene from thermolysis was higher than the cost of virgin ethylene produced from fossil fuel (Hagström *et al.*, 2006).

### 2.4.3 Regulations covering EOL communications and building cables

#### 2.4.3.1 Abandoned cable provision of National Electrical Code (NEC)

The National Fire Protection Association (NFPA) estimates that there are approximately 60 billion feet of communications cables installed in the United States, many of which are abandoned (Network Cabling, 2005). Section 800.2 of the NEC defines abandoned cable as “installed communications cable that is not terminated at both ends at a connector or other equipment and not identified ‘For Future Use’ with a tag.” Abandoned cabling poses a substantial risk to health and safety because it increases the amount of combustible material in concealed spaces (i.e., risers and plenum spaces), may generate toxic fumes when subjected to fire, can affect air flow in ceiling plenums, and generates a significant amount of smoke (Fishman, 2006; DuPont, 2007). In order to address the growing concern over abandoned cable, the NFPA added a new provision to the NEC in 2002 that mandates the removal of all accessible abandoned copper and fiber optic cabling from buildings. (The 2005 NEC also contains this abandoned cable provision.) Although the NEC itself is not codified as law, any jurisdiction that has adopted the 2002 or the updated 2005 NEC (which incorporates the 2002 NEC) into its building code can enforce the abandoned cable provision (BOMA, 2006).

#### 2.4.3.2 Basel Convention

The Basel Convention addresses the production, management, and international transport of certain hazardous wastes, including metal cables with plastic insulation containing lead stabilizers. The convention states that regulated wastes are not exportable without the consent of the government of the receiving country. These wastes include “waste metal cables coated or insulated with plastics containing or contaminated with coal tar, PCB, lead, cadmium, other organohalogen compounds” or other constituents regulated by the convention (Annex VIII, Basel Convention, 1992).

Waste metal cables using plastics that do not contain coal tar, PCB, lead, cadmium, or other toxic components are not regulated by the convention as long as they are disposed of via operations “which do not lead to the possibility of resource recovery, recycling, reclamation, direct re-use or alternative uses”; or “operations involving, at any stage, uncontrolled thermal processes, such as open burning” (Basel Convention, 1992). FEP is listed in the convention as a substance that is unregulated in its pure form, but PVC and PE are not explicitly mentioned anywhere in the treaty (Annex IX, Basel Convention, 1992).

The convention issued technical guidance regarding plastic coated cables in 2002, stating that “open burning is not an environmentally acceptable solution for any kind of waste” and that it “must not be applied to processing of cable scrap” (UNEP, 2002). Cable chopping and stripping are recommended as the most economical and environmental methods of recycling cable scrap, especially if the cable is pre-sorted so that the separated plastic insulation will be relatively pure. The guidance goes on to recommend incineration in state-of–the-art furnaces as the only environmentally responsible method of burning cable waste, and that energy should be recovered whenever possible (ENS, 2002).

Though the United States is a party to the convention, which took effect in 1992, the U.S. Senate has not yet ratified it. An amendment that bans the export of hazardous waste from developed to developing countries for purposes of final disposal or recycling was adopted in 1995, but has not been ratified by a sufficient number of countries to come into force.

#### 2.4.3.3 Landfill restrictions

The NEC does not address the *disposal* of abandoned cabling that has been removed from buildings. Given the likely presence of lead stabilizers in PVC jacketing in the abandoned cable, some municipalities may be concerned about its disposal in construction and demolition (C&D) landfills or municipal solid waste (MSW) landfills. After reviewing the types of hazardous materials (HAZMAT) that are in the waste stream for landfills, some municipalities are beginning to route the heavy metal wastes from the unlined C&D landfills to the lined HAZMAT waste facilities. This may in turn increase the costs of disposal for abandoned cable (Bisbee, undated).

### 2.4.4 EOL disposition options

The major EOL dispositions for cables that are removed from the structure in which they were installed include recycling, incineration, and landfilling. In addition to the EOL dispositions that would occur when a cable is physically removed, a fire could cause a cable to reach its end of life. The WCP considers reuse to be part of the use stage, so reuse is not discussed here. Also, while post-industrial cable scrap generated by manufacturers could follow the same dispositions as EOL cables, this is not included under the EOL discussion. The following sub-sections qualitatively examine the EOL options for communications cables and low-voltage power cables.

### 2.4.4.1 Recycling

Recycling of copper cables is motivated by the high value of copper. The first step of recycling is to separate the conductor from the insulation and jacketing. The copper is then sent to a copper smelter for reprocessing. The remaining resins are either disposed of or also reprocessed. As the focus of the WCP is on the resin systems, we do not describe the copper smelting process.

***Separation***

BIR (2006) reports that there are two primary, economically viable and environmentally sound methods for separating the plastic insulation and jacketing from the metal conductor of EOL cable: chopping and stripping. According to UNEP (2002), these methods have been able to prevail worldwide due to the development of pre-sorting techniques and the expanded chopping capacity, plus the concurrent development of a better technique for separating tailings. Developed countries primarily recover the metal from cable scrap using automated cable chopping operations. Developing countries typically use cable stripping machines, which are less expensive than cable chopping operations, but have a much lower throughput (BIR, 2006). One advantage of cable stripping over cable chopping is the improved purity of the recovered jacketing and insulation materials. According to UNEP (2002), the recovered materials are claimed to be completely free of conducting metal, and with careful segregation of the cable scrap prior to processing, the recovered materials can consist of one type of polymer. Cable stripping often results in a waste plastic stream that is more than 99.5 percent pure, which facilitates recycling of the plastic waste. In contrast, a cable chopping operation that uses a pre-segregated feedstock of EOL cable and an electrostatic process to remove all residual metal from the plastic fraction produces a plastic stream that is 90 to 95 percent pure. Both metal and polymer tailings, therefore, are more easily recyclable using cable stripping (UNEP, 2002).

***Cable chopping***

In North America, an estimated 55 facilities (51 in the United States) were operating one or more cable chopping lines in 2003 (Taylor and Toto, 2003). Systems vary in size from 225 to 680 kg/hr (496 to 1499 lb/hr) to 4,770 to 5,455 kg/hr (10,516 to 12,026 lb/hr), and costs (based on 1997 prices) vary from $150,000 for small chopping machinery to $1.8 million for larger machines. U.S. cable choppers typically operate lines with capacities reaching at least 5.5 tons/hr (5 metric tons/hr). Cable chopping typically involves the following steps (BIR, 2006; Finlay, 2004; UNEP, 2002):

- *Pre-sorting* involves the separation of long cable sections by type of insulation and jacketing (e.g., PVC, FEP, or PE), by conductor diameter, or as plated or unplated conductor; the separation of densely baled cables; and the separation of pieces of ferrous and non-ferrous metal, which can be fed directly into a metal shredder, from loose cable. One of the most important functions of pre-sorting is the separation of copper cable from aluminum cable.

  Pre-sorting is the most important step in the cable chopping process, because it allows maximum value to be obtained for the recovered metal scrap and it makes further separation of plastics easier. Long cable sections are sheared into lengths of about one yard so that they can be fed into a granulator, whereas densely baled cable is broken up into loose streams. Material not well-suited to such automated systems (e.g., superfine wire and grease or tar-filled cables that can obstruct the system) can be separated out manually beforehand.

- *Cable chopping* is used to reduce long cable sections into an acceptable size for the granulator. It is commonly performed in large operations but is optional at smaller facilities.

- *Granulation* uses primary and secondary granulators to strip the plastic insulation and jacketing from the metal conductor. These machines process cables from about three inches diameter to thin cable of about 26-gauge (0.016 in). A secondary granulator reduces the cable lengths to about 0.6 cm (0.24 in.), which typically liberates most of the metal from the plastic; however, small amounts of metal will remain imbedded in the plastic fraction.
- *Screening* is often used in cable chopping operations to enhance the recovery of metal by yielding the desired chop size. Smaller chop sizes allow for more-efficient removal of the metal. Oversize material can be reprocessed in the granulator. Fines, which contain metal, plastics, fibers, and dirt, drop through the bottom of the screen. Metal particles are recovered from the fines by removing lighter, non-metallic particles and dust using an aspirator.
- Separation techniques, such as gravity or air density tables, washing systems, and fluidized bed separators, are used to separate the metal fraction from the plastic residue. The metal content of residue streams can vary from less than 1 percent to more than 15 percent, depending on the separation technique employed. Some cable processors have installed dry electrostatic systems, which can reduce the metal content of tailings to less than 0.1 percent, thereby increasing the value of the recovered plastic.

#### ***Cable stripping***

Cable stripping is a less expensive method for recovering the copper from EOL cable, but it has much lower throughput than cable chopping. Cable stripping equipment is designed to handle only single strands of cable waste at rates up to 60 m/min (197 ft/min) or 1,100 kg/hr (2425 lb/hr) with cable as thin as 1.6 mm (0.06 in.) or as thick as 150 mm (5.9 in.). Based on 1997 prices, machines that operate at 24 m/min (78.7 ft/min) sell for about $5,000, whereas small tabletop machines that operate at rates of only 8 m/min (26.2 ft/min) sell for as little as $1,800 in the United States and Europe (BIR, 2006). Developing countries typically prefer cable stripping machines rather than the more expensive cable chopping machines; cable stripping machines are also used in most developed countries by utilities, cable manufacturers, cable chopping companies, and metal scrap dealers.

#### ***Separation by incineration***

Cable scrap can be incinerated to obtain the conductor metal using authorized controlled atmosphere furnaces that seek to prevent the formation of persistent organic pollutants (POPs). Only a few such furnaces have been authorized in the world. Plans to build new incinerators or to expand the capacities of existing facilities are often met with public resistance, often due to concerns about PVC incineration, which generates a large amount of hydrogen chloride and potentially forms dioxins and furans (Braun, 2002). Recovery of the metal fraction of EOL cable using incineration is less preferable than chopping or stripping because burning can oxidize the metal, thus decreasing its value. State-of-the-art furnaces, however, are better able to control the combustion conditions and avoid oxidizing the metal (UNEP, 2002).

#### ***Other separation methods***

Cables are often exported to developing countries for reuse or recycling. According to UNEP (2002) about 30 percent of the total amount of EOL cables is reused rather than recycled. For cables exported annually from the United States, Japan, and Europe to developing countries, and which are not reused, the copper (and aluminum) conductors have a sale value to smelter operators, but the PVC or PE insulation and jacketing is frequently disposed of, often by open burning (Lemieux *et al.*, 2004; *Recycling Today*, 2002).[12]

### *Polymer recycling*

Due to its high value, the copper in cables is often recovered and recycled; however, only in some cases is the plastic material recycled. In order to increase their value and expand their reuse options, mixed plastic tailings from both cable chopping and cable stripping operations are often further separated into a clean PE fraction and a clean PVC fraction using either sink and float (hydrogravimetric) or cryogenic processing (UNEP, 2002). Sink and float processing, which employs a liquid medium, separates lower density plastics (i.e., PE), which float on the liquid, from higher density plastics (i.e., PVC), which sink (Hagström *et al.*, 2006). Cryogenic processing uses liquid nitrogen to freeze the mixed plastic tailings. At liquid nitrogen temperatures, PVC shatters into small particles when it is impacted; polyethylene and some other plastics do not. The relatively small PVC particles are then screened from the other larger plastics to produce a purer PVC fraction (UNEP, 2002).

The separated polymers can then be recycled using either mechanical or chemical processes. Currently four different chemical processes—cracking, gasification, hydrogenation, and pyrolysis—are being considered for chemical recycling, which is the conversion of polymers back into short-chain chemicals for reuse in polymerization or other chemical processes (Braun, 2002). Mechanical recycling processes use mills and extruders to convert the separated plastic fractions into re-granulates of a defined size and composition (Plinke *et al.*, 2000).

#### ***PVC recycling***

One method of reprocessing the PVC fraction of cable waste is the The Solvay Vinyloop® process. According to a representative at Vinyloop® in Ferrara, Italy, the primary feedstock to the Vinyloop® process from the wire and cable industry is end-of-life PVC-based cable insulation that is generated by copper reclaiming operations. More than 90 percent of the PVC-based insulation that the Vinyloop® process recycles is from EOL building cables; less than 10 percent of the cable scrap is from EOL communications cables (Leitner, 2006). According to Hagström *et al*. (2006), however, the Vinyloop® process is better suited to the recycling of pre-consumer production scrap because the input material conforms to today's environmental requirements. EOL cables, in contrast, are likely to contain additives that were permitted some years ago, but may not be so freely used today, thus contaminating the final recycled PVC product. For economic reasons, the Vinyloop® plant in Ferrara, Italy, is designed for processing waste with an average minimum PVC content of 85 percent. Plastic scrap with a PVC content of 50 to 60 percent requires a triboelectric step, which separates other polymers and makes a waste containing at least 85 percent PVC (Hagström *et al.*, 2006; Scheirs, 2003).

The Vinyloop® process selectively dissolves the PVC in a solvent, such as tetrahydrofuran or methylethylketone; separates the PVC from insoluble or secondary materials, including polyethylene, copper, and other elastomers; and then precipitates the regenerated PVC compound, including all components of the original formulation (i.e., heat stabilizers, plasticizers, flame retardants, and colorants), as microgranules for resale. The regenerated PVC can be reprocessed by extrusion, injection, or calendaring (continuous extrusion between a pair of cylinders). The solvent is fully recovered and

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[12] The Recycling Today article did not specify the type of burning (e.g., controlled or uncontrolled), or who burns the waste insulation and jacketing; while Lemieu *et al*. specified that open burning occurs. (See *Smouldering of Copper Cables*: http://www.pops.int/documents/meetings/bat_bep/2nd_session/egb2_followup/draftguide/6LCopperCablesDRAFT.pdf.)

recycled within the process. A study by PE Europe did not detect dioxin formation when the Vinyloop® process was used to recycle scrap PVC cables (Kreissig *et al*., 2003). Solvay has a demonstration plant operating in Ferrara, Italy, and opened a commercial-scale facility in Chiba, Japan, in May 2006 (Glew and Grune, 2004; Vinyloop, 2006).

The Stigsnæs Plant in Denmark also has a process for recycling PVC waste. The plant, owned by RGS 90, uses a two-step chemical process to recycle all types of PVC waste. First, PVC is hydrolyzed to an inorganic (chlorine) fraction and an organic (hydrocarbon) fraction. Then the organic fraction is post-heated. Salt (NaCl), a fluent oil fraction, and a sandblasting material are the products from the process. The capacity of the plant is approximately 50,000 metric tons per year, and the gate fee is in the range of $200 to $300 per metric ton (Hagström *et al.*, 2006). As of 2005, RGS 90 has been forced to stop accepting PVC waste while they consider other options for the plant. Technical difficulties and an inability to compete with other options, especially landfills, on price led to the suspension of operations (Vinyl 2010, 2006). Currently, a feasibility study is underway to build a Vinyloop® facility in the United States (Vinyloop, 2007).

***FEP recycled into cross web***

Since FEP does not have the additives that PVC has, it can more easily be reprocessed into product. Thus, FEP is sometimes reprocessed as crossweb for CMP communications cables by extruding the scrap FEP. However, the small volumes and difficulty of separation makes the recycling of FEP from EOL cables problematic (Ring *et al.*, 2002). As noted previously, some cable manufacturers recover 100 percent of their pre-consumer waste FEP to manufacture pair separators used in Category 6 plenum cables (Uniprise, 2006).

***Other recycling methods***

There are other methods that are mentioned here only briefly, as they are not believed to constitute common practices. However, if they become more prevalent in the future, they may be applicable to the EOL disposition of the cables studied in this project once they finally reach their end of life. These methods include:

- Low Smoke-PVC from plenum jacketing recycled and blended with virgin PVC for new riser jackets (Glew & Grune 2004).
- Center for Research into Plastic Materials (CEREMAP) is a plastics recycling company based in France. CEREMAP recovers mixed plastic material into “low-value” products that are adapted for regional markets (e.g., palettes, boxes, outdoor furniture, building materials, etc.) (Ecolink, 2003).
- Japanese microwave radiation technique to assist in the separation of the wire and insulation materials (Glew & Grune 2004).

#### 2.4.4.2 Waste-to-energy (WTE) incineration

Incineration with energy recovery is a viable option for treating the polymer fraction of EOL cables because of the high energy content that is liberated upon combustion of polymers. Polyethylene has a heat of combustion of 46 MJ/kg and generates only water and carbon dioxide upon combustion at temperatures typical of WTE incineration (1,000°C). PVC, which has a heat of combustion of 18 MJ/kg, consists of carbon, hydrogen, and chlorine, and generates hydrochloric acid upon combustion. The PVC and PE fractions are typically separated prior to incineration because the hydrochloric acid formed by burning PVC requires special measures (Hagström *et al.*, 2006). FEP, on the other hand, generates very little energy: its heat of combustion is 5.1 MJ/kg (Plastech, 2007). Although FEP does not burn easily, it emits hydrogen fluoride, a highly toxic gas (Wilson, 2004). Comparatively, the heat of combustion for automotive gasoline is about 44 MJ/kg (DOE, 1997).

#### 2.4.4.3 Landfilling

According to Scheirs (2003), landfilling is the predominant means for disposing of PVC waste throughout the world. There is a concern that, over time, the PVC matrix will break down under landfill conditions, allowing the additives to leach from the PVC. Mersiowsky *et al*. (2001) found that, after 28 months under simulated landfill conditions, a lead-stabilized PVC cable lost around 40 percent of its original content of a secondary phthalate-based plasticizer; the content of the primary plasticizer, di-isodecyl phthalate (DIDP), did not change. This study also found that none of the PVC samples underwent changes in molecular weight distribution, nor was vinyl chloride detectable in the biogas of the sample vessels (Mersiowsky *et al.*, 2001).

Lead stabilizers are primarily immobilized in the PVC matrix, which ensures that leachability into the environment is extremely low; however, the increased surface area of finely divided PVC waste from cable chopping operations might facilitate extraction under certain landfill conditions (e.g., acidic leachate conditions; see Scheirs, 2003). Leachate rates for lead from CMR cables are estimated to be between 1 to 2 percent if the cable has not been chopped/stripped significantly, and approximately 10 percent for smaller, chopped cable particles (personal communication with Dr. Townsend, University of Florida, 2007). These leachate rates would apply to a 100-year lifetime of a landfill.

According to Hagström *et al*. (2006), combustion as a high-grade fuel is the only technical, economical, and environmentally acceptable method currently available for dealing with the PE fraction of the polymer waste from EOL cable.

According to Scheirs (2003), "On the basis of the available research and evidence, the landfilling of end-of-life PVC seems to be environmentally acceptable when mechanical recycling and thermal treatment processes are not possible. The overall conclusion of the most recent studies is that PVC products do not constitute a substantial impact on toxicity of landfill leachate and gas."

#### 2.4.4.4 Fire scenario

A building fire could cause a cable to reach the end of its life prematurely. While CMR and CMP cables are primarily installed in commercial and educational buildings, NM-B cable is found in the vast majority of buildings, including residential, agricultural, and industrial structures. Further discussion on frequency estimates are provided below in section 2.4.5.1.

### 2.4.5 LCI Methodology

Modeling the EOL stage required two key steps: (1) estimating the EOL distribution among the disposition options (i.e., recovery, incineration, and landfilling), and (2) estimating the inventory flows for each disposition option. These steps are described in detail below.

#### 2.4.5.1 Distribution Estimates of EOL

Figure 2-4 presents the major disposition options for EOL cable. The schematic shows that a certain fraction of the resins can end up in a variety of final dispositions, including recovery, landfilling, and incineration. As noted previously, although most cable reaches the EOL stage after the end of its useful life, some may reach this stage prematurely through a building fire. A conservative upper-bound estimate for the annual frequency of fires in buildings is about 1.1 percent for those buildings that have CMR and CMP cabling and approximately 0.5 percent for buildings with NM-B cabling (however, due to the lack of complete life-cycle data the NM-B analysis did not ultimately use include the EOL scenarios). Appendix B provides the methodology for making these assumptions, which used National Fire Protection Association Data and U.S. census data.

There was not, however, sufficient quantitative information regarding the percent of cable burned in a fire to empirically determine a central estimate. Thus, we applied a default estimate: 10 percent of the cables contained in a building where a fire has occurred are assumed to have been consumed in the fire (based on best professional judgment, which considered the fact that cable fires occur but are expected to occur at relatively low frequencies). This estimate was varied in the uncertainty analysis, assuming complete uncertainty for this parameter (see Section 3.4). The default estimate recognizes that 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, either percent would be in the range of the uncertainty analysis. Further, the CMR is not being compared to the CMP, precluding any effect on the analyses in this LCA. Based on the above considerations, the point estimate calculations conducted in this LCA used a value of 0.11 percent of CMR and CMP cables that reach the EOL stage through fires.

Estimates for the distribution of cable after its useful life were not readily available; however, wire and cable recycling for copper recovery is currently estimated at 95 percent (Bartley, 2006). We assume that this includes the proportion that is sent overseas, and that the estimate recognizes that a proportion of what is sent for recycling is sometimes first re-used. However, we still assume that the ultimate disposition (after it is reused) is to recycle the cables for the copper content. Provided the value of copper continues to remain high, we expect recycling to continue to be prevalent at the time when the cables produced now reach their end-of-life (e.g., 10 or 15 years for communications cables, and 25 or 40 years for the low-voltage power cables).

The cables sent for recycling could either undergo wire chopping, wire stripping, or burning to separate the copper from the plastic material. Data is limited, however, on the distribution of recovered cable amount associated with these separation options. Although cable chopping may be more prevalent in North America, as stated earlier, there may be a large amount of EOL cables going to developing countries where stripping and burning might be more established. However, as noted above, the UNEP Basel Convention has restricted the shipment of plastic insulated cables for uncontrolled burning (Basel Convention, 1992). For the analysis in this study, we assumed 100 percent of the recovered cable undergoes chopping, given the lack of LCI data on the other separation options.

Once the copper and plastics fraction are separated, the copper is sent to a copper smelter and the plastics fraction is either recycled or disposed. Because the copper smelting process is beyond the scope of this study, our analysis focuses on the plastics fraction that is sent for recycling versus disposal. The percent of chopped resin that is recycled is very uncertain. A European Commission study completed in 2000 (Plinke, 2000) provides an upper estimate that 20 percent of resin in cables sent for recycling is sent to thermoplastic recycling.[13] We assumed an arbitrary midpoint of 10 percent of the resins going to thermoplastic recycling. This parameter was then varied in the uncertainty analysis presented in Section 3.4.

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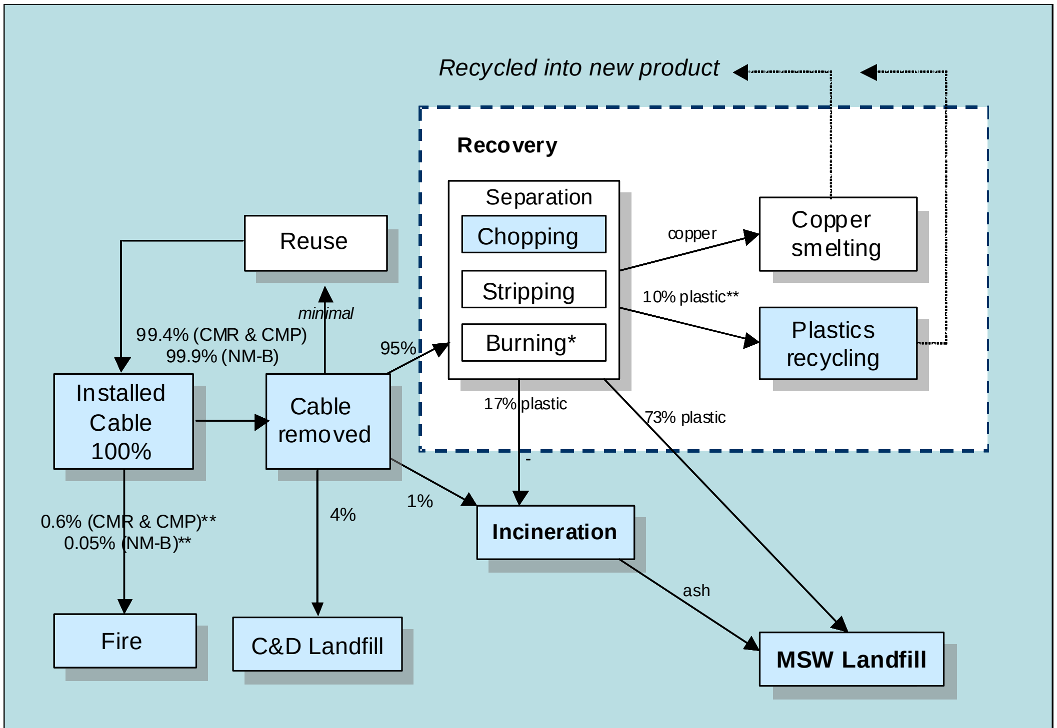
[13] Note that this estimate is from a historical point in time and other factors such as different recycling rates, international shipping of wires and cables, and the introduction of new technologies since the study was done could affect the accuracy of this bounding estimate.

The remainder of the chopped resin is assumed to be incinerated or landfilled (at the same MSW percentage split described below). Any conclusions regarding recycling rates should be understood in the context of probable future progress in the area of recovery technology (e.g., Vinyl2010, 2006).

As illustrated in Figure 2-4, EOL cables that are not recycled are landfilled or incinerated. Given the limited data on the distribution of EOL cable, our analysis assumes that the plastics content disposed follows the same distribution as U.S. municipal solid waste to landfills (81 percent) and incinerators (19 percent) (U.S. EPA, 2005). Accordingly, we estimate that of the 5 percent of EOL cables not recovered, approximately 4 percent is disposed in a C&D landfill and 1 percent is incinerated. After chopping for recovery of copper, of the estimated 90 percent of plastics disposed (i.e., not sent for thermoplastic recycling), 17 percent would be incinerated and 73 percent would be sent to a MSW landfill.

Finally, in addition to identifying the percentage distribution for the EOL cable, distinguishing among the alternatives at the EOL stage is of particular interest for the LCA. For example, since we are comparing alternatives within a cable type, we assume transportation is equivalent and therefore do not incorporate these inventory flows in the analysis. In addition, given the limited information available, we assume that the distributions among the cable types are alike. However, there are differences in the amount of NM-B cable that are disposed as a result of a larger percentage assumed to end in a fire. The EOL analysis in this study did not include unregulated or uncontrolled burning.



* Burning within recovery process to segregate cable could include open burning (under an "unregulated" recycling scenario) or incineration to separate conductor from resin system.
** These estimates are not well documented and are used as defaults based on available data and best professional judgment, which are varied in a multivariate uncertainty analysis.
Shaded boxes illustrate EOL distribution options modeled in this analysis.
Figures may not sum due to rounding.

Figure 2-4. Illustration of EOL Distribution Options: Baseline and Lead-free Alternative

### 2.4.5.2 EOL Inventory for Disposition Options

To model the EOL LCI, the analysis relied on primary data for cable chopping and thermoplastic recycling and secondary data (Simonson *et al*. 2001) to identify the emissions and inventory flows for landfilling, incineration, and structure fires.

Simonson, *et al*. (2001) conducted an LCA to compare the impacts resulting from cable fires of two cable constructions: (a) PVC jacketing over PVC insulation, and (b) PE jacketing over PE insulation. Fire tests were performed on both cable constructions using two temperatures (350º C and 650º C) and two oxygen concentrations (5 percent and 21 percent), and the emissions were analyzed. Accordingly, the outputs for the study are primarily based on the PVC plastics, PE plastics, and the copper conductor. Because our analysis does not include the copper component, and the cable types we are addressing in this analysis include PVC jacketing, we used inventory data for the PVC plastics from the Simonson *et al*. study. However, the cable types in the WCP also include other materials (e.g., FEP) and other compounds and resins, thus the EOL inventory flows from these materials are not captured. An earlier study conducted by DuPont (Leung and Kasprzak, 1999) looked at the combustion products likely to be emitted during the burning of cable at temperatures expected to be reached during building fires (350 to 450º C). This study was not used to identify combustion products due to lack of clarity about the jacketing and insulation formulations, but will potentially be used to inform further study of the wire and cable fire EOL disposition.

The Simonson *et al*. assessment studied the outputs resulting from both ventilated and vitiated PVC cable fires, where no spreading of the fire beyond the cable occurs. We chose to use the vitiated fire data as it better represents a secondary fire (i.e., one that originates away from the cables), which is the only type expected given the placement of fire retardancy features of the cables.

The Simonson *et al*. study also provided emissions data on a per kilometer of cable basis for landfilling and incineration. Since their data did not have lead emissions from the PVC cable emissions associated with the baseline alternative were incorporated from other sources. For example, based on estimates provided by the University of Florida, discussed above (Section 2.4.4.3), we assume a leachate rate of 1.5 percent for removed cable disposed in a C&D landfill. For the incineration and the fire scenarios, we assumed 98.5 percent of the lead content is disposed of with the ash to a landfill and 1.5 percent is released to the air (Chang-Hwan, no date, and Abanades, 2002, cited in Geibig and Socolof, 2005). Of the lead assumed to be disposed of in a MSW landfill, we assumed the higher leachate rate of 10 percent, given that the cable is disposed of in smaller, chopped pieces. Given the uncertainty in these estimates, the leachate rates were varied in the multivariate uncertainty analysis (Section 3.4).

Primary data were collected for two cable recycling facilities: cable separation (i.e., chopping) and PVC recycling (i.e., Vinyloop® process). Only one facility for each process supplied inventory data. Following are key assumptions for each disposition option based on available primary and secondary data:

- *Landfill:* Emission data for landfilling lead-free cables are based on a time period of 100 years. The analysis assumes that a “minor” part of the emissions will be released during this period, whereas the majority of materials will remain in the landfill and will be broken down over time. Accordingly, the model assumes that only 3 percent of the original polymer materials will be broken down during the first 100 years. However, it assumes that 80 percent of the plasticizers in the PVC cable will decompose (Simonson *et al*., 2001, page 114). These data were supplemented with lead leachate data for the baseline cables.

- *Incineration:* The study assumes that incineration occurs in “standard waste incinerators with a relatively high degree of flue gas cleaning” (Simonson *et al*., 2001, page 117). Typically, cables are only part of the total waste flow to the incinerator. Therefore, where possible, emissions outputs are calculated directly from the material content (e.g., carbon dioxide and hydrochloric acid). However, emissions related to combustion conditions in a typical incinerator are allocated to the cable material. For example, carbon monoxide emissions are allocated based on the carbon content of the materials in the cable (Simonson *et al*., 2001). These data were supplemented with assumptions about the lead releases to air and to landfill as ash.

- *Recycling (Separation):* As noted previously, the inventory data for the separation stage is based on a small cable recycling facility employing a mechanical, cable chopping operation. Although the recycler primarily accepts cable to extract the valuable copper component, it also recycles much of the plastic component of the cable.

- *Recycling (Thermoplastics):* As noted previously, more than 90 percent of the PVC-based insulation recycled is from EOL building cables (e.g., low-voltage power cables); and less than 10 percent of the cable scrap is from EOL communications cables (Leitner, 2006). However, our analysis assumes the energy and material input and output flows to be the same per unit of PVC recycled for power cable and telecom cables.

- *Fire:* Simonson *et al*. (2001) included fire inventory data for both ventilated and vitiated fires. The latter represents an oxygen deficient fire, which they assume represents a secondary fire (i.e., are not started with the cable but capable of consuming the cable and not spreading beyond the cable). Our analysis includes data for only vitiated fires, which represent the most probable scenario for CMR/CMP cable fires. In addition, the analysis uses a default of 10 percent of the cables are burnt during the fire.

#### 2.4.5.3 Limitations and Uncertainties

Assumptions about the disposition percentages may not truly represent the actual dispositions. For example, our analysis currently assumes that the dispositions of the EOL cables (after any fires) for all three cable types will be the same once the cable is removed. However, it is likely that each cable has different percentages of the plastic component that are recovered. In addition, estimates of the distribution between landfilling and incineration were based on processing MSW rather than specifically on processing cable. Sensitivity analyses, which vary these assumptions, can be conducted if results show enough impacts at EOL to warrant further analysis.

Furthermore, the analysis does not give credit for open loop recycling of mixed plastics into other non-recyclable material/products. That is, this analysis does not account for environmental savings from the recycled content of materials/products created from the recycled plastics from the cables. In addition, although the recovery of FEP follows more of a closed-loop process, the LCA only accounts for this in the data received by crossweb manufacturers whose data incorporated recycled FEP in their process estimates.

With respect to the LCI data for the GaBi analysis, as noted above, our analysis primarily relied on secondary data from the Simonson *et al*. (2001) study. Although this study was useful in providing estimates of emission outputs for PVC for the EOL disposition options, it did not include data to account for the other material in the cable wire we assessed (e.g., FEP, PE, plasticizers, resins). Therefore, differences in the outputs for each cable type were primarily based on the amount of PVC per unit length for each cable type.  In addition, the Simonson *et al*. study did not include estimates for emissions resulting from lead content.  Thus, lead outputs from landfilling were estimated based on leachate rates for the metal.  In addition, although the recovery of plastics using the Vinyloop® process was based on primary data, our analysis does not account for the triboelectric step, which is necessary to separate plastic scrap with a PVC content of 50 to 60 percent (Hagström *et al*., 2006; Scheirs, 2003).

## 2.5 LCI Summary

The LCIs of each cable alternative are the combinations of the upstream, manufacturing, and EOL data described in the preceding sections.  Presented under each subsection below are figures showing all the processes modeled for each cable alternative, followed by the total inventories.  The total input and output mass inventory data are summarized by general categories of flows (e.g., emissions to air, emissions to water).  When possible, given proprietary restrictions, more detailed breakdowns of the inventory are also provided, such as the top contributing processes to the total inventory, and the top contributing inventory flows associated with the modeled life cycle of each cable alternative.

This section presents only the mass flows.  Energy inputs are presented in Chapter 3 under the energy impact category (Section 3.2.2).  For the remaining impact categories included in the WCP analyses, the mass inventory data are then used as the basis of the other impact assessment calculations in Chapter 3.

### 2.5.1 CMR LCIs

Figures 2-5 and 2-6 show the processes modeled for the CMR baseline (lead-stabilized) and CMR lead-free cables from materials extraction through to the end of life.  Figure 2-7 shows the processes modeled for the zero-halogen CMR cables.  Incomplete data on the zero-halogen extrusion process resulted in only a cradle-to-gate analysis comparing the lead and lead-free CMR cables to the zero-halogen cables in Chapter 3.

In the flow charts below, the “cable installation/use” process is shaded in gray, showing that inventory data were not included for this stage, except to set the functional unit to 1 kilometer of linear length of cable.  Processes in bold represent those for which primary data were collected.  For the zero-halogen alternative, the jacketing and insulation extrusion process is in hash marks to show it is a mostly incomplete dataset.  The processes noted in parentheses next to each upstream (ME&P) process indicates the process to which the upstream process feeds.  For example, “electricity (cmpdg)” indicates the inventory from the generation of electricity that is needed for the compounding process.  This notation is used so that subsequent figures showing top contributing processes can be identified with the linked downstream process.  When confidentiality agreement restrictions prohibited the presentation of an individual process contribution, some processes have been combined as needed.

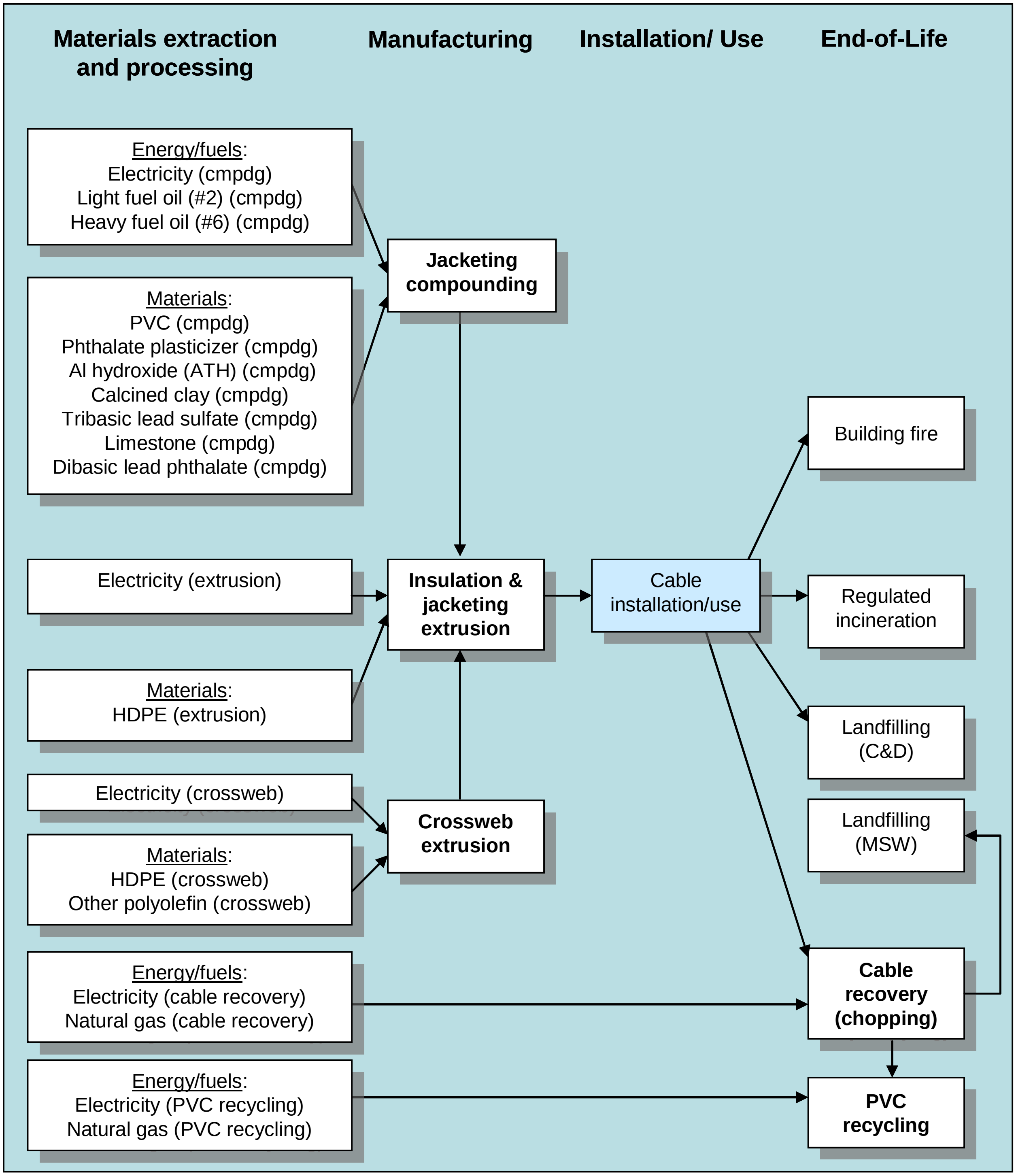


Figure 2-5. CMR Baseline (Lead-Stabilized): Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

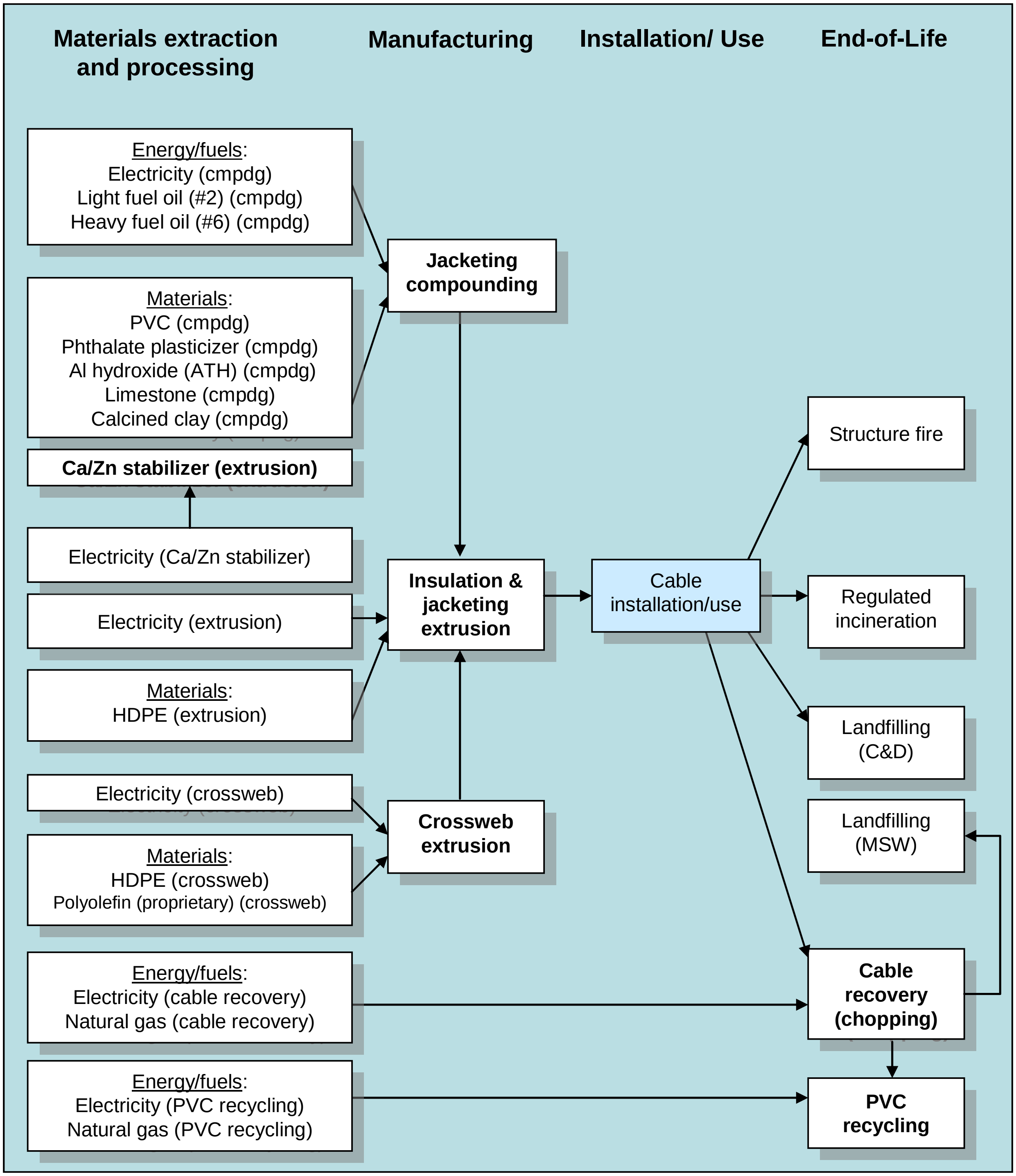


Figure 2-6. CMR Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

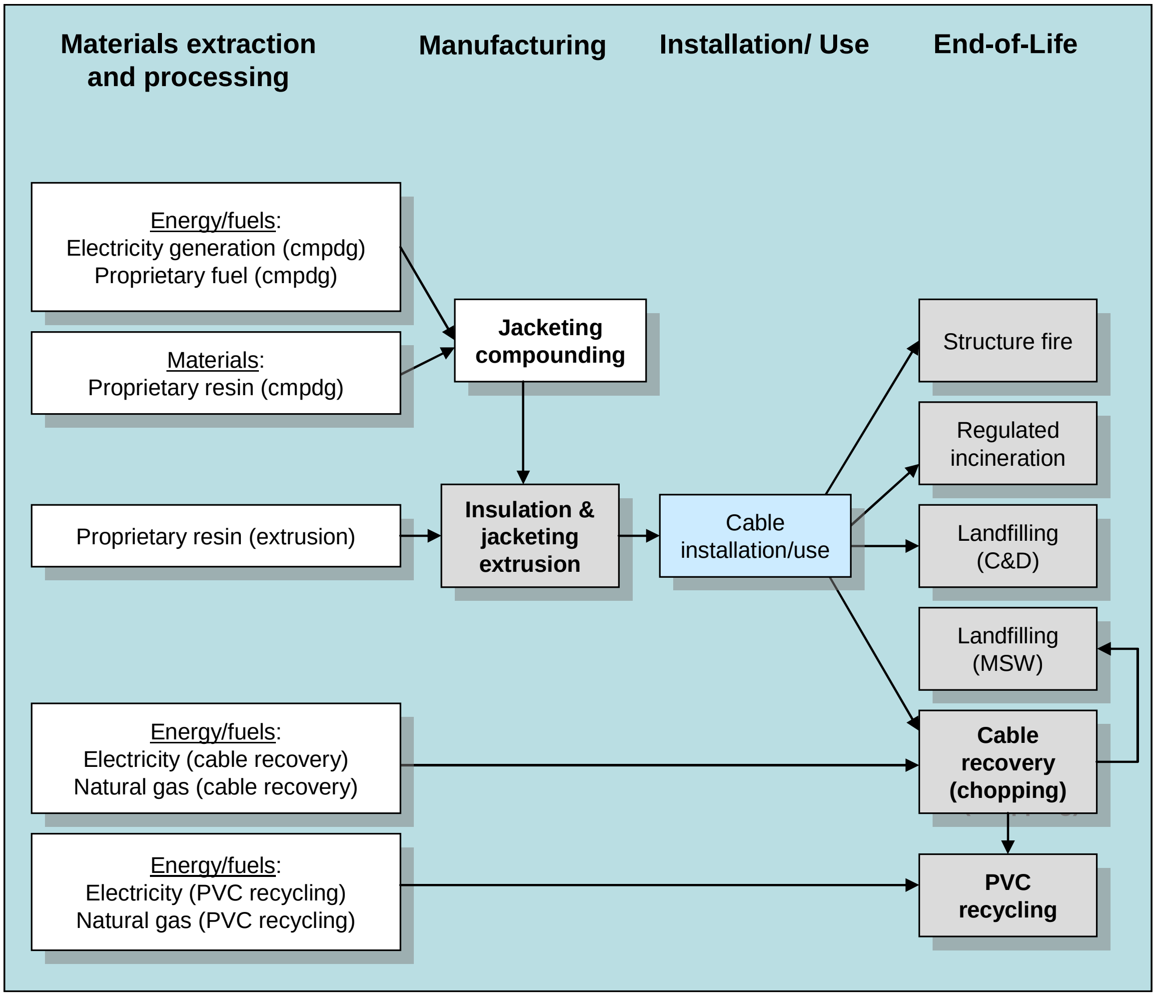


Figure 2-7. CMR Zero-Halogen Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

Figures 2-8 through 2-10 compare the mass inputs for the baseline and the lead-free CMR alternatives. Figure 2-8 presents the total mass inputs and Figures 2-9 and 2-10 provide a breakdown of the processes and individual flows that contribute greater than 1 percent to the total mass inputs. The total mass inputs for CMR are 19 percent greater for the baseline than the lead-free alternative (3,156 kg/km cable and 2,641 kg/km cable, respectively). For both alternatives, water is 88 percent of the total inputs, and the process that contributes greatest to each alternative's mass inputs is electricity production used for cable extrusion (69 percent for the baseline and 65 percent for the lead-free alternative) (Figures 2-9 and 2-10). To protect confidentiality, Figure 2-9 combines the mass inputs from all upstream electricity generation.

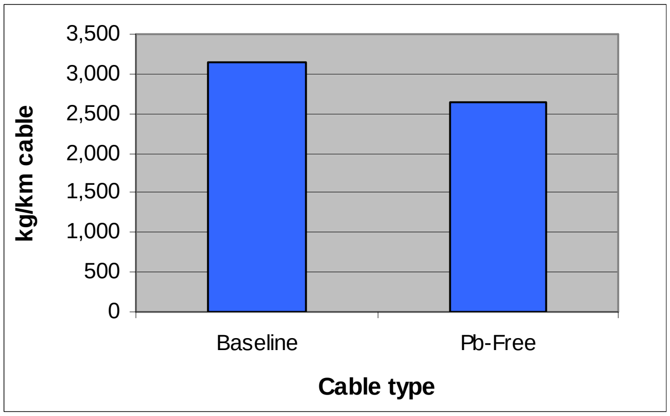


Figure 2-8. CMR Total Mass Inputs

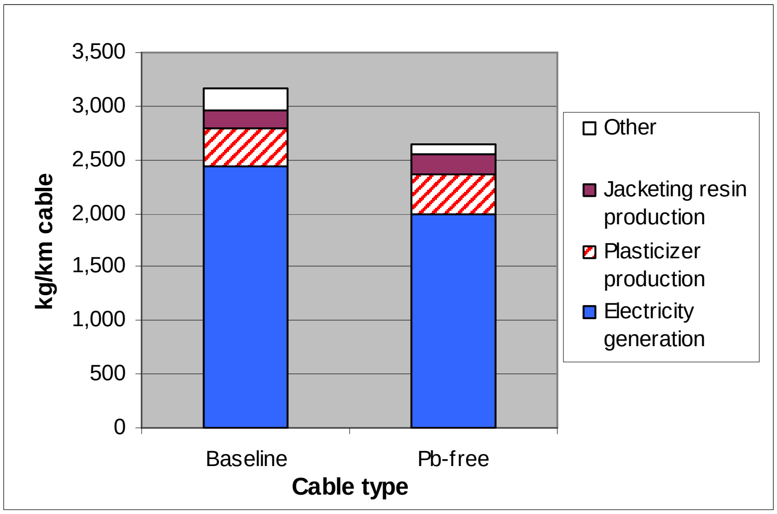


Figure 2-9. CMR Mass Inputs – Top Contributing Processes

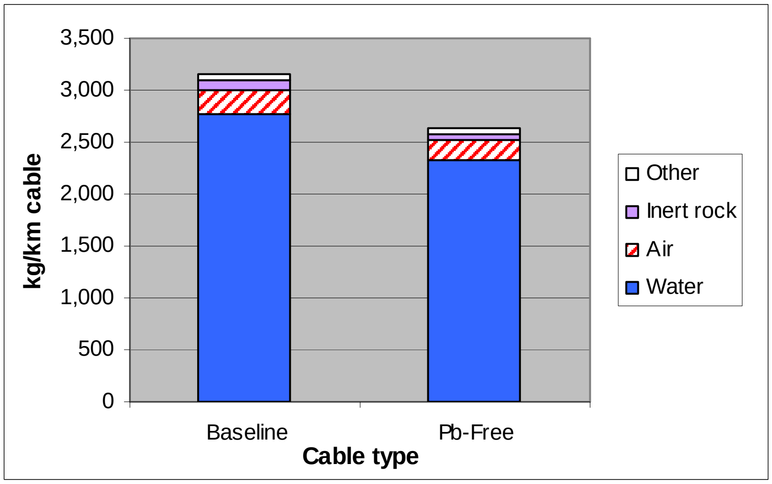


Figure 2-10. CMR Mass Inputs – Top Contributing Flows

The mass outputs are presented in Figures 2-11 through 2-13. Outputs include: deposited goods, which include consumer waste, hazardous waste and stockpile goods (e.g., overburden[14]); production residues, which include hazardous and non-hazardous waste for disposal; and substances such as intermediate products (e.g., PVC). Note also, emissions to water include the total mass of wastewater itself, as well as pollutants contained therein. Since data for the zero-halogen alternative were incomplete, similar comparative inventory results are not shown. The mass outputs are 23 percent greater for the baseline compared to the lead-free cable (2,542 and 2,073 kg/km cable, respectively). The mass outputs are mostly releases to fresh water (79 percent for both leaded and lead-free cables). 86 percent and 83 percent of the mass outputs are from the production of electricity needed for the cable extrusion and compounding processes for the lead and lead-free alternatives, respectively. To protect confidentiality, Figure 2-12 combines the mass outputs from all upstream electricity generation. The figures indicate that water from electricity generation contributes the most to the mass inputs and outputs for both the baseline and lead-free alternatives.

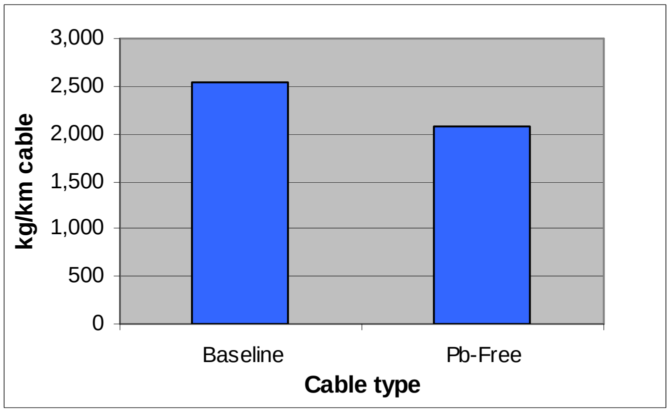


Figure 2-11. CMR Total Mass Outputs

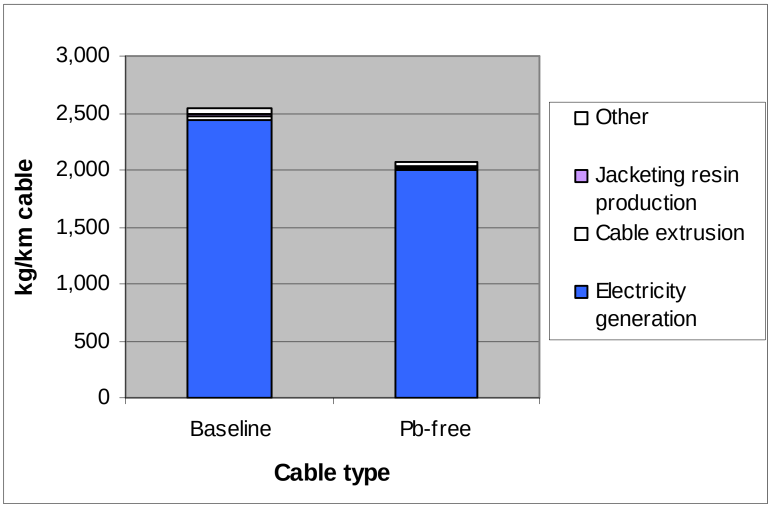


Figure 2-12. CMR Mass Outputs – Top Contributing Processes

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[14] Surface soil that must be moved away to access coal seams and mineral deposits.

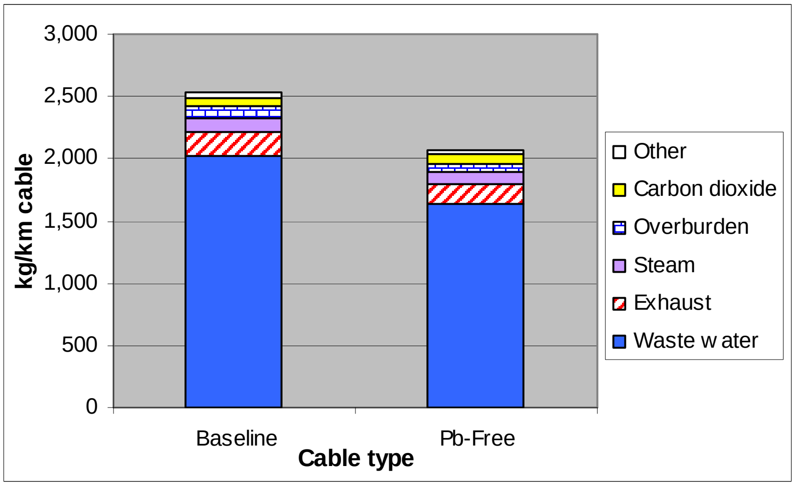

Figure 2-13. CMR Mass Outputs – Top Contributing Flows

The halogen-free alternative did not have complete data to compare the full life cycles of the alternatives. The only comparison that could be made for the zero-halogen (X-free) alternative is comparing the compounding process and the production of electricity and fuels associated with compounding. This comparison found that the zero-halogen process had greater mass inputs and outputs compared to the baseline (leaded) (Figures 2-14 and 2-15). This does not account for any differences in the production processes of the additives in the compounded resin.

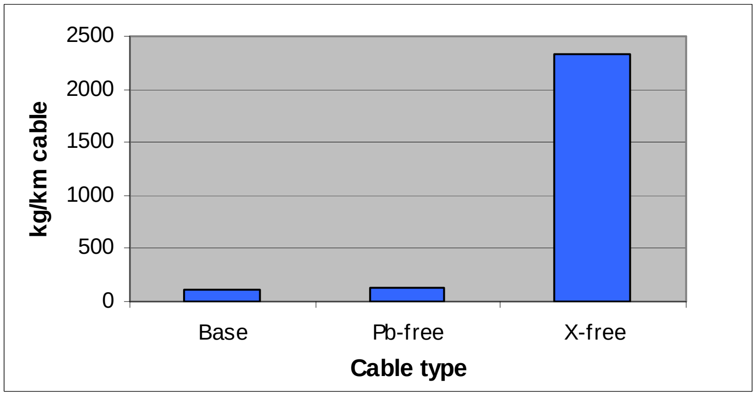

Figure 2-14. CMR 3-way Cradle-to-gate Mass Inputs

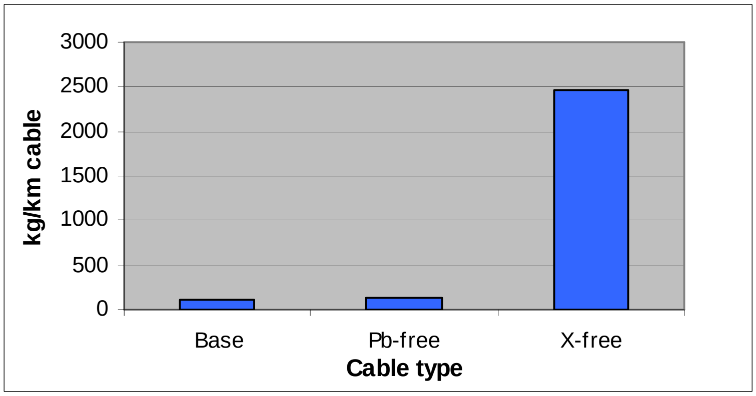

Figure 2-15. CMR 3-way Cradle-to-gate Mass Outputs

The primary explanation for the discrepancy in the halogen-free cable cradle-to-gate mass inputs and outputs compared to the baseline and lead-free alternatives is the difference in energy use as well as the mass of cable jacket per unit length, which is far higher than the two other types of cable (see Table 1-2).

### 2.5.2 CMP LCIs

Figures 2-16 and 2-17 show the processes modeled for the CMP baseline (lead-stabilized) and CMP lead-free cables from materials extraction through to the end of life. As in the CMR flow charts, the inventory data for the "cable installation/use" process were not included, the functional unit is set to 1 kilometer of linear length of cable, and processes in bold represent those for which primary data were collected.

Figures 2-18 through 2-20 compare the mass inputs for the baseline and the lead-free CMP alternatives. Figure 2-18 presents the total mass inputs while Figures 2-19 and 2-20 provide a breakdown of the processes that contribute greater than 5 percent to the total mass inputs and the individual flows that contribute greater than 1 percent to the total mass inputs, respectively. The total mass inputs for CMP are 9 percent greater for the baseline than the lead-free alternative (4,480 kg/km cable and 4,123 kg/km cable, respectively). The top contributing process for both alternatives is the generation of electricity for use in the cable extrusion process (Figure 2-19). To protect confidentiality, Figure 2-19 combines the mass input from all upstream electricity generation. Water is the greatest individual flow contributing to the mass input for both alternatives (Figure 2-20). Figure 2-19 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 87 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 2-20 includes individual flows that contribute >1 percent to the total impacts and represents 95 percent of the total input mass for both the baseline and lead-free alternatives. The overall differences in mass input between the cables are primarily a function of the differences in energy use, as electricity generation uses substantial amounts of water. Energy inputs are presented in Section 3.2.2 under Energy Impacts.

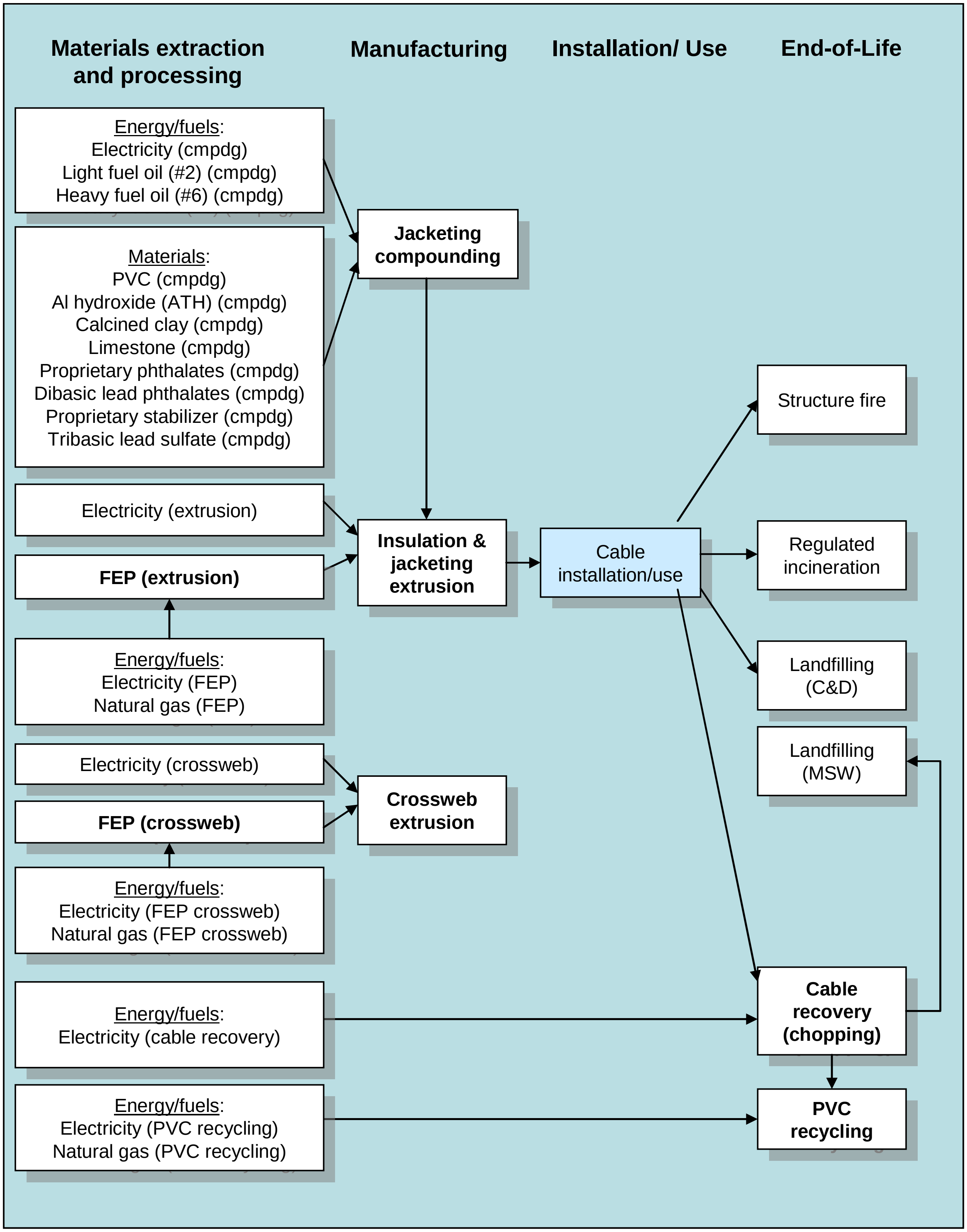

Figure 2-16. CMP Baseline (Lead-Stabilized): Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

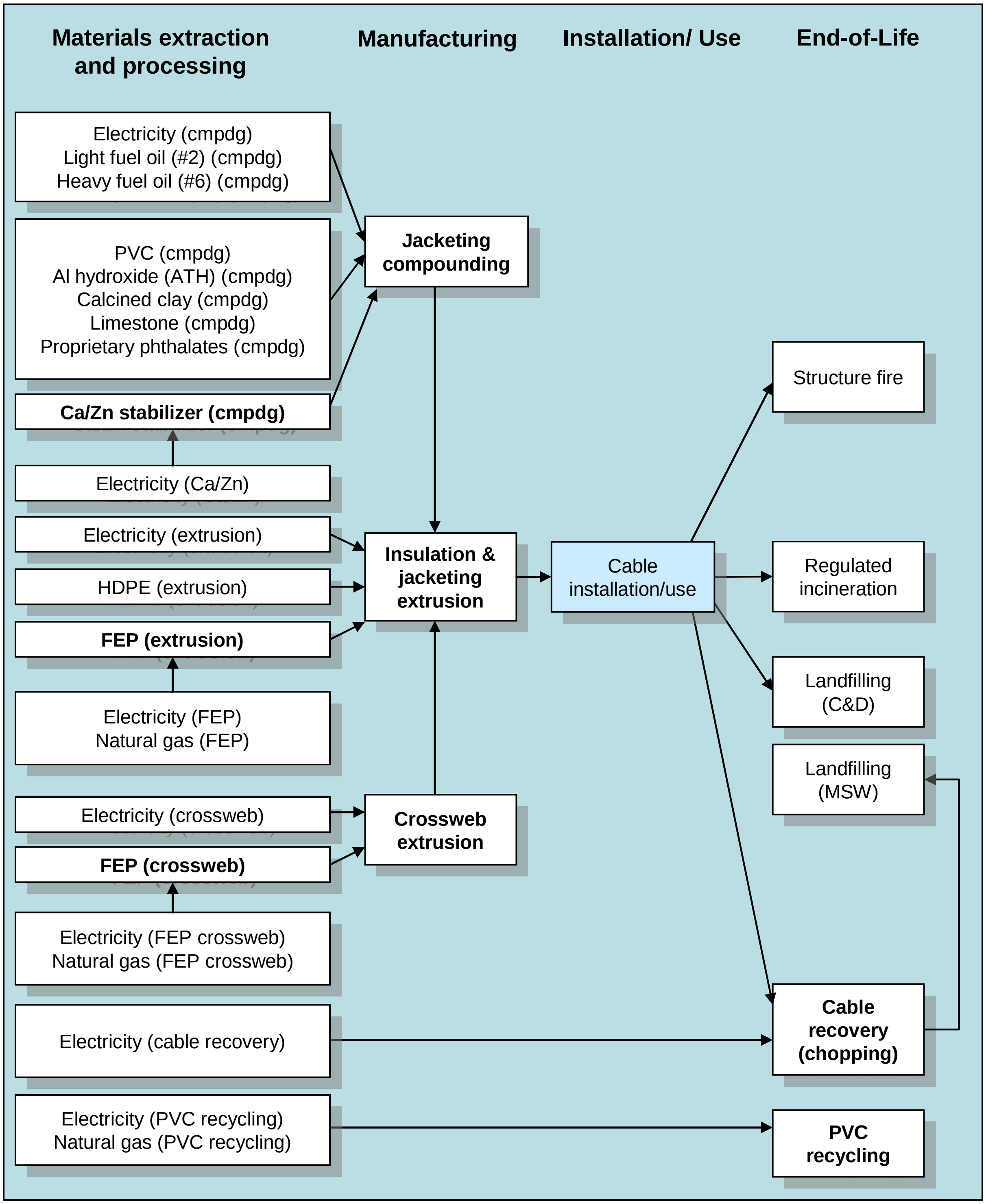

Figure 2-17. CMP Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

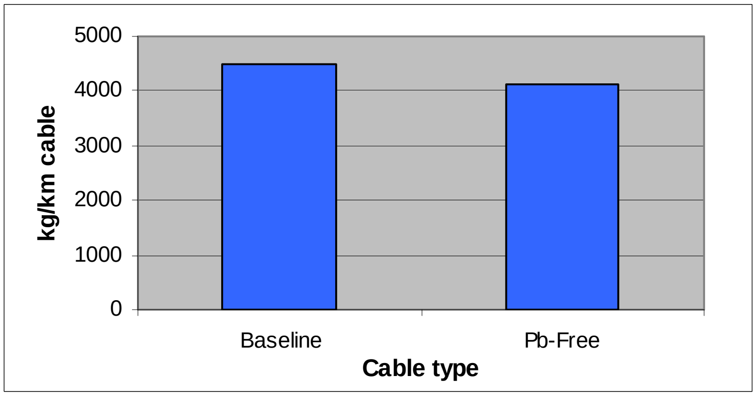

Figure 2-18. CMP Total Mass Inputs

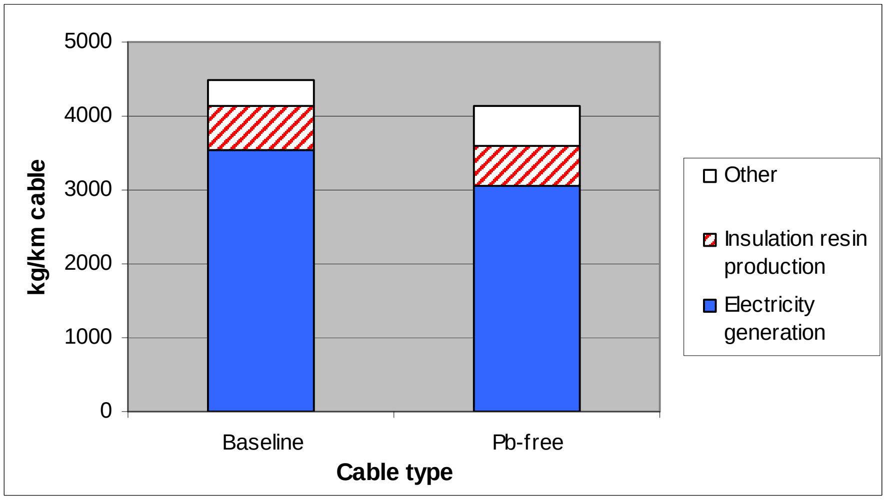

Figure 2-19. CMP Mass Inputs – Top Contributing Processes

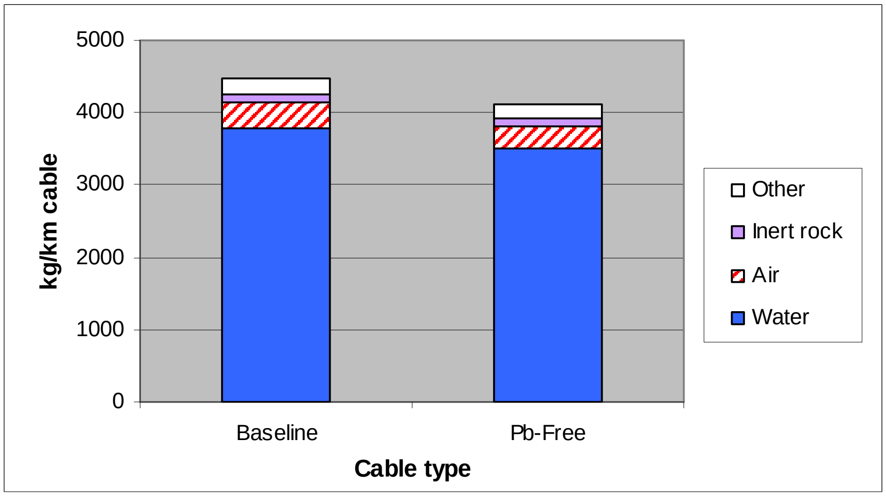

Figure 2-20. CMP Mass Inputs – Top Contributing Flows

Similar to the inputs, the mass outputs are presented in Figures 2-21 through 2-23. The baseline cable generates 10 percent more mass output than the lead-free alternative, which is shown in Figure 2-21. The top contributing process for both alternatives is the generation of electricity for use in the cable extrusion process (Figure 2-22). To protect confidentiality, Figure 2-22 combines the mass output from all upstream electricity generation. Wastewater is the greatest individual flow contributing to the mass output for both alternatives (Figure 2-23). Figure 2-22 includes the processes that contribute >3 percent of the total mass output, which represent 98 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 2-23 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total output mass for both the baseline and lead-free alternatives. The overall differences in mass output between the cables are primarily a function of the differences in energy use, as electricity generation generates substantial amounts of wastewater.

The total water outputs are tallied separately from individual constituents in the water that might be considered hazardous or toxic. The impacts associated with those are translated into appropriate impact categories as presented in Chapter 3.

The inventory is used to generate impact results, as described in Chapter 3. Further details, such as the inventories for specific processes are not provided for reasons of confidentiality.

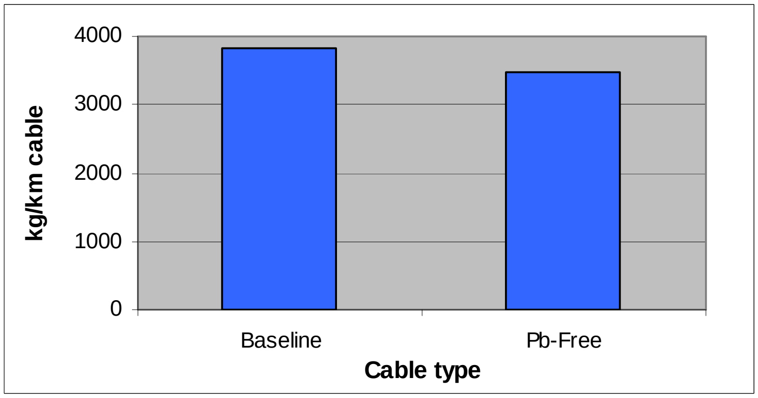

Figure 2-21. CMP Total Mass Outputs

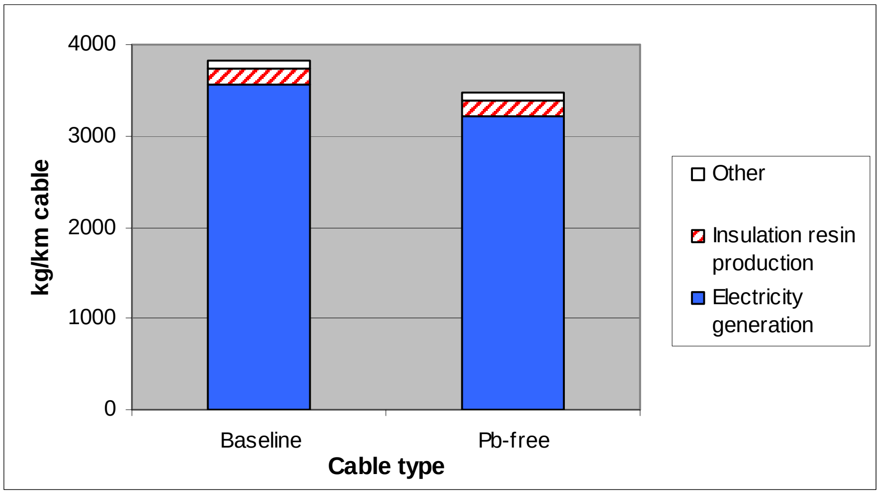

Figure 2-22. CMP Mass Outputs – Top Contributing Processes

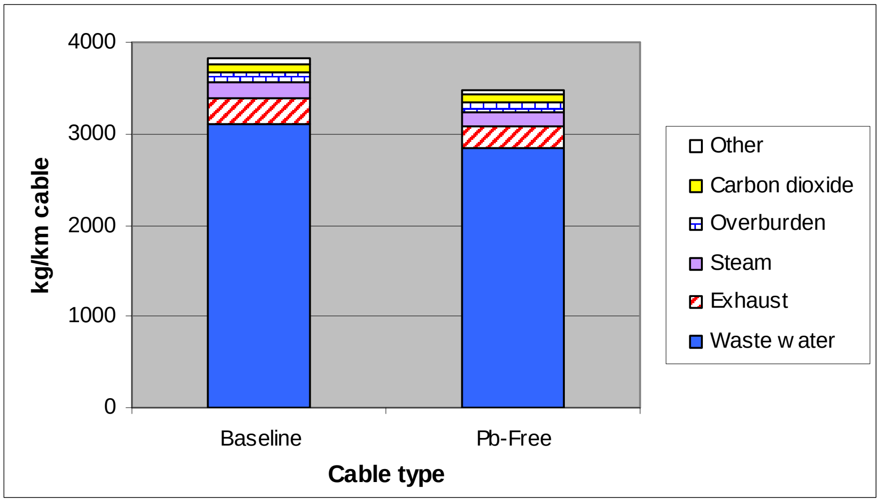

Figure 2-23. CMP Mass Outputs – Top Contributing Flows

### 2.5.3 NM-B LCIs

Figures 2-24 and 2-25 show the processes modeled for the NM-B baseline (lead-stabilized) and NM-B lead-free cables from materials extraction through to the end of life. Note that the lead-free alternative only represents materials extraction up to compounding, while the baseline includes materials extraction through EOL (thus in the LCIA results in Chapter 3, the NM-B comparisons are only based on the upstream through compounding processes). As in the CMR and CMP flow charts, the inventory data for the shaded process boxes (e.g., “cable installation/use”) are not included in the inventory, the functional unit is set to 1 kilometer of linear length of cable, and processes in bold represent those for which primary data were obtained.

Figures 2-26 through 2-28 compare the cradle-to-gate mass inputs for the baseline and the lead-free NM-B alternatives. Energy inputs are presented in Section 3.2.2 under Energy Impacts. Figure 2-26 presents the total cradle-to-gate mass inputs, while Figures 2-27 and 2-28 provide a breakdown of the processes that contribute greater than 5 percent to the total cradle-to-gate mass inputs and the individual flows that contribute greater than 1 percent to the total cradle-to-gate mass inputs, respectively. The total cradle-to-gate mass inputs for NM-B are 11 percent greater for the baseline than the lead-free alternative (1,836 kg/km cable and 1,657 kg/km cable, respectively). For both alternatives, the production of plasticizers is the greatest contributing process (59 percent of the total inputs for the baseline and 63 percent for the lead-free alternative) and the top contributing input flow is water, which contributes 93 percent of the total inputs for the baseline and 94 percent for the lead-free alternative. To protect confidentiality, Figure 2-27 combines the cradle-to-gate mass input from all upstream electricity generation.

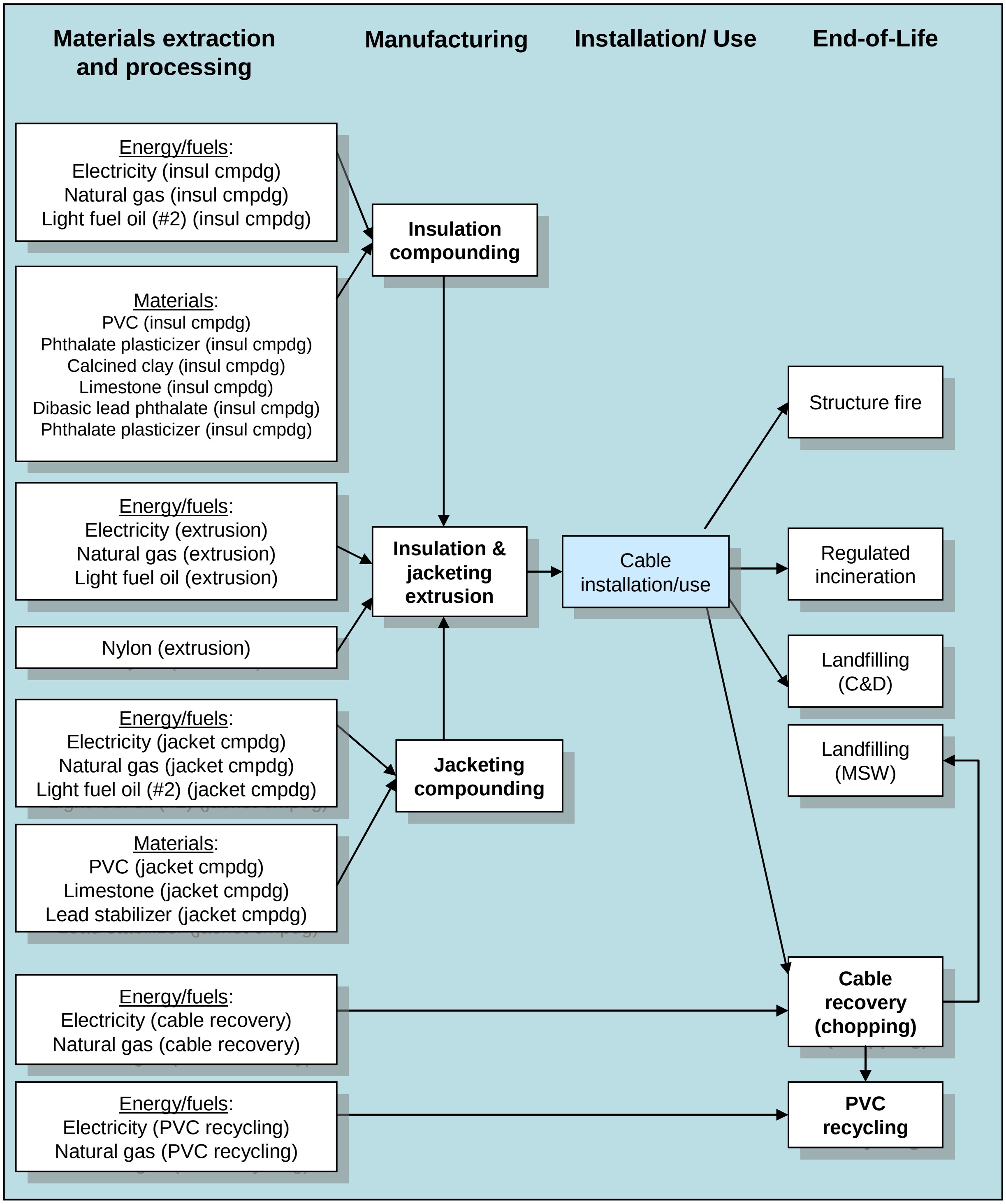

Figure 2-24. NM-B Baseline (Lead-Stabilized): Processes Modeled for the NM-B LCI

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

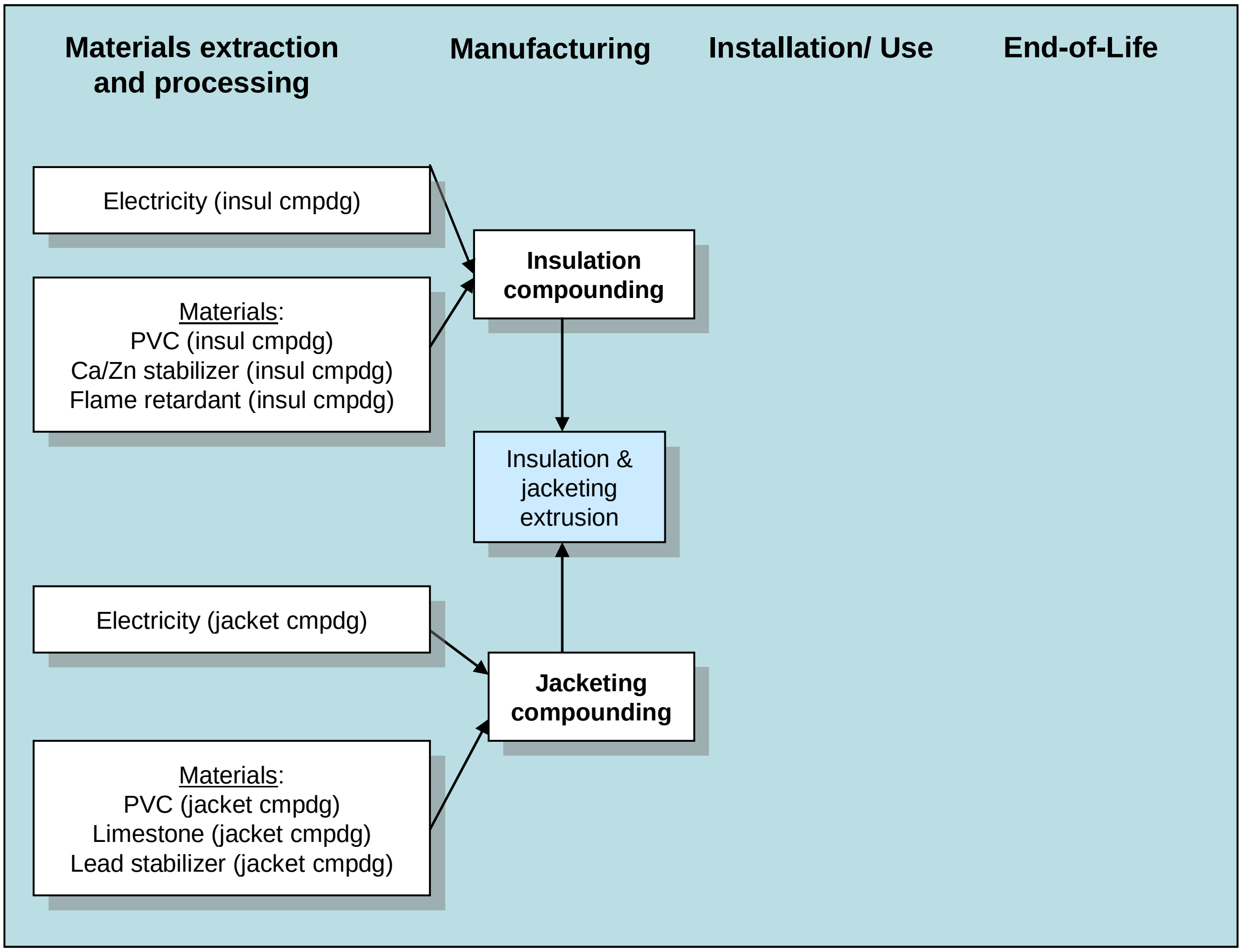

Figure 2-25. NM-B Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicates no inventory data included for that process. Bold text indicates primary data collection for that process.

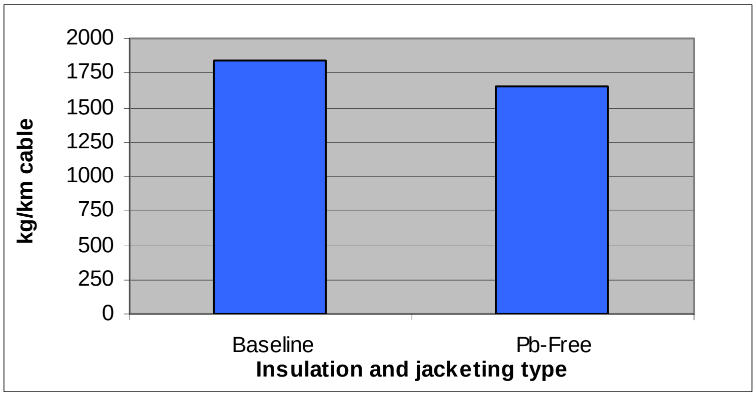

Figure 2-26. NM-B Total Mass Inputs – Partial Life Cycle

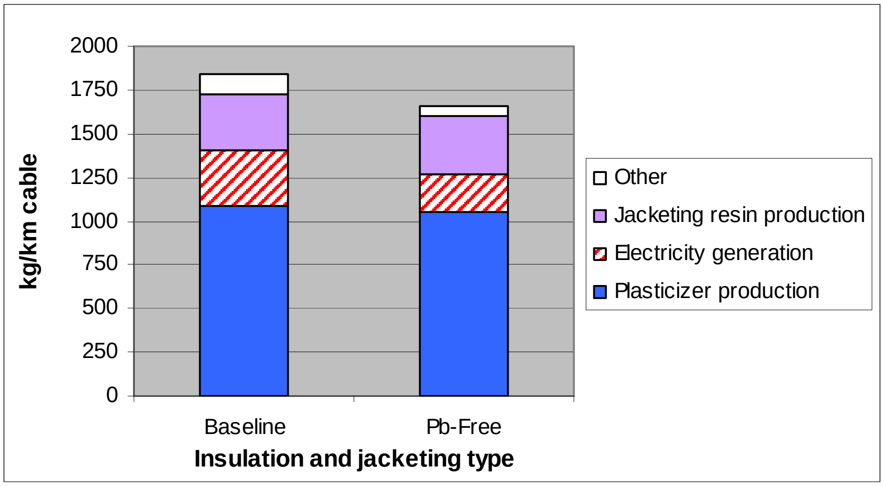

Figure 2-27. NM-B Mass Inputs – Top Contributing Processes – Partial Life Cycle

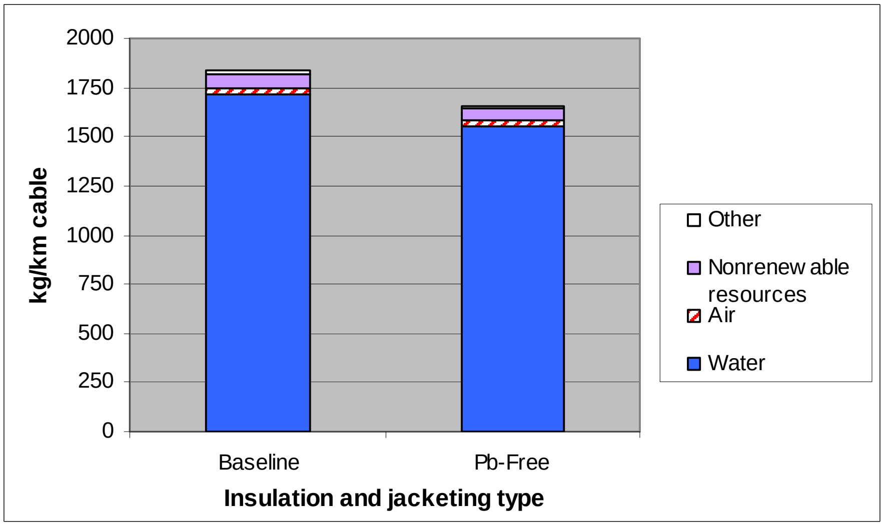

Figure 2-28. NM-B Mass Inputs – Top Contributing Flows – Partial Life Cycle

The baseline NM-B cable generates 35 percent more cradle-to-gate mass output than the lead-free alternative, which is shown in Figure 2-29. The top contributing process for both alternatives is the generation of electricity for use in the compounding of cable insulation and jacketing (Figure 2-30). To protect confidentiality, Figure 2-30 combines the cradle-to-gate mass output from all upstream electricity generation. Wastewater is the greatest individual flow contributing to the cradle-to-gate mass output for both alternatives (Figure 2-31). Figure 2-30 includes the processes that contribute >5 percent of the total mass output, which represent 94 and 96 percent of the total cradle-to-gate mass output baseline and lead-free alternatives, respectively. Figure 2-31 includes individual flows that contribute >1 percent to the total impacts, and represents 101 and 108 percent of the total cradle-to-gate output mass for both the baseline and lead-free alternatives (the fact that they account for greater than 100 percent is due to the aggregation of mass inputs and outputs in the calculation of totals). The overall differences in cradle-to-gate mass output between the cables are primarily a function of the differences in energy use, as electricity generation generates substantial amounts of wastewater.

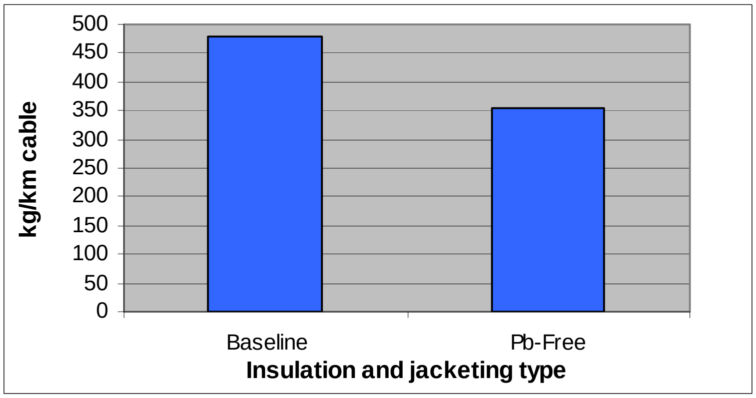

Figure 2-29. NM-B Total Mass Outputs – Partial Life Cycle

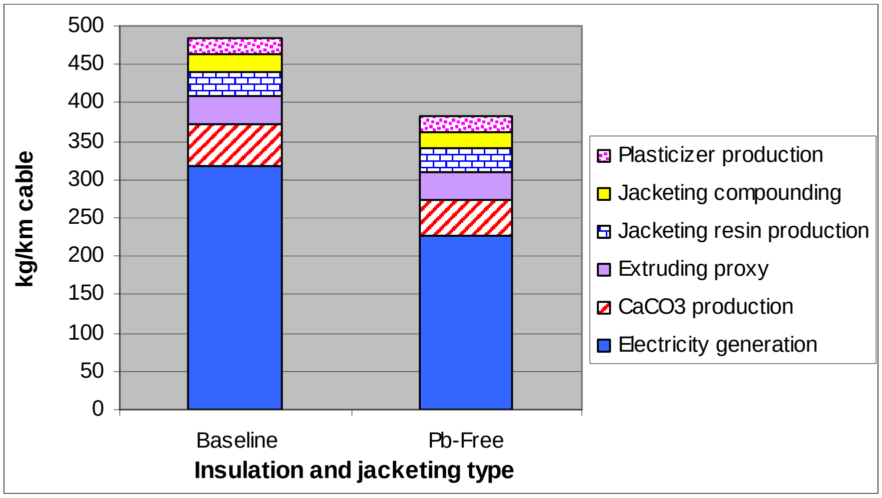

Figure 2-30. NM-B Mass Outputs – Top Contributing Processes – Partial Life Cycle

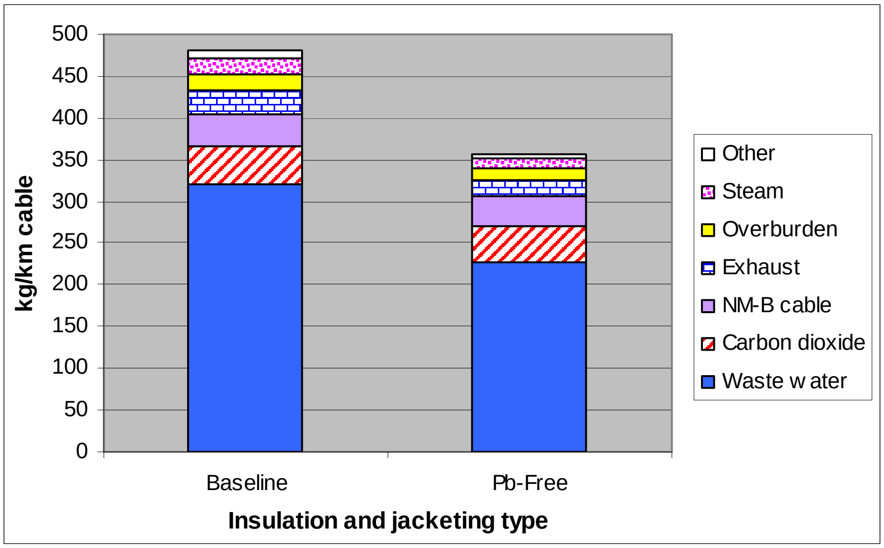

Figure 2-31. NM-B Mass Outputs – Top Contributing Flows – Partial Life Cycle

# Chapter 3 LIFE-CYCLE IMPACT ASSESSMENT

Within LCA, the LCI is a well-established methodology; however, LCIA methods are less well-defined and continue to evolve (Barnthouse *et al.*, 1997; Fava *et al.*, 1993). For LCIA toxicity impacts in particular, some of the methods commonly being applied include toxicity potential, critical volume, and direct valuation (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996). There is currently no general consensus among the LCA community concerning which, if any, of these methods are preferable, however. Efforts are under way to determine the appropriate level of analytical sophistication in LCIA for various types of decision-making requirements and for adequately addressing toxicity impacts (Bare, 1999).

Section 3.1 of this chapter presents the general LCIA methodology used in this WCP study, which takes a more detailed approach to chemical toxicity impacts than some of the methods currently being used. This section also describes the data management and analysis software used to calculate LCIA results. Section 3.2 presents the detailed characterization methodologies for each impact category, as well as the LCIA results for each cable type. This section also discusses data sources, data quality, and the limitations and uncertainties in this LCIA methodology, as well as in the LCIA results.

Our LCIA methodology calculates life-cycle impact category indicators using established calculation methods for a number of traditional impact categories, such as global warming, stratospheric ozone depletion, photochemical smog, and energy consumption. In addition, this method calculates relative category indicators for potential impacts on human health and aquatic ecotoxicity, impacts not always considered in traditional LCIA methodology. The toxicity impact method is based on work for Saturn Corporation and the EPA Office of Research and Development by the University of Tennessee Center for Clean Products and Clean Technologies and used in the DfE Computer Display Project's LCA study (Socolof *et al*., 2001), and updated in the LCA conducted by the DfE Lead-Free Solder Project (Geibig and Socolof, 2005).

The LCIAs conducted in this study are done to compare the baseline cables (i.e., lead-stabilized) to alternatively constructed cables (i.e., lead-free or zero-halogen). The comparative impacts presented in this section are based on LCI data described in Chapter 2. The baseline and lead-free comparisons for both the CMR and CMP cables use the inventories from upstream through EOL. For the CMR zero-halogen alternative and the NM-B lead-free alternative, cable manufacturing (i.e., insulation and jacketing extrusion) data were not obtained; thus in order to compare these cables to the respective alternatives for the appropriate cable type, only comparable processes are included, as appropriate.

## 3.1 Methodology

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al*., 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and, therefore, cannot be directly compared.

Conceptually, there are three major phases of LCIA, as defined by the SETAC (Fava *et al.*, 1993):

- **Classification** – The process of assignment and initial aggregation of data from inventory studies to impact categories (i.e., greenhouse gases or ozone depletion compounds).
- **Characterization** – The analyses and estimation of the magnitude of potential impacts for each impact category, derived through the application of specific impact assessment tools. (In the WCP, impact scores are calculated for inventory items that have been classified into various impact categories and then aggregated into life-cycle impact category indicators.)
- **Valuation** – The assignment of relative values or weights to different impacts, and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories.

The international standard for life-cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCIA; valuation ("weighting") is an optional element to be included depending on the goals and scope of the study. Both the classification and characterization steps are completed in the WCP, while the valuation step is left to industry or other interested stakeholders. The methodologies for life-cycle impact classification and characterization are described in Sections 3.1.1 and 3.1.2, respectively.

### 3.1.1 Classification

In the first step of classification, impact categories of interest are identified in the scoping phase of the LCA. The categories included in the WCP LCIA are listed below:

- non-renewable materials use/depletion
- energy use
- landfill space use
- global warming (global climate change)
- stratospheric ozone depletion
- photochemical smog
- air acidification
- air quality (particulate matter loading)
- water eutrophication (nutrient enrichment)
- chronic cancer human health effects - occupational
- chronic cancer human health effects - public
- chronic non-cancer human health effects - occupational
- chronic non-cancer human health effects - public
- aquatic ecotoxicity

Radioactivity and radioactive landfill waste are not included as impact categories because they are simply proportional to the use of electricity across all alternatives. Terrestrial ecotoxicity is not included as a separate impact category because the method for calculating chronic non-cancer public health impacts would be the same as for terrestrial ecotoxicity.

The second step of classification is assigning inventory flows to applicable impact categories. Classification includes whether the inventory item is an input or output, the disposition of the output, and, in some cases, the material properties for a particular inventory item. Figure 3-1 shows a conceptual model of classification for the WCP. Table 3-1 presents the inventory types and material properties used to define which impact category is applicable to an inventory item. One inventory item may have

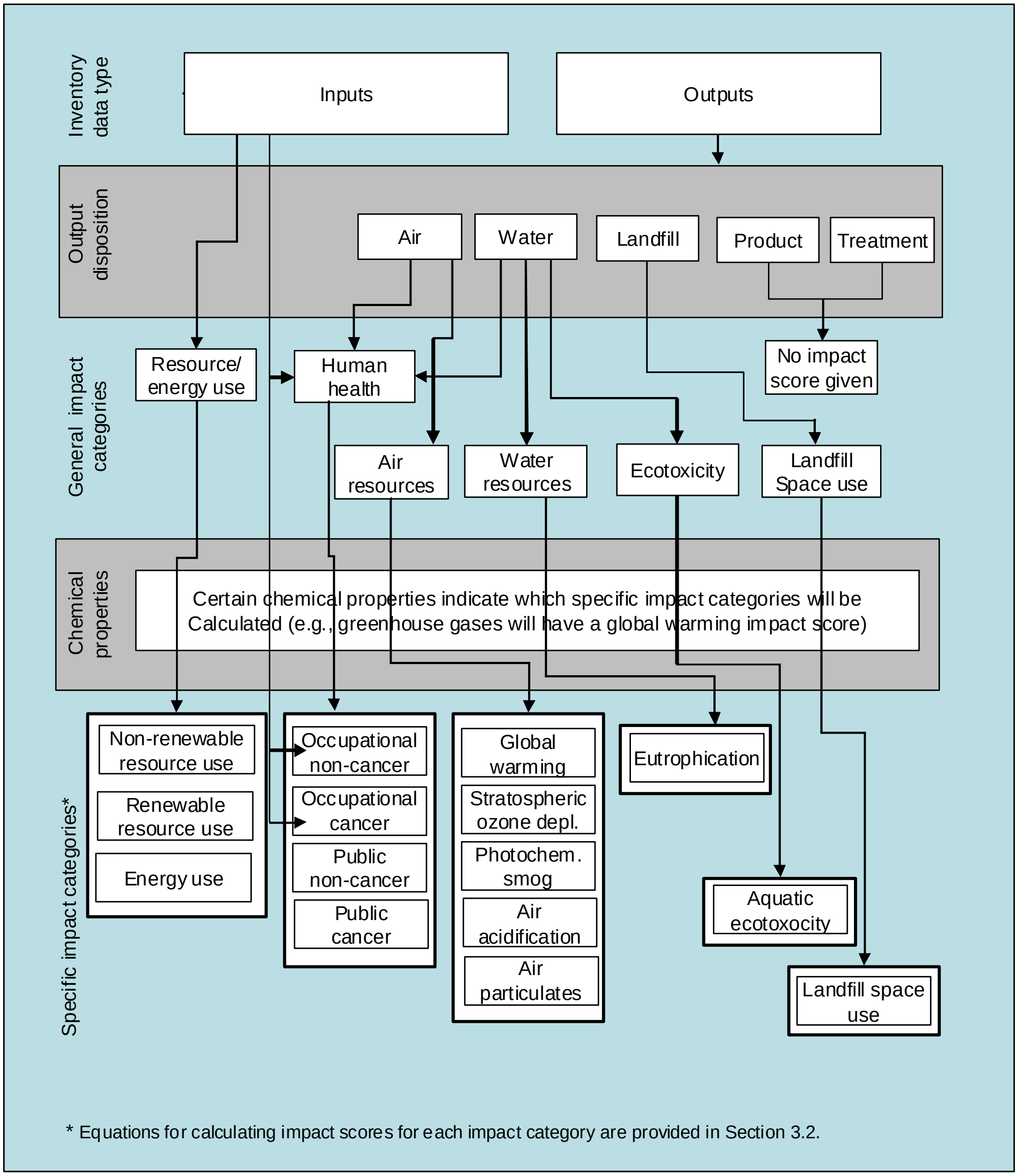

Figure 3-1. Impact Classification Conceptual Model

**Table 3-1**

**Inventory Types and Properties for Classifying Inventory Items Into Impact Categories**

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

[a] Acronyms: particulate matter with average aerodynamic diameter less than 10 micrometers (PM10); total suspended particulates (TSP); biological oxygen demand (BOD); total suspended solids (TSS).

N/A=not applicable.

multiple properties and, therefore, would have multiple impacts. For example, methane is a global warming gas and has the potential to create photochemical oxidants (to form smog).

Output inventory items from a process may have such varying dispositions as direct release (to air, water, or land), treatment, or recycle/reuse. Outputs with direct release dispositions were classified into impact categories for which impacts were calculated in the characterization phase of the LCIA. Outputs sent to treatment are considered inputs to a treatment process and impacts were not calculated until direct releases from that process occur. Similarly, outputs to recycle/reuse were considered inputs to previous processes and impacts were not directly calculated for outputs that go to recycle/reuse. Figure 3-1 graphically depicts the relationships between inventory type, dispositions, and impact categories. Note that a product is also an output of a process; however, product outputs were not used to calculate any impacts. Once impact categories for each inventory item were classified, life-cycle impact category indicators were quantitatively estimated through the characterization step.

### 3.1.2 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.
  - *Full equivalency* – all substances are addressed in a unified, technical model.
  - *Partial equivalency* – a subset of substances can be converted into equivalency factors.
- **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 3-2 lists the characterization approach used with each impact category. The **loading** approach either uses the direct inventory amount to represent the impact or slightly modifies the inventory amount to change the units into a meaningful loading estimate, such as characterizing the impact of either non-renewable resource depletion or landfill use. Use of nonrenewable resources is directly estimated as the mass loading (input amount) of that material consumed; use of landfill space applies the mass loading (output amount) of hazardous, non-hazardous, or radioactive waste, and converts that loading into a volume to estimate the landfill space consumed.

The **equivalency** method uses equivalency factors in certain impact categories to convert inventory amounts to common units relative to a reference chemical. Equivalency factors are values that provide a measure (weighting) to relate the impact of an inventory amount of a given chemical to the effect of the same amount of the reference chemical. For example, for the impact category “global warming potential (GWP),” the equivalency factor is an estimate of a chemical’s atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical carbon dioxide ($CO_2$); therefore, GWPs are given in units of $CO_2$ equivalents.

**Scoring of inherent properties** is applied to impact categories that may have different effects for the same amount of various chemicals, but for which equivalency factors do not exist or are not widely accepted. The scores are meant to normalize the inventory data to provide measures of potential impacts. Scoring methods are employed for the human and ecological toxicity impact categories, based on the Chemical Hazard Evaluation Management Strategies (CHEMS-1) method described by Swanson *et al*. (1997) and presented below. The scoring method provides a relative score, or hazard value, for each potentially toxic material that is then multiplied by the inventory amount to calculate the toxicity impact score.

Using the various approaches, the WCP LCIA method calculates impact scores for each inventory item for each applicable impact category. These impact scores are based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact category. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

Inventory amounts are identified on a functional unit basis and used to calculate impact scores. For each inventory item, an individual score is calculated for each applicable impact category. The detailed characterization equations for each impact category are presented in Sections 3.2.1 through 3.2.12 and summarized in Section 3.3. The equations presented in those subsections calculate impacts for individual inventory items that could later be aggregated as defined by the user. Impact scores represent relative and incremental changes rather than absolute effects or threshold levels.

**Table 3-2**

**LCIA Characterization Approaches for the WCP**

| Impact category | Characterization approach |
|---|---|
| ***Natural Resource Impacts*** | |
| Non-renewable materials use/depletion | Loading |
| Energy use | Loading |
| Landfill space use | Loading |
| ***Abiotic Ecosystem Impacts*** | |
| Global warming | Equivalency (full) |
| Stratospheric ozone depletion | Equivalency (full) |
| Photochemical smog | Equivalency (partial) |
| Acidification | Equivalency (full) |
| Air particulates | Loading |
| Water eutrophication (nutrient enrichment) | Equivalency (partial) |
| ***Human Health and Ecotoxicity*** | |
| Cancer human health effects occupational | Scoring of inherent properties |
| Cancer human health effects public | Scoring of inherent properties |
| Chronic non-cancer human health effects occupational | Scoring of inherent properties |
| Chronic non-cancer human health effects public | Scoring of inherent properties |
| Aquatic ecotoxicity | Scoring of inherent properties |

## 3.2 CHARACTERIZATION AND RESULTS

This section presents the impact assessment characterization methods and the impact results by impact category. Within each impact category subsection (3.2.1 through 3.2.12), the characterization equations are presented, followed by the results for each cable type. The full life-cycle results for CMR and CMP, and the NM-B cradle-to-gate analyses are presented (the CMR 3-way analysis is presented in Chapter 4 since limited data prevented the presentation of detailed results). Finally, a discussion of the limitations and uncertainties associated with that impact category concludes each section. The LCIA results are based on the boundaries outlined in Chapter 1 and the inventory described in Chapter 2. Within the results subsections of Sections 3.2.1 through 3.2.12, the impacts are presented as total impacts, followed by top contributing processes and top contributing flows. Section 3.3 briefly summarizes the characterization methods and the overall life-cycle impact category indicators for the 14 impact categories for each cable type. A summary of the limitations and uncertainties also is provided in Section 3.3. Uncertainty and sensitivity analyses are presented in Section 3.4.

It should be reiterated that the LCIA results presented throughout this section are indicators of the relative potential impacts of the baseline (lead-based) and the alternative cables in various impact categories and are not a measure of actual or specific impacts. The LCIA is intended to provide a screening level evaluation of impacts and in no way provides absolute values or measures actual effects. Results herein are referred to as impact category indicators (representing the total impact score of a cable alternative in an impact category), impact results, impact scores, or simply impacts. Each of these terms refers to relative potential impacts and should not be confused with an assessment of actual impacts.

## 3.2.1 Non-renewable Resource Use

### 3.2.1.1 Characterization

Natural resources are materials that are found in nature in their basic form, rather than being manufactured. Non-renewable ("stock") natural resources are typically abiotic, such as mineral ore or fossil fuels. Renewable ("flow") natural resources are those that can be regenerated, typically biotic resources, such as forest products or other plants, animal products, and water. Consumption impacts from non-renewable resources (NRRs) are calculated using direct consumption values (e.g., material mass) from the inventory. Renewable resource use is not included in the impact assessment.

For the non-renewable materials use/depletion category, depletion of materials results from the extraction of non-renewable resources. Non-renewable resource impact scores are based on the amount of material inputs (which can be product or process materials), water, and fuel inputs of non-renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{NRR})_i = [Amt_{NRR} \ x \ (1 - RC)]_i$$

where:

| | |
|---|---|
| $IS_{NRR}$ | equals the impact score for use of non-renewable resource *i* (kg) per functional unit; |
| $Amt_{NRR}$ | equals the inventory input amount of non-renewable resource *i* (kg) per functional unit; and |
| $RC$ | equals the fraction recycled content (post-industrial and post-consumer) of resource *i*. |

Accounting for the data collection limitations in the inventory and the characterization method, we have assigned a "medium" data quality measure for the NRR impact category results. The following subsections describe the impacts for each cable type.

### 3.2.1.2 CMR results

The baseline (leaded) CMR cable uses 17 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-2. The top contributing process is electricity production for cable extrusion for both alternatives (Figure 3-3) and inert rock is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-4). To protect confidentiality, Figure 3-3 combines the non-renewable resource inputs from all upstream electricity generation. Figure 3-3 includes the processes that contribute >5 percent of the total impacts, which represent 90 and 92 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-4 includes individual flows that contribute >1 percent to the total impacts and represents 99 percent of the total NRR impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are mostly a function of the differences in extrusion energy. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the non-renewable resource impact category (see Section 3.4). However, of potentially greater interest to manufactures is that when comparing insulation and jacketing of CMR cables, electricity production is the largest contributor to non-renewable resource depletion.

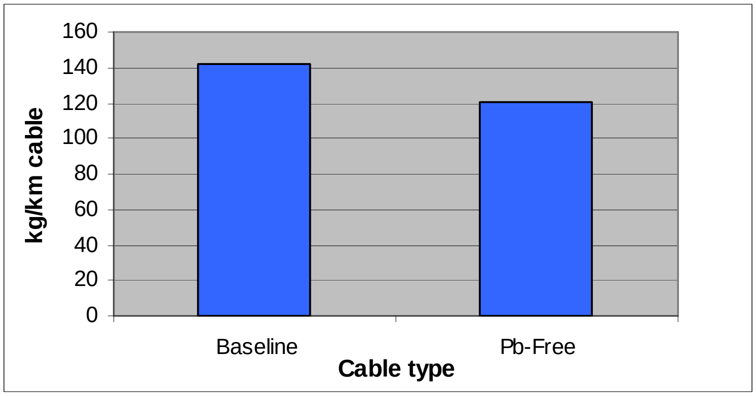

Figure 3-2. Total NRR Impacts – CMR Full life cycle

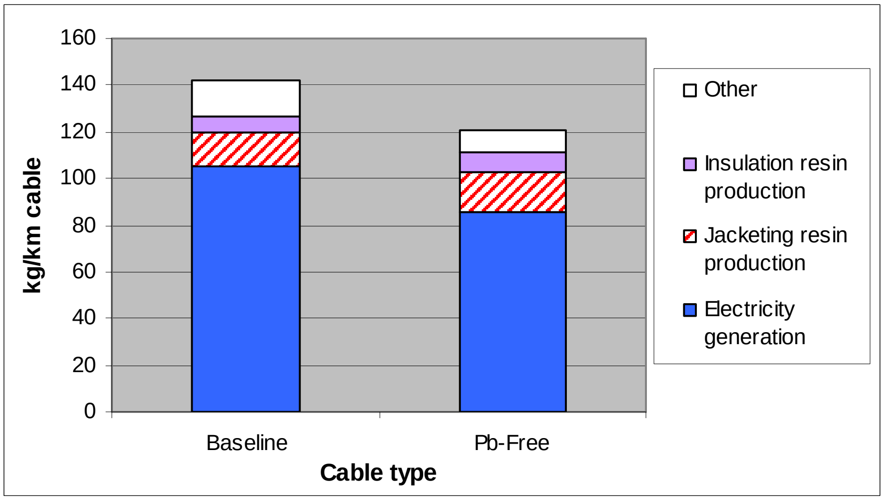

Figure 3-3. Top Contributing Processes to NRR Impacts – CMR Full life cycle

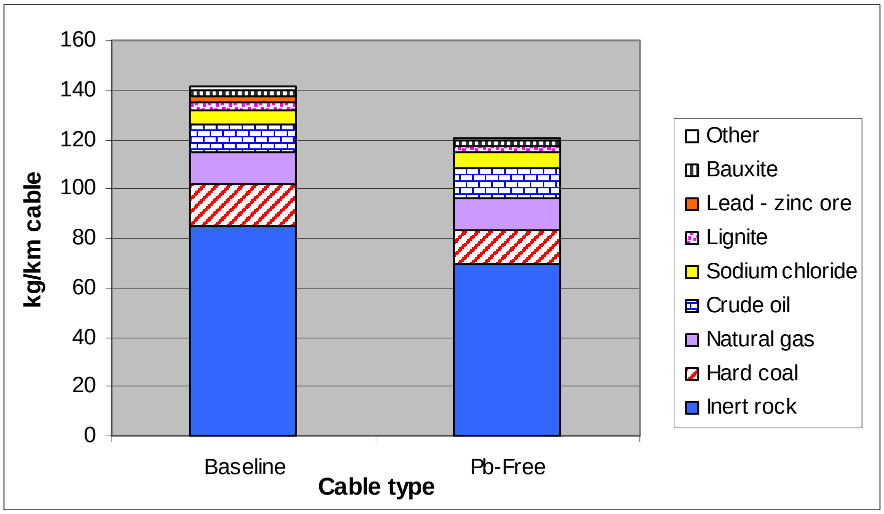

Figure 3-4. Top Contributing Flows to NRR Impacts – CMR Full life cycle

### 3.2.1.3 CMP results

The baseline cable uses 8 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-5. The top contributing process is electricity generation for cable extrusion for both alternatives (Figure 3-6). To protect confidentiality, Figure 3-6 combines the non-renewable resource inputs from all upstream electricity generation and natural gas production. Inert rock is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-7). Figure 3-6 includes the processes that contribute >2 percent of the total impacts, which represent 90 and 89 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-7 includes individual flows that contribute >1 percent to the total impacts and represents 99 percent of the total NRR impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the non-renewable resource impact category (see Section 3.4). However, of potentially greater interest to manufactures is that when comparing insulation and jacketing of CMP cables, electricity production is the largest contributor to non-renewable resource depletion.

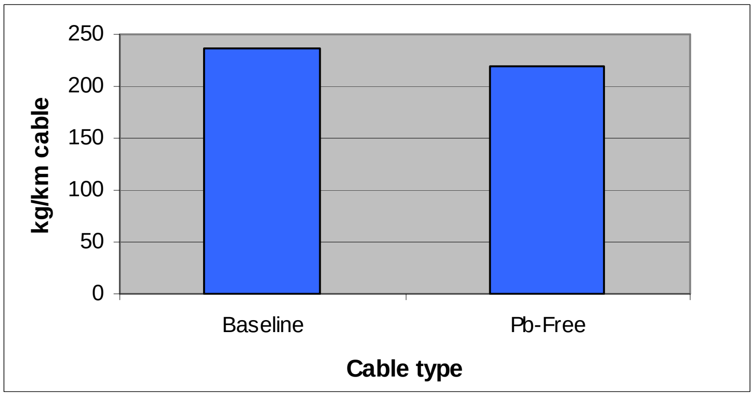

Figure 3-5. Total NRR Impacts – CMP Full life cycle

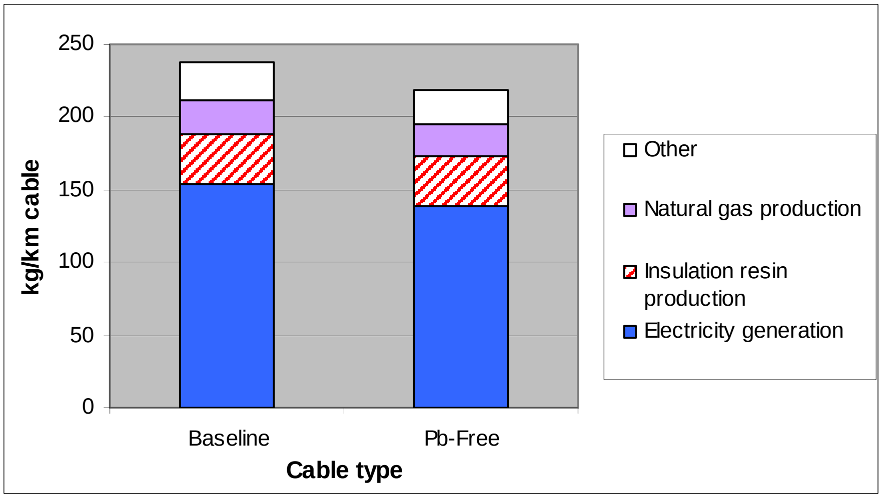

Figure 3-6. Top Contributing Processes to NRR Impacts – CMP Full life cycle

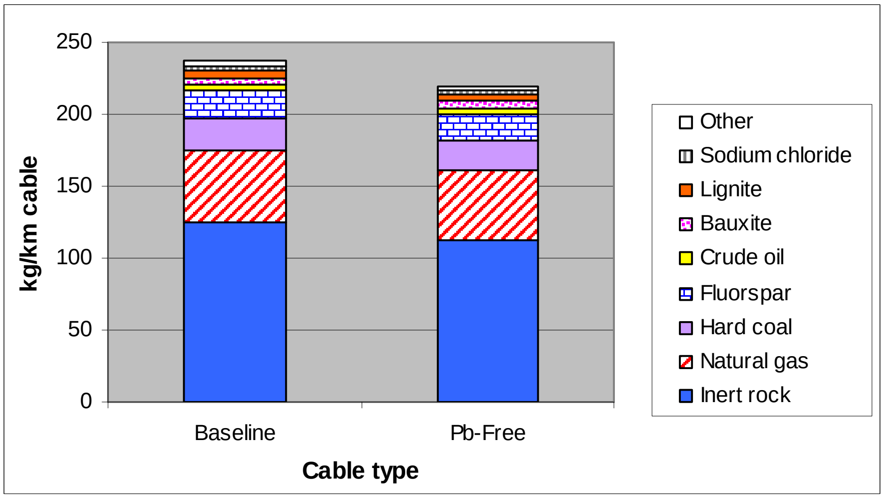

Figure 3-7. Top Contributing Flows to NRR Impacts – CMP Full life cycle

### 3.2.1.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable uses 18 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-8. The top contributing process is production of the jacketing resin, PVC, for both alternatives (Figure 3-9). To protect confidentiality, Figure 3-9 combines the non-renewable resource inputs from all upstream electricity generation. The greatest individual flow is inert rock for the baseline cable and natural gas for the lead-free alternative (Figure 3-10). Figure 3-3 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-4 includes individual flows that contribute >1 percent to the total impacts and represent 99 and >99 percent of the total NRR impacts for the baseline and lead-free alternatives, respectively.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Understanding that jacketing resin production contributes greatest to NRR depletion for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of jacketing resin used. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

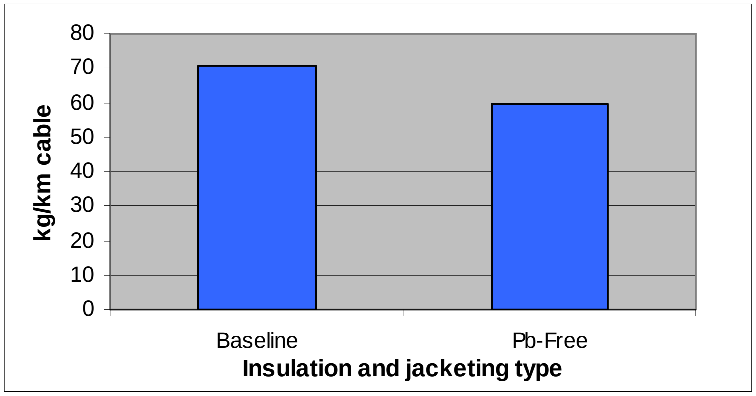

Figure 3-8. Total NRR Impacts – NM-B Partial life cycle

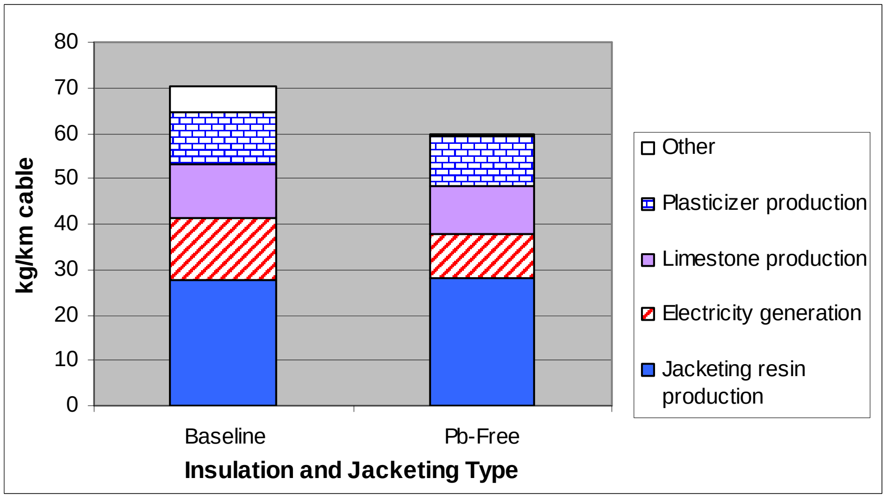

Figure 3-9. Top Contributing Processes to NRR Impacts – NM-B Partial life cycle

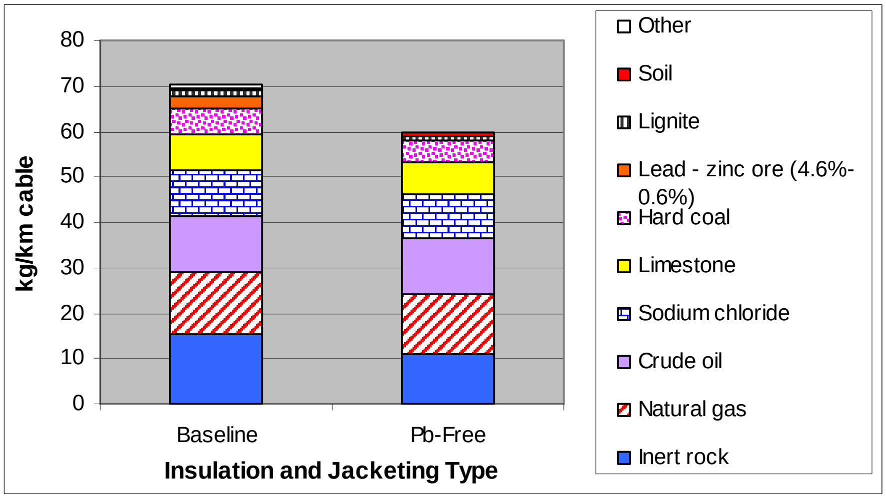

Figure 3-10. Top Contributing Flows to NRR Impacts – NM-B Partial life cycle

### 3.2.1.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. A limitation to the LCIA methodology for the NRR use category is that the results are based on the mass of a material consumed. Depletion of NRRs occurs from the extraction of these NRRs; however, the impact indicators do not relate consumption rates to the Earth's ability to sustain that consumption.

For all cable types, the inventory data was limited in the number of primary data sets collected for each process. Primary data were collected for each process from between 1 and 3 companies; where primary data were not available, secondary data were used, or in some cases, materials meeting decision rule criteria were not included.

The major uncertainty in the CMR and CMP inventory data that contribute to the NRR impacts is electricity for extrusion during cable manufacturing. This is explained in Section 2.2.4 and included in the uncertainty analysis in Section 3.4.1 and also discussed further in the sensitivity analysis (Section 3.4.2).

While the primary extrusion energy varied greatly among companies, another source of uncertainty is that the electricity generation process used in this study is from secondary data provided in the GaBi4 database. Data quality of the electricity generation inventory, as determined by GaBi4, is considered "good." In addition, an average U.S. electric grid mix was selected for use in the study to conform to the data collected from the manufacturing process, which were all in the United States, and which are within the geographic boundaries of this study. As a result, use of a secondary data set for electricity generation is not expected to be a large source of uncertainty.

The complete life-cycle of the NM-B cables was not available, and thus only limited cradle-to-gate analysis was conducted. As stated earlier, the NRR impact category is given an overall relative data quality rating of "medium" for all cable types.

## 3.2.2 Energy Use

### 3.2.2.1 Characterization

Energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy use impact scores are based on both *fuel* and *electricity* flows. The impact category indicator is the sum of electrical energy inputs and fuel energy inputs. Fuel inputs are converted from mass to energy units using the fuel's heat value (H) and the density (D), presented in Table 3-3 below.

**Table 3-3**

**Fuel Conversion Factors**

| Fuel | Heat Value (H) (MJ/L) | Reference | Density (D) (kg/L) | Reference |
|---|---|---|---|---|
| Heavy fuel oil #6 (residual) | 38.579 | (1) | 0.944 | (2) |
| Light fuel oil #2 (distillate) | 36.739 | (1) | 0.843 | (2) |
| Natural Gas | 0.034 | (3) | $7.58 \times 10^{-4}$ | (4) |

1. Davis, S.C. 1999. Transportation Energy Data Book, Edition 19. 1999. Center for Transportation Analysis, Oak Ridge National Laboratory, ORNL 6958, Appendix B, Table B1. Oak Ridge, Tennessee, September.
2. Energy Information Administration (EIA) 1999. International Energy Annual 1997. U.S. Department of Energy. DOE/EIA 0219 (97), Washington, DC. April.
3. Based on: Wang, M. 1999. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.5. Argonne National Laboratory, University of Chicago.
4. Calculated from: Perry, R.H. and D. Green (Eds.) 1984. Perry's Chemical Engineer's Handbook, 6th Edition, page 9-15, Table 9-13, and p. 9-16, Table 9-14. McGraw-Hill, Inc., New York, NY.

The impact score is calculated by:

$$(IS_E)_i = (Amt_E)_i \text{ or } [Amt_F \times (H / D)]_i$$

where:

$IS_E$ equals the impact score for energy use (MJ) per functional unit;

$Amt_E$ equals the inventory input amount of electrical energy used (MJ) per functional unit;

$Amt_F$ equals the inventory input amount of fuel used (kg) per functional unit;

$H$ equals the heat value of fuel *i* (MJ/L); and

$D$ equals the density of fuel *i* (kg/L).

This category addresses energy use only. The emissions from energy production are outputs from the energy production process and are classified to applicable impact categories, depending on the disposition and chemical properties of the outputs (see Classification Section 3.1.1).

Accounting for the data collection limitations in the inventory and the characterization method, we have assigned a "medium" data quality measure for the energy use impact category results.

#### 3.2.2.2 CMR results

The baseline (leaded) CMR cable uses 5 percent more energy than the lead-free alternative, which is shown in Figure 3-11. The top contributing process for both alternatives is electricity generation for the cable extrusion process. To protect confidentiality, Figure 3-12 combines the energy impacts from all upstream electricity generation. For both alternatives (Figure 3-13), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to fuel electricity. Figure 3-12 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-13 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total energy impacts for both alternatives.

The overall differences between the cables are largely a function of the differences in energy associated with the extrusion process, which is slightly offset by a slightly greater amount of the jacketing resin, PVC, used in the lead-free alternative. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the energy use impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that energy generation for cable extruding is the largest contributor to energy impacts for both alternatives. As a result, reductions in extrusion energy could lead to larger reductions in energy impacts relative to other processes.

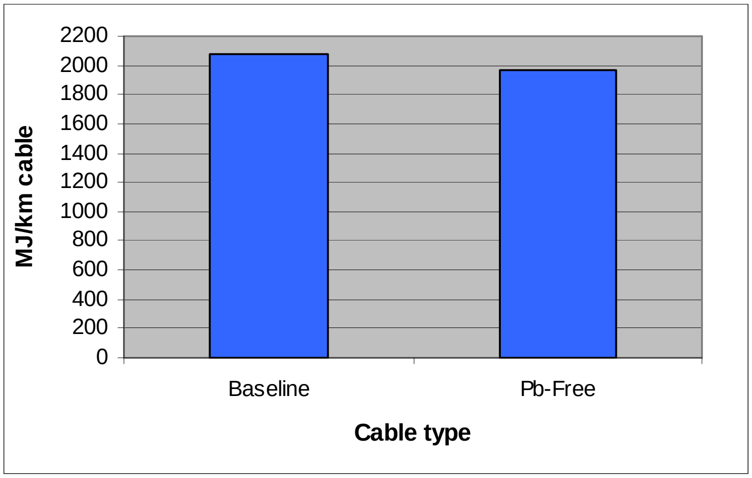

Figure 3-11. Total Energy Impacts – CMR Full life cycle

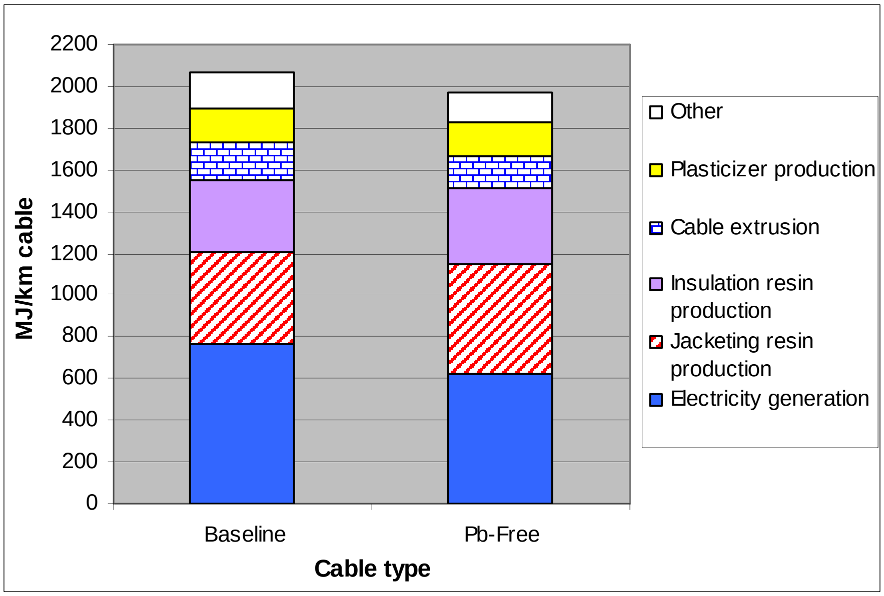

Figure 3-12. Top Contributing Processes to Energy Impacts – CMR Full life cycle

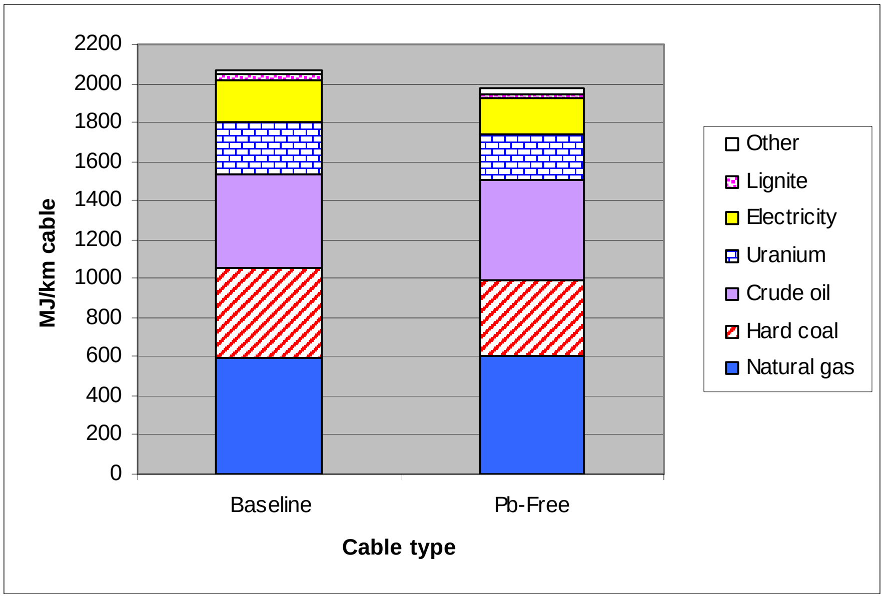

Figure 3-13. Top Contributing Flows to Energy Impacts – CMR Full life cycle

### 3.2.2.3 CMP results

The baseline (leaded) cable uses 6 percent more energy than the lead-free alternative, which is shown in Figure 3-14. The top contributing process for both alternatives is the generation of electricity for the cable extrusion process (Figure 3-15). To protect confidentiality, Figure 3-15 combines the energy impacts from all upstream electricity generation and natural gas production. For both alternatives (Figure 3-16), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to fuel electricity. Figure 3-

15 includes the processes that contribute >5 percent of the total impacts, which represents 89 percent of the total impacts for both the baseline and lead-free alternatives, respectively. Figure 3-16 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total energy impacts for both alternatives.

The overall differences between the cables are mostly a function of the differences in energy associated with cable extrusion and the FEP insulation resin production processes. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the energy use impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that generation of electricity for cable extrusion is the largest contributor to energy impacts for both alternatives, followed by natural gas production, and FEP resin production.

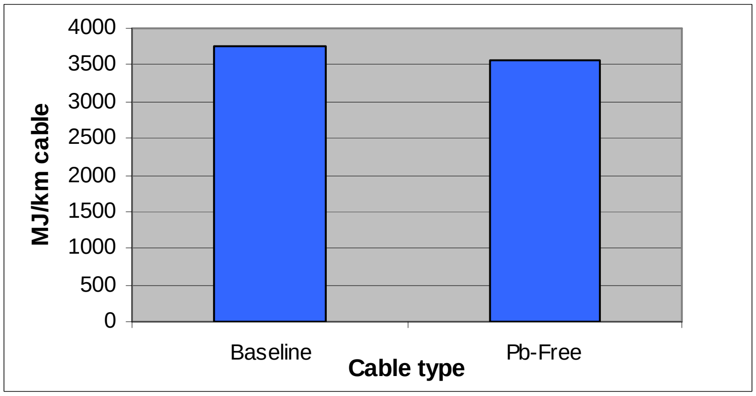

Figure 3-14. Total Energy Impacts – CMP Full life cycle

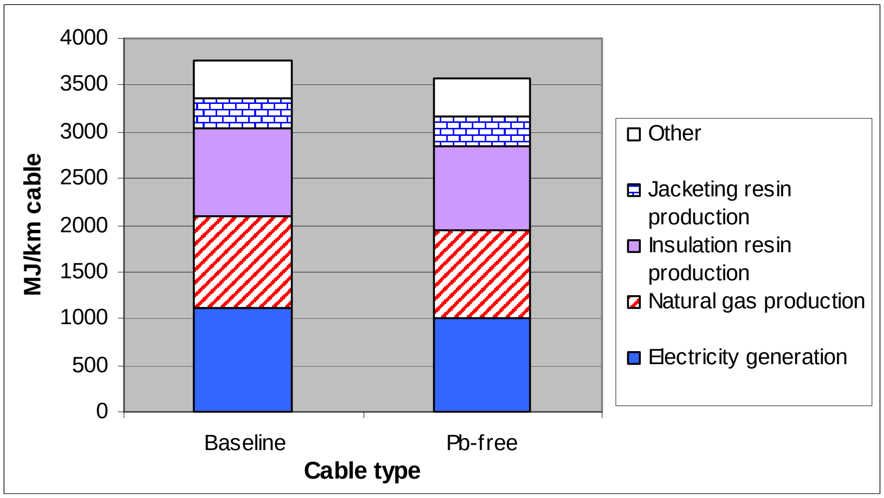

Figure 3-15. Top Contributing Processes to Energy Impacts – CMP Full life cycle

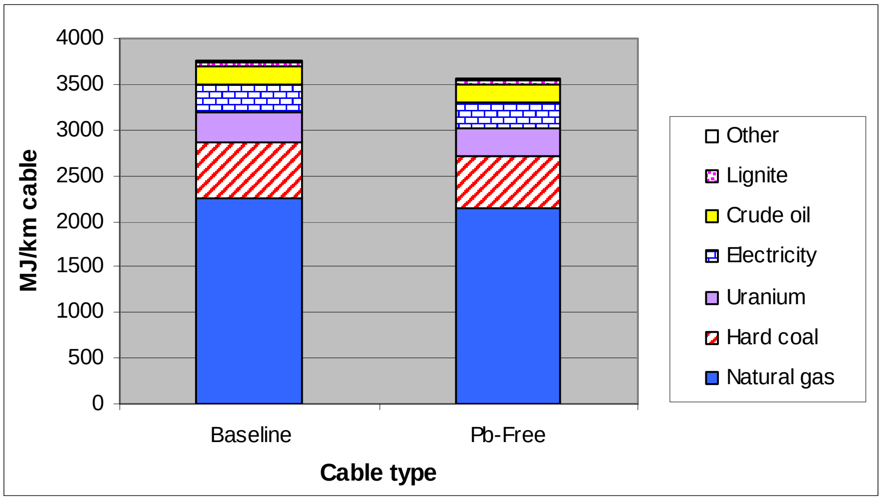

Figure 3-16. Top Contributing Flows to Energy Impacts – CMP Full life cycle

### 3.2.2.4 NM-B results

The baseline cable uses 6 percent more energy than the lead-free alternative, which is shown in Figure 3-17. The top contributing process for both alternatives is the production of the cable jacketing resin, PVC (Figure 3-18). To protect confidentiality, Figure 3-18 combines the energy impacts from all upstream electricity generation. For both alternatives (Figure 3-19), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to generate electricity. Figure 3-18 includes the processes that contribute >5 percent of the total impacts, which represent 90 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-19 includes individual flows that contribute >1 percent to the total impacts, which represent 98 and 99 percent of the total energy impacts for the baseline and lead-free alternatives, respectively.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Understanding that jacketing resin production contributes greatest to energy use impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of jacketing resin used. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

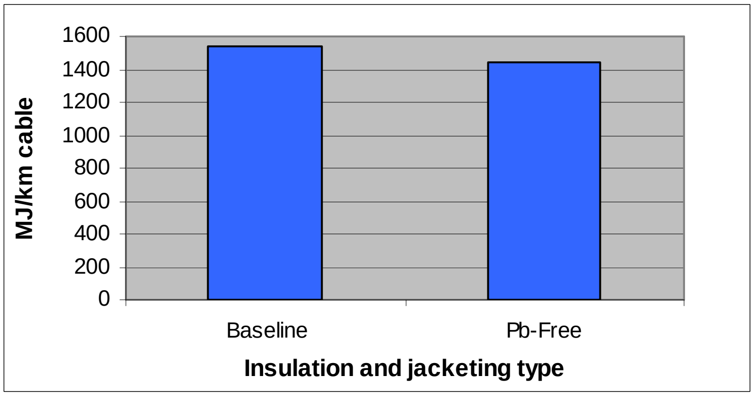

Figure 3-17. Total Energy Use Impacts – NM-B Partial life cycle

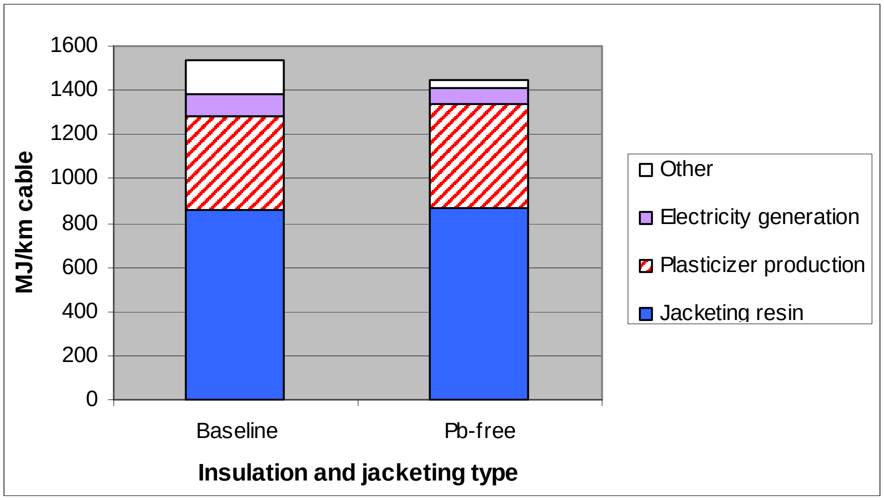

Figure 3-18. Top Contributing Processes to Energy Use Impacts – NM-B Partial life cycle

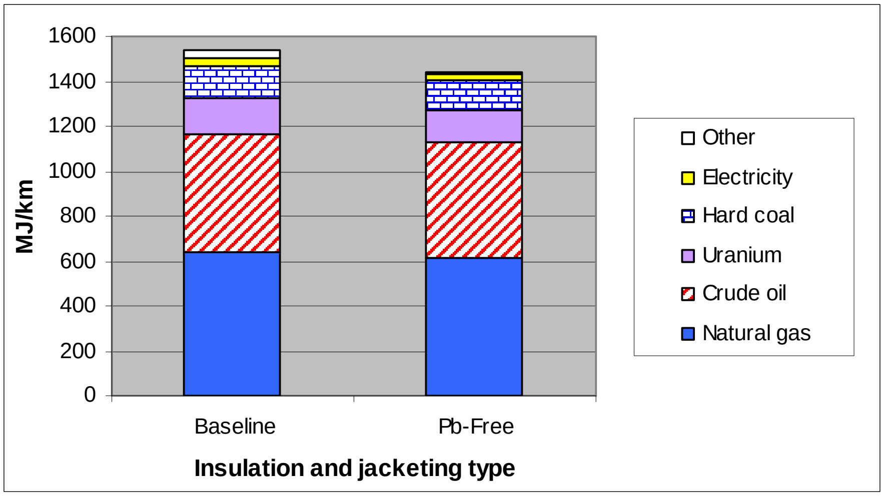

Figure 3-19. Top Contributing Flows to Energy Use Impacts – NM-B Partial life cycle

### 3.2.2.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the Energy Use category is a direct measure of the net calorific value of energy inputs,[15] and is not associated with great uncertainty.

---

[15] The calorific value of a fuel (or other substance, e.g., food) is the amount of heat released during the combustion of a specified amount of the substance. The *gross* calorific value is the heat evolved when all products of combustion are cooled to atmospheric temperature and pressure, and therefore includes the latent heat of vaporization and the sensible heat of water in the combustion products. This is the maximum energy that can be derived from a fuel. The *net* calorific value is the heat evolved when the products of combustion are cooled so that

The LCI contributes greater to the Energy Use category uncertainty. For the telecommunication cables, cable extruding, resin production, and electricity production contributed to most of the energy impacts. The extrusion and FEP production processes were each based on two primary data sets. As discussed in Section 2.2.4, extrusion data were highly variable, leading to sufficient uncertainty to be included in the uncertainty analysis is Section 3.4. The PVC and HDPE production processes, largely contributing as well, were from secondary data (described in Section 2.1.2.1).

The complete life cycle of the NM-B cables was not available, and thus only a limited cradle-to-gate analysis was conducted. Within the processes modeled, PVC production and phthalate plasticizer production were top contributing processes. PVC is discussed above, and phthalate production data were also from secondary data, and represent s a mix of various phthalate plasticizers in one process, as opposed to being specific to the plasticizers identified by the manufacturers. However, the most prevalent compounds are represented in the dataset used in this analysis. As stated earlier, based on the LCIA methodology and the LCI data, the Energy Use impact category is given an overall relative data quality rating of “medium” for all cable types.

### 3.2.3 Landfill Space Use Impacts

#### 3.2.3.1 Characterization

Landfill impacts are calculated using solid, hazardous, and radioactive waste flows to land as the volume of landfill space is consumed. For solid waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where municipal waste or construction debris is accepted. For hazardous waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where hazardous waste, as designated and regulated under the Resource Conservation and Recovery Act (RCRA), is accepted. Similarly, radioactive wastes are included. For non-U.S. activities, equivalent hazardous or special waste landfills are considered for this impact category. Impact scores are characterized from solid, hazardous, and radioactive waste outputs with a disposition of landfill. The only radioactive waste outputs in the inventory of cables are from the portion of electricity produced using nuclear fuel. Impact characterization is based on the volume of waste, determined from the inventory mass amount of waste and material density of each specific hazardous waste type:

$$(IS_L)_i = (Amt_W / D)_i$$

where:

| | |
|---|---|
| $IS_L$ | equals the impact score for landfill (L) use for waste *i* cubic meters ($m^3$) per functional unit; |
| $Amt_W$ | equals the inventory output amount of solid waste *i* (kg) per functional unit; and |
| $D$ | equals density of waste *i* ($kg/m^3$) (see Appendix C). |

---

the water remains as a gas. It is equal to the gross calorific value minus the sensible heat and latent heat of vaporization of water. This study uses net calorific energy value as the measure of energy impacts.

Accounting for the inventory and the characterization method, we have assigned a “medium” data quality measure for the landfill space use impact category results.

### 3.2.3.2 CMR results

The lead-free alternative cable uses 9 percent more landfill space than the baseline cable (Figure 3-20). The top contributing process for the baseline cable and lead-free alternative is the landfilling of chopped cable (<0.014 $m^3$/km cable, Figure 3-21), and PVC waste and other industrial wastes are the greatest individual flow contributing to the impacts for both alternatives (Figure 3-22). Figure 3-21 includes the processes that contribute >3 percent of the total impacts, which represent 94 percent of the total impacts for both alternatives. Figure 3-22 includes individual flows that contribute >1 percent to the total impacts, which represent 99.5 and 99.2 percent of the total landfill space use impacts for the baseline and lead-free alternatives, respectively.

The overall difference between the cables is mostly due to the greater amount of cable sent to EOL, which is a function of the functional unit difference (i.e., there was greater resin mass in the lead-free cable as compared to the leaded cables to meet the same function. The uncertainty analysis described in Section 3.4 revealed that the landfill space use impacts are sensitive to the energy and EOL uncertainty parameters that were varied; thus, the difference between the baseline and lead-free alternative is not expected to be greatly distinguishable.

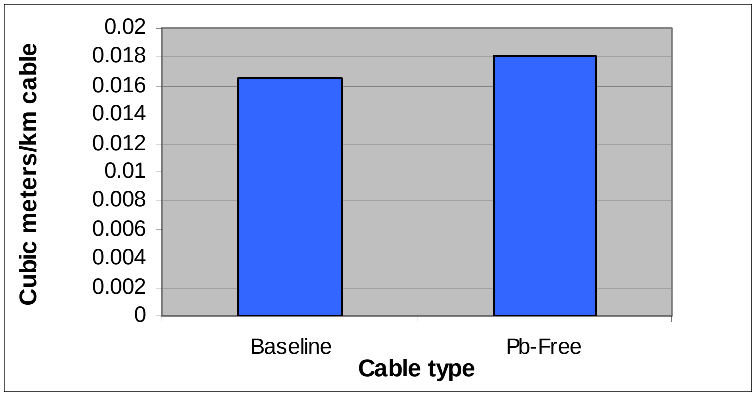

Figure 3-20. Total Landfill Space Impacts – CMR Full life cycle

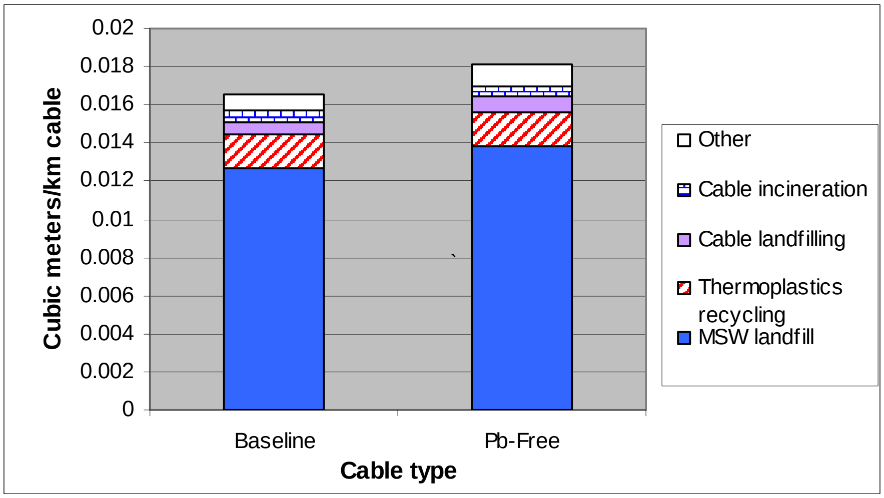

Figure 3-21. Top Contributing Processes to Landfill Space Impacts – CMR Full life cycle

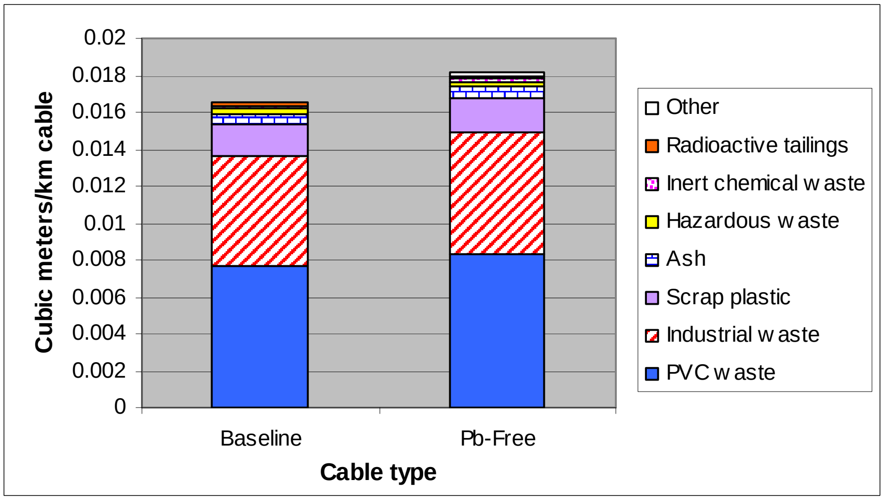

Figure 3-22. Top Contributing Flows to Landfill Space Impacts – CMR Full life cycle

### 3.2.3.3 CMP results

The lead-free alternative cable uses 9 percent more landfill space than the baseline cable, which is shown in Figure 3-23. The top contributing process for the baseline cable and lead-free alternative is the landfilling of chopped cable (Figure 3-24). The top contributing flow for both the baseline and lead-free alternatives is PVC waste (Figure 3-25). Figure 3-24 includes the processes that contribute >5 percent of the total impacts, which represent 81 and 82 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-25 includes individual flows that contribute >1 percent to the total impacts and represents 98 percent of the total landfill space use for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in cable composition and cable recycling. Due to the uncertainty associated with the cable recycling at end-of-life (see Section 2.4.5.1), an uncertainty analysis was conducted, which showed that by varying the proportion of the resins recycled after cable chopping from 0 to 20 percent of the cable, the differences between the cables was not greatly distinguishable for the landfill space use category (see Section 3.4).

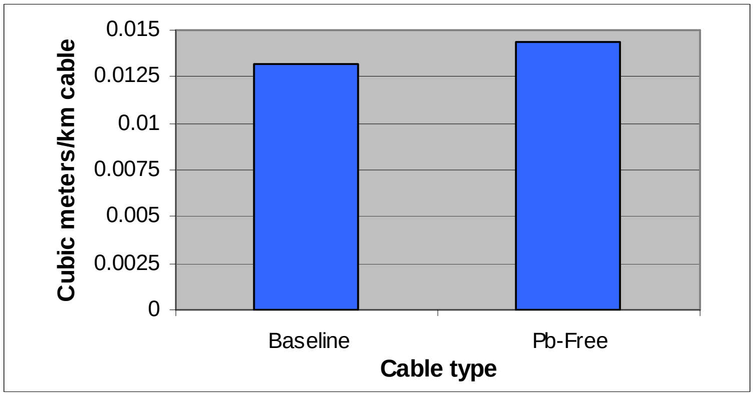

Figure 3-23. Total Landfill Space Use Impacts – CMP Full life cycle

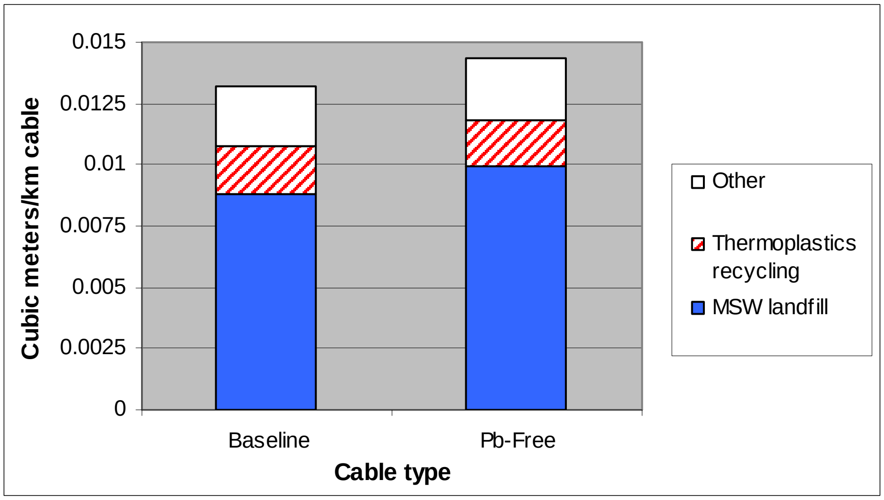

Figure 3-24. Top Contributing Processes to Landfill Space Impacts – CMP Full Life Cycle

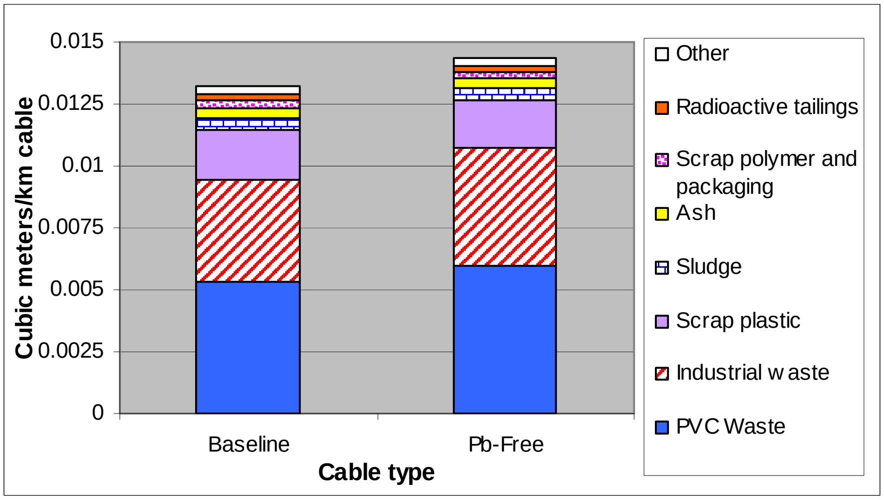

Figure 3-25. Top Contributing Flows to Landfill Space Impacts – CMP Full Life Cycle

#### 3.2.3.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 13 percent greater landfill space use impacts than the lead-free alternative, which is shown in Figure 3-26. The top contributing process is the production of the limestone filler for both alternatives (Figure 3-27), and mineral treatment residue is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-28). Figure 3-27 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-28 includes individual flows that contribute >1 percent to the total impacts, and represent 99 percent of the total landfill space use impacts for both the baseline and lead-free alternatives.

Of note is that the impacts for both the leaded and lead-free constructions are driven by the limestone production process, the top contributing flow was copper ions, and the volume of waste is much smaller than the CMR and CMP results, which included EOL. When EOL was included, the leaded telecommunication cables had much greater burdens due to impact of lead during the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B, these results would be driven by other processes and materials. Because we expect EOL to be a large driver of impacts for this category, the landfill space category for NM-B is given a “medium-to-low” quality rating (ratings are summarized in Chapter 4, Table 4-6).

Therefore, care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that limestone production contributes greatest to landfill space use for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of limestone. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

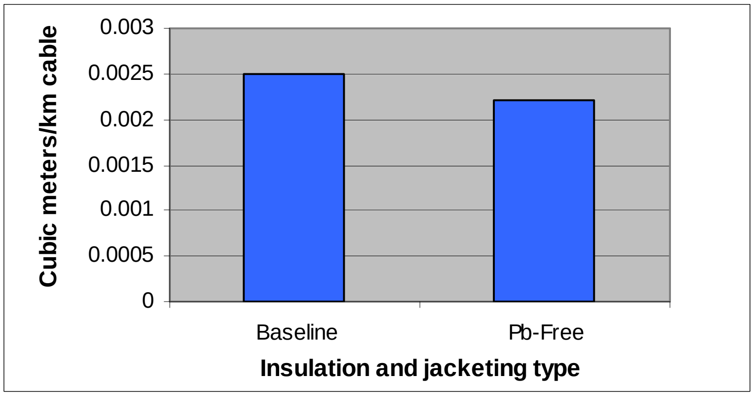

Figure 3-26. Total Landfill Space Use Impacts – NM-B Partial life cycle

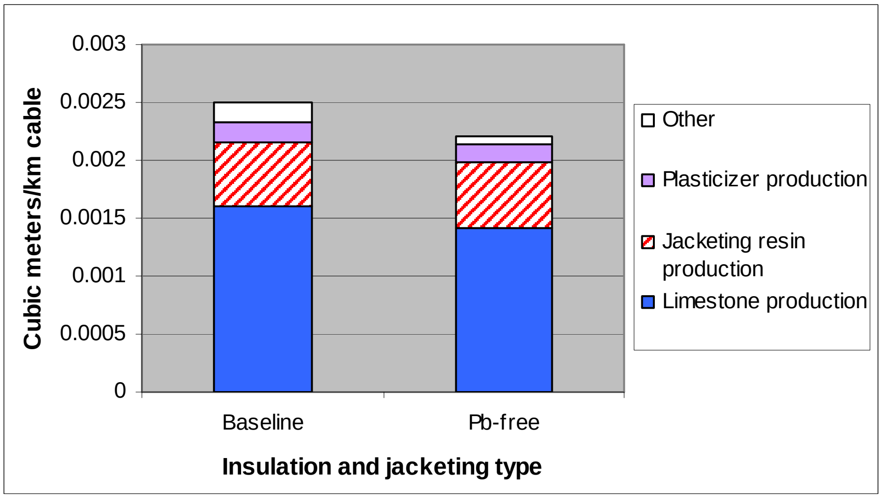

Figure 3-27. Top Contributing Processes to Landfill Space Use Impacts – NM-B Partial life cycle

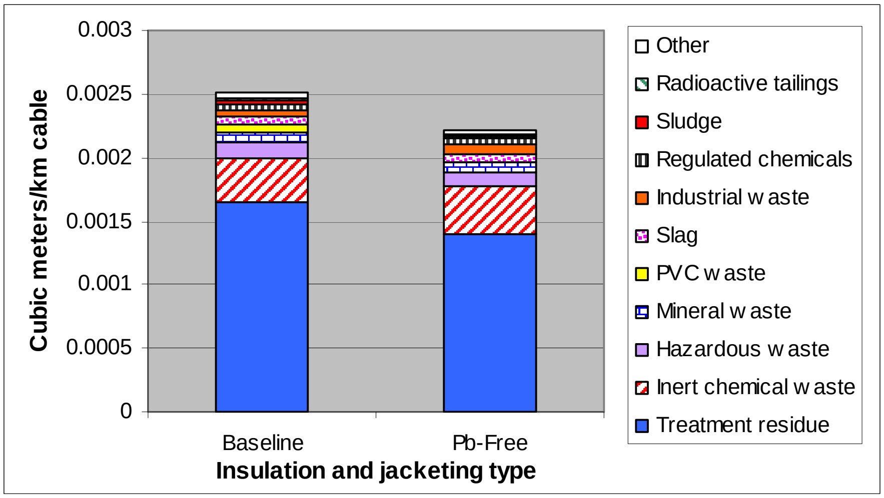

Figure 3-28. Top Contributing Flows to Landfill Space Use Impacts – NM-B Partial life cycle

### 3.2.3.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the Landfill Space Use category is a direct measure of the volume of waste put in landfills. The uncertainty in the LCIA methodology is whether accurate bulk densities are used to convert the mass data into a volume. For primary data, companies were asked for the bulk densities of wastes sent to landfills. For densities of output flows from secondary data, or when densities were not provided by the primary data suppliers, general bulk densities were collected from secondary sources (Appendix C).

The LCIA methodology for landfill space use is only used to represent the volume of landfill space used, and not the type of materials in the landfill waste. Toxic materials that are landfilled, and that potentially leach from a landfill, are addressed in other impact categories (e.g., public toxicity and aquatic ecotoxicity).

For LCI-based uncertainties, the CMR/CMP results showed landfill volume impacts deriving mostly from the landfilling of the PVC waste after chopping. The chopping data were from one primary data source.

The complete life cycle of the NM-B cables was not available, and thus only a limited cradle-to-gate analysis was conducted. Within the processes modeled, limestone and PVC production were top contributing processes. Secondary PVC and phthalate production data are discussed above under Energy Impacts (Section 3.2.2.5). As stated earlier, based on the LCIA methodology and the LCI data, the Landfill Space Use impact category is given an overall relative data quality rating of "medium" for all cable types.

### 3.2.4 Global Warming Impacts

#### 3.2.4.1 Characterization

The build up of carbon dioxide ($CO_2$) and other greenhouse gases in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. Global warming potential (GWP) refers to the warming, relative to $CO_2$, that chemicals contribute to this effect by trapping the Earth's heat. 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 GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical $CO_2$; therefore, GWPs are in units of $CO_2$ equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology employed in the WCP uses GWPs having effects in the 100 year time horizon. Although LCA does not necessarily include a temporal component of the inventory, impacts from releases during the life cycle of cables are expected to be within the 100 year time frame. Appendix D presents the GWPs of global warming gases in the cable inventories. The equation to calculate the impact score for an individual chemical is as follows:

$$(IS_{GW})_i = (EF_{GWP} \text{ x } Amt_{GG})_i$$

where:

| | |
|---|---|
| $IS_{GW}$ | equals the global warming impact score for greenhouse gas chemical *i* (kg $CO_2$ equivalents) per functional unit; |
| $EF_{GWP}$ | equals the GWP equivalency factor for greenhouse gas chemical i ($CO_2$ equivalents, 100-year time horizon); and |
| $Amt_{GG}$ | equals the inventory amount of greenhouse gas chemical *i* released to air (kg) per functional unit. |

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the global warming impact category results.

#### 3.2.4.2 CMR results

The baseline cable has an 8 percent greater global warming potential than the lead-free alternative, which is shown in Figure 3-29. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-30). To protect confidentiality, Figure 3-30 combines the global warming potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is carbon dioxide (Figure 3-31). Figure 3-30 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 95 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-31 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the global warming potential impact category (see Section 3.4). The generation of electricity for cable extrusion is the greatest contributor to global warming impacts. As a result, reductions in extrusion energy could lead to larger reductions in global warming impact relative to other processes.

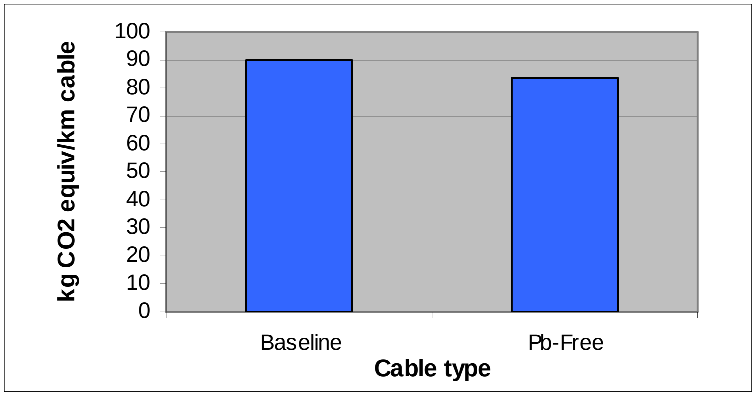

Figure 3-29. Total Global Warming Impacts – CMR Full life cycle

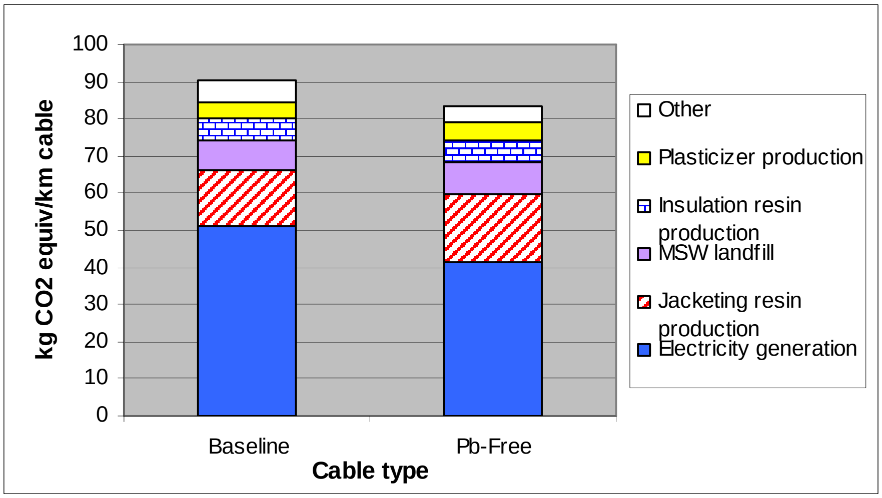

Figure 3-30. Top Contributing Processes to Global Warming Impacts – CMR Full life cycle

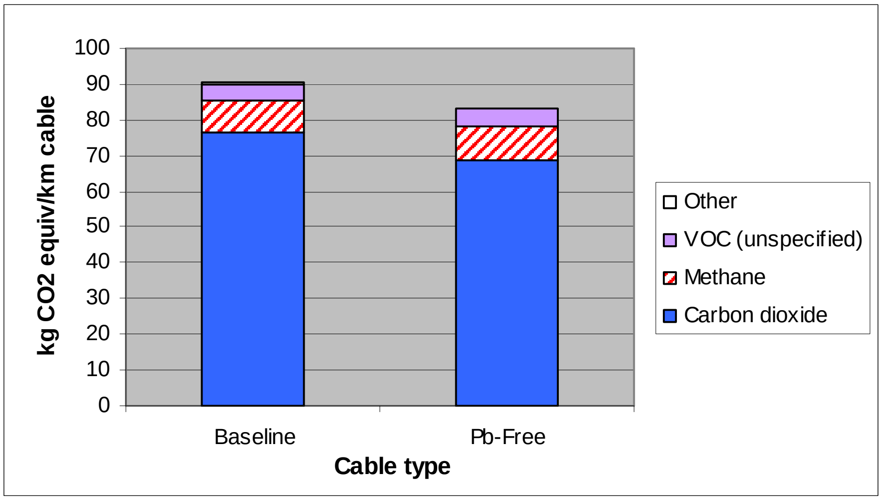

Figure 3-31. Top Contributing Flows to Global Warming Impacts – CMR Full life cycle

#### 3.2.4.3 CMP results

The baseline cable has a 6 percent greater global warming potential than the lead-free alternative, which is shown in Figure 3-32. The top contributing process for the baseline cable and lead-free alternative is the production of the insulation resin, FEP (Figure 3-33). To protect confidentiality, Figure 3-33 combines the global warming potential impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is carbon dioxide (Figure 3-34). Figure 3-33 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 91 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-34 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the global warming potential impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that the production of insulation resin is the largest individual contributor to global warming for both alternatives.

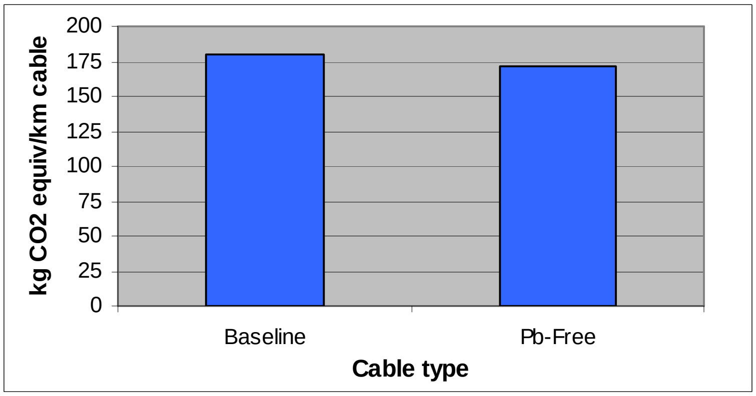

Figure 3-32. Total Global Warming Impacts – CMP Full life cycle

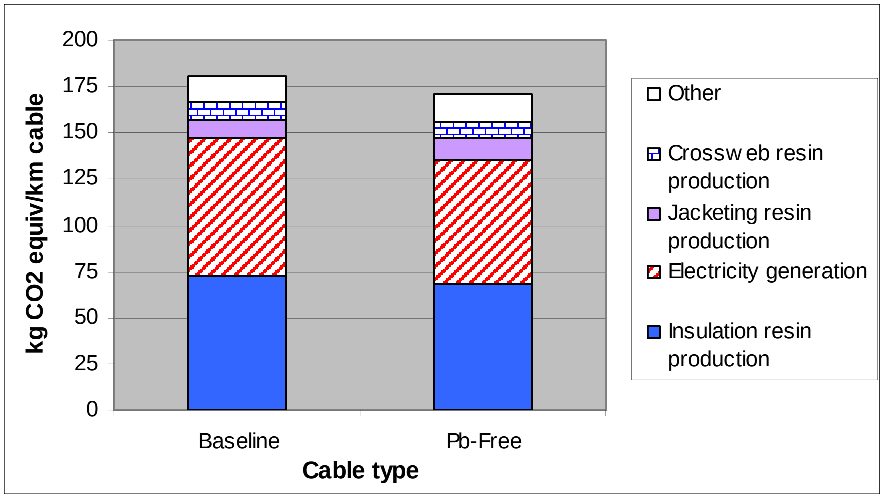

Figure 3-33. Top Contributing Processes to Global Warming Impacts – CMP Full Life Cycle

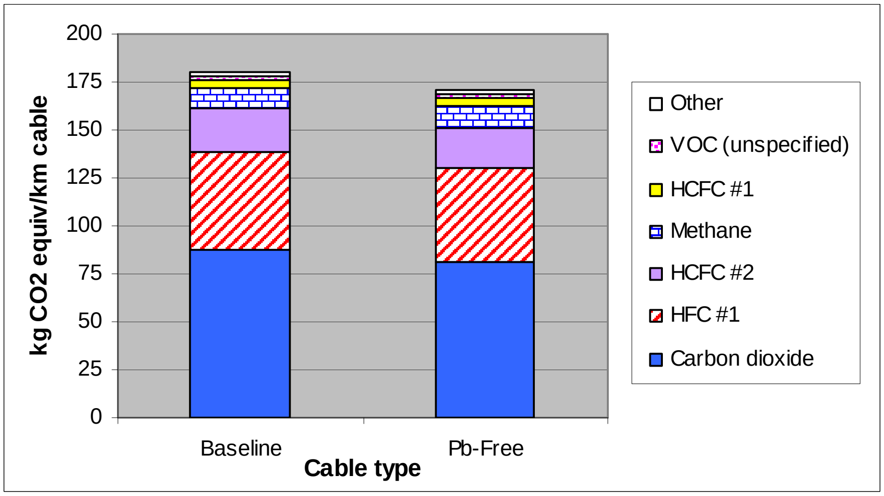

Figure 3-34. Top Contributing Flows to Global Warming Impacts – CMP Full Life Cycle

### 3.2.4.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 8 percent higher global warming potential impacts than the lead-free alternative, which is shown in Figure 3-35. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-36). To protect confidentiality, Figure 3-36 combines the energy impacts from all upstream electricity generation. Carbon dioxide is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-37). Figure 3-36 includes the processes that contribute >5 percent of the total impacts, which represent 95 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-37 includes individual flows that contribute >1 percent to the total impacts, which represents >99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to global warming impacts for both alternatives could provide the opportunity to reduce these impacts. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce carbon dioxide emissions).

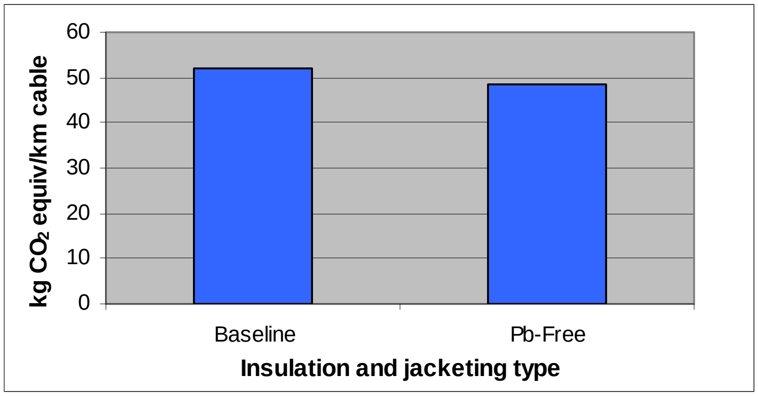

Figure 3-35. Total Global Warming Impacts – NM-B Partial life cycle

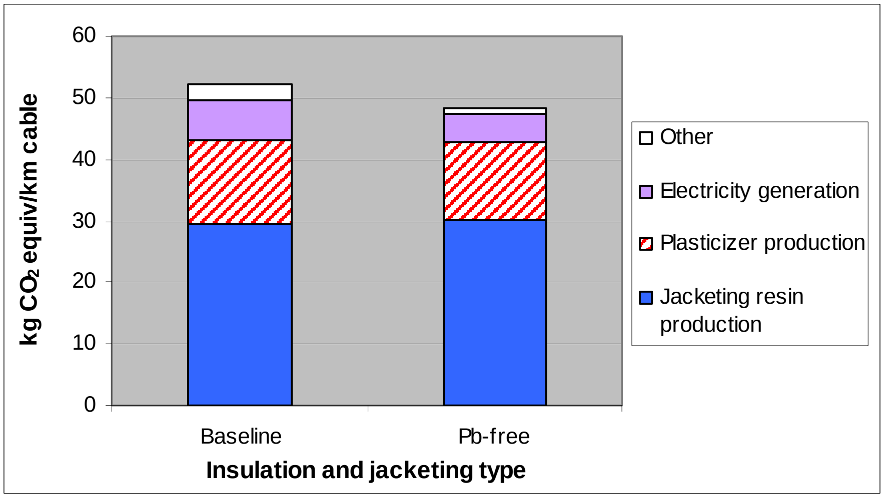

Figure 3-36. Top Contributing Processes to Global Warming Impacts – NM-B Partial life cycle

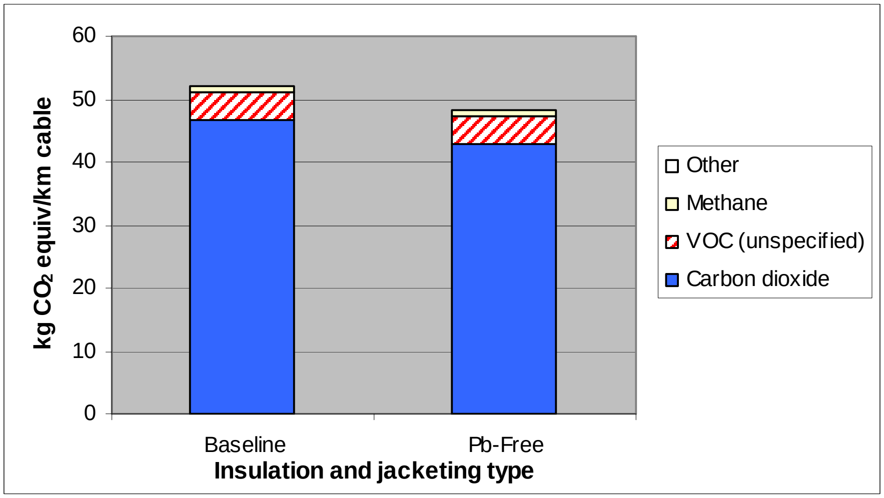

Figure 3-37. Top Contributing Flows to Global Warming Impacts – NM-B Partial life cycle

### 3.2.4.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the global warming category is based on equivalency factors for chemicals with global warming potentials, which are commonly used in LCA and are considered reliable data, to the extent that science is able to predict the radiative forcing of chemicals.

The LCI-based uncertainty is similar to that discussed under the Energy impact category (Section 3.2.2.5), as similar processes drive the global warming impacts. As stated earlier, based on the LCIA methodology and the LCI data, the Energy Use impact category is given an overall relative data quality rating of “medium” for all cable types.

## 3.2.5 Stratospheric Ozone Depletion Impacts

### 3.2.5.1 Characterization

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone-depleting chemicals released to air. Currently identified ozone-depleting chemicals are those with an ozone depletion potential (ODP), which is a measure of the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC), CFC 11 (trichlorofluoromethane) (Heijungs *et al.*, 1992; CAAA, 1990). The ODPs of chemicals in the cable inventories are provided in Appendix D. The individual chemical impact score for stratospheric ozone depletion is based on the ODP and inventory amount of the chemical:

$$(IS_{OD})_i = (EF_{ODP} \text{ x } Amt_{ODC})_i$$

where:

$IS_{OD}$ equals the ozone depletion (OD) impact score for chemical $i$ (kg CFC-11 equivalents) per functional unit;

$EF_{ODP}$ equals the ODP equivalency factor for chemical $i$ (CFC-11 equivalents); and

$Amt_{ODC}$ equals the amount of ozone depleting chemical $i$ released to air (kg) per functional unit.

Accounting for the inventory and the characterization method, we have assigned a "low" data quality measure for the stratospheric ozone depletion impact category results. The low rating is due to the absence of upstream data on brominated phthalates and the generally high ozone depletion potentials of brominated compounds (see Section 3.2.5.5).

#### 3.2.5.2 CMR results

The baseline cable has a 19 percent greater potential to deplete the stratospheric ozone layer than the lead-free alternative, which is shown in Figure 3-38. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-39). To protect confidentiality, Figure 3-39 combines the ozone depletion potential from all upstream electricity production. The top contributing flow for both the baseline and lead-free alternatives is CFC-11 (Figure 3-40). Figure 3-39 includes the processes that contribute >5 percent of the total impacts, which represent 99 and >99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-40 includes individual flows that contribute >1 percent to the total impacts and represents >99 percent of the total stratospheric ozone depletion impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the ozone depletion impact category (see Section 3.4). Given that complete upstream data were not included in the model for this analysis, electricity for extrusion was the greatest contributor. Increasing the energy efficiency of life cycle processes (particularly extrusion energy) would thus reduce the ozone depletion impacts.

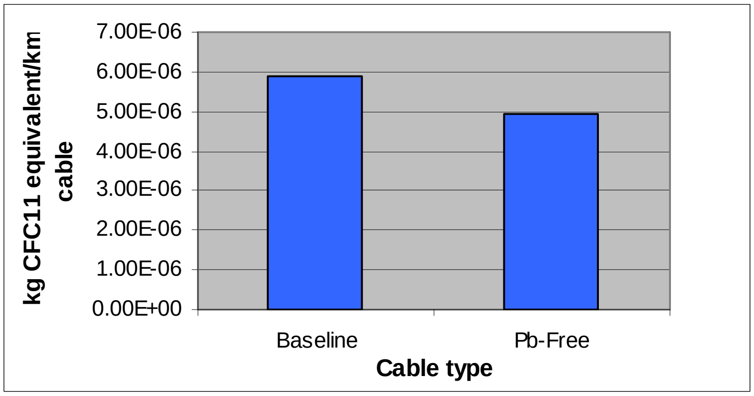

Figure 3-38. Total Stratospheric Ozone Depletion Impacts – CMR Full life cycle

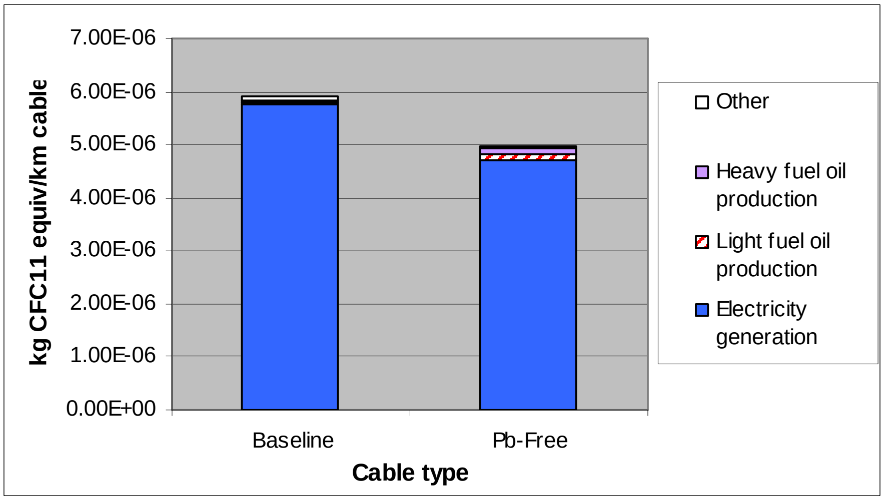

Figure 3-39. Top Contributing Processes to Ozone Depletion Impacts – CMR Full life cycle

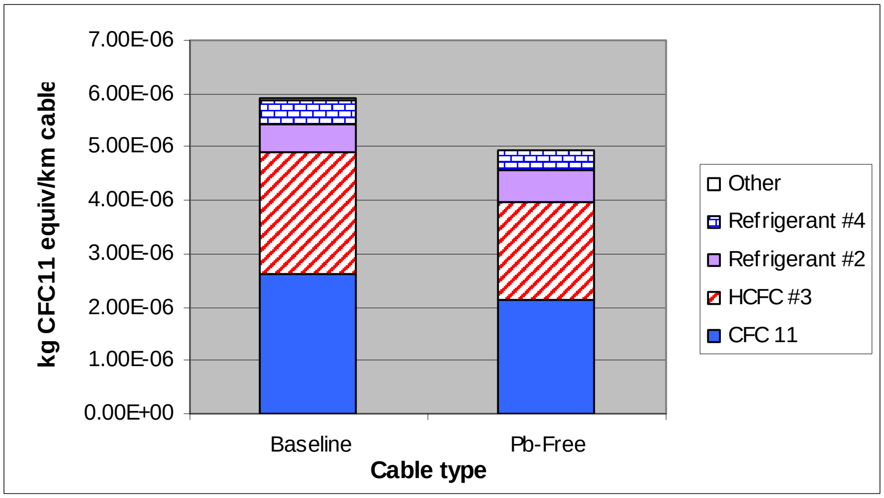

Figure 3-40. Top Contributing Flows to Ozone Depletion Impacts – CMR Full life cycle

### 3.2.5.3 CMP results

The baseline cable has a 5 percent greater impact on the stratospheric ozone depletion potential than the lead-free alternative, which is shown in Figure 3-41. The top contributing process for the baseline cable and lead-free alternative is the production of the insulation resin, FEP (Figure 3-42). The top contributing flow for both the baseline and lead-free alternatives is Refrigerant #5 (Figure 3-43). Figure 3-42 includes the processes that contribute >5 percent of the total impacts, which represent 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-43 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total stratospheric ozone depletion potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in the amount of FEP used in the cable. As the uncertainty analysis did not take into consideration differences in product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the differences between the cables remained for the ozone depletion potential impact category (see Section 3.4). In light of incomplete upstream data in the model for this analysis, production of insulation resin was the greatest contributor to impacts.

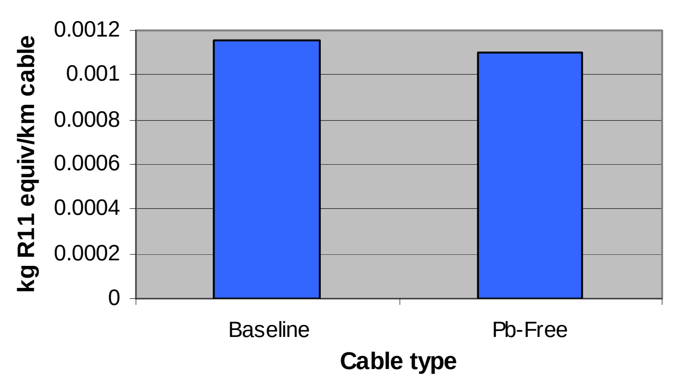

Figure 3-41. Total Stratospheric Ozone Depletion Impacts – CMP Full life cycle

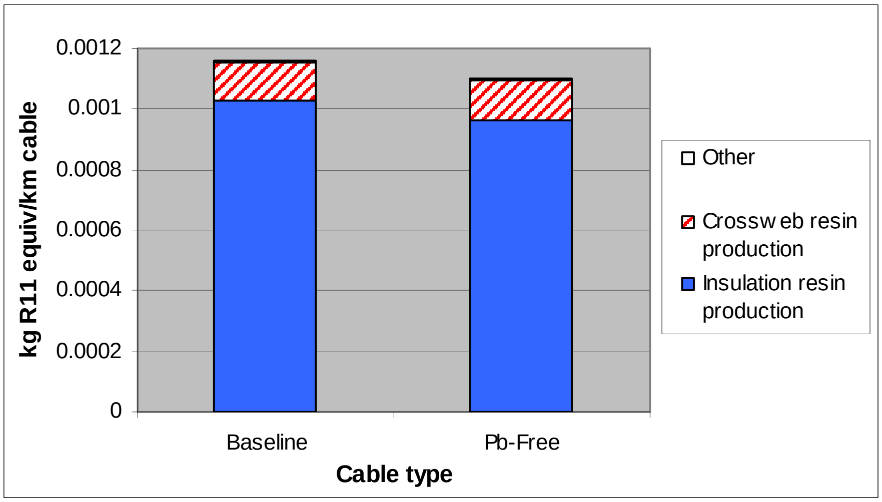

Figure 3-42. Top Contributing Processes to Stratospheric Ozone Depletion Impacts – CMP Full Life Cycle

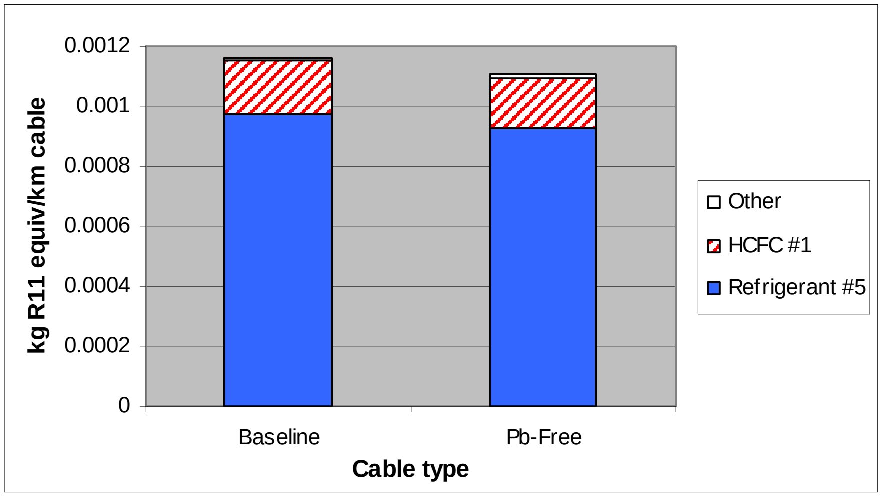

Figure 3-43. Top Contributing Flows to Stratospheric Ozone Depletion Impacts – CMP Full life cycle

#### 3.2.5.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 48 percent higher ozone depletion potential impacts than the lead-free alternative, which is shown in Figure 3-44. The top contributing process is the generation of electricity for cable jacket compounding for both alternatives (Figure 3-45). CFC-11 is the greatest individual flow contributing to the impacts for both alternatives, followed closely by an HCFC (Figure 3-46). Figure 3-45 includes the processes that contribute >5 percent of the total impacts, which represents 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-46 includes individual flows that contribute >1 percent to the total impacts, and represent >99 percent of the total ozone depletion potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that electricity production contributes greatest to stratospheric ozone depletion impacts for both alternatives could provide the opportunity to reduce these impacts. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., CFC-11).

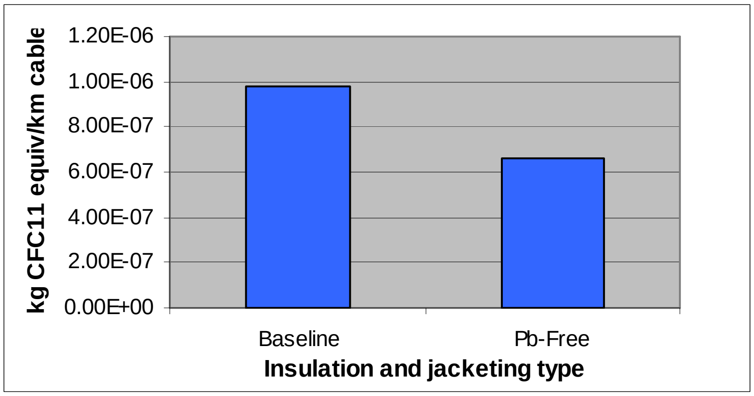

Figure 3-44. Total Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

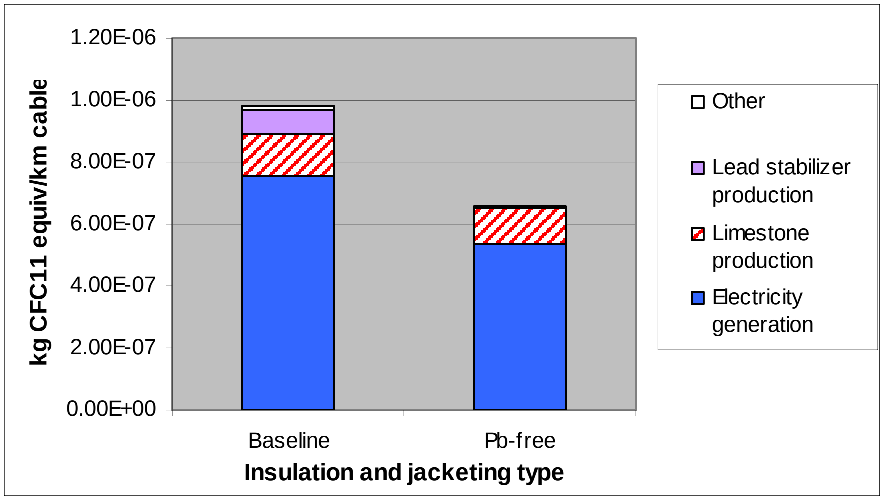

Figure 3-45. Top Contributing Processes to Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

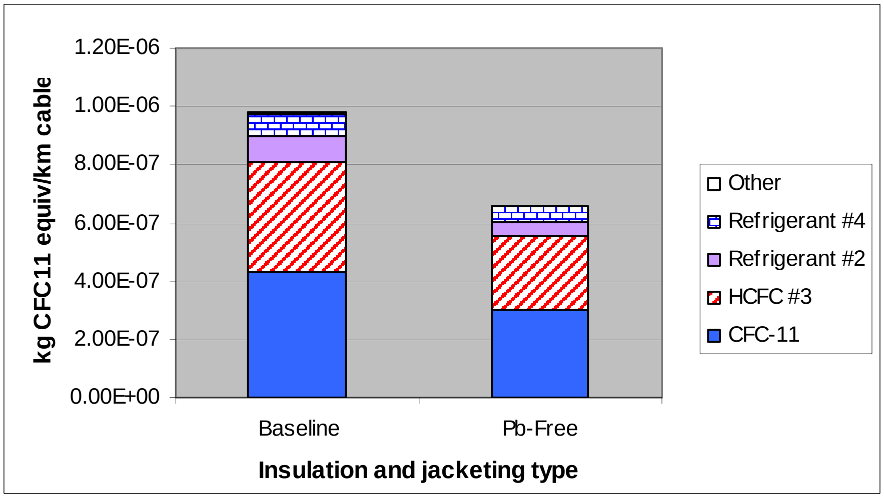

Figure 3-46. Top Contributing Flows to Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

### 3.2.5.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology is based on ozone depletion potential equivalency factors, which are commonly used in LCA and are considered reliable data.

For the CMR results, the LCI-based uncertainty is similar to that discussed under the Energy impacts (Section 3.2.2.5) and Global Warming impacts (Section 3.2.4.5), as electricity generation drives impacts for each of these categories. The partial life-cycle results for NM-B were also driven by electricity generation, but since there were no extrusion data in the NM-B model, the uncertainty is related to limitations of the process of electricity generation (discussed in Section 3.2.1.5, NRR impacts), recognizing also that the scope of the NM-B analysis is limited to cradle-to-gate processes. For the CMP results, FEP production was a greater contributor to stratospheric ozone impacts, and the production data were derived from 2 companies.

Further limitations to all cable types are related to missing upstream data. For example, the production process of brominated phthalates was not available, and small brominated hydrocarbons, expected to be among the byproducts of brominated phthalate production, typically have large ozone depleting potentials. Thus, these impacts may be underestimated, and cables with greater quantities of brominated phthalates would be even more underestimated. Based on the bill of materials from primary data collected, the leaded CMR used brominated compounds, while the lead-free ones did not. For CMP, both alternatives used brominated compounds; however, the lead-free cables used about 13 percent more than the leaded cables. Therefore, the CMR results might show a greater difference between the baseline and lead-free cable constructions, potentially resulting in a significant difference between alternatives. For the CMR results, the point estimate results showed the baseline cable construction to yield only 5 percent greater ozone depletion impacts than the lead-free. Given that 13 percent more of the brominated compound is used in the lead-free, this could reverse the results, which would likely remain indistinguishable, given energy uncertainty, as mentioned above in Section 3.2.4.5 and included in the uncertainty analysis (Section 3.4). Neither NM-B alternative used brominated compounds in the construction, and thus the limitations from brominated compounds are not expected to affect the NM-B results.

Based on the LCIA methodology and the LCI data, the Stratospheric Ozone Depletion impact category is given an overall relative data quality rating of “low” for all cable types.

## 3.2.6 Photochemical Smog Impacts

### 3.2.6.1 Characterization

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production both with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs *et al*., 1992). The list of chemicals with POCPs used in this methodology is presented in Appendix D. As shown in Table 3-2, photochemical smog impacts are based on partial equivalency, because some chemicals cannot be converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP; however, VOCs are assumed to be the limiting factor, and if VOCs are present, there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \times Amt_{POC})_i$$

where:

| | |
|---|---|
| $IS_{POCP}$ | equals the photochemical smog (POCP) impact score for chemical *i* (kg ethane equivalents) per functional unit; |
| $EF_{POCP}$ | equals the POCP equivalency factor for chemical (ethene equivalents); and |
| $Amt_{POC}$ | equals the amount of photochemical smog-creating oxidant *i* released to the air (kg) per functional unit. |

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the photochemical smog impact category results.

#### 3.2.6.2 CMR results

The lead-free alternative has a 7 percent greater potential to form photochemical smog than the baseline cable, which is shown in Figure 3-47. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-48). To protect confidentiality, Figure 3-48 combines the photochemical smog formation potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is unspecified volatile organic compounds (Figure 3-49). Figure 3-48 includes the processes that contribute >5 percent of the total impacts, which represent 89 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-49 includes individual flows that contribute >1 percent to the total impacts, and represents 99 and >99 percent of the total photochemical smog formation potential impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are a function of a number of different parameters, one of which is highly uncertain: energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the photochemical smog formation potential impact category (see Section 3.4). However, the results do indicate that production of jacketing resin is the major contributor to smog formation potential.

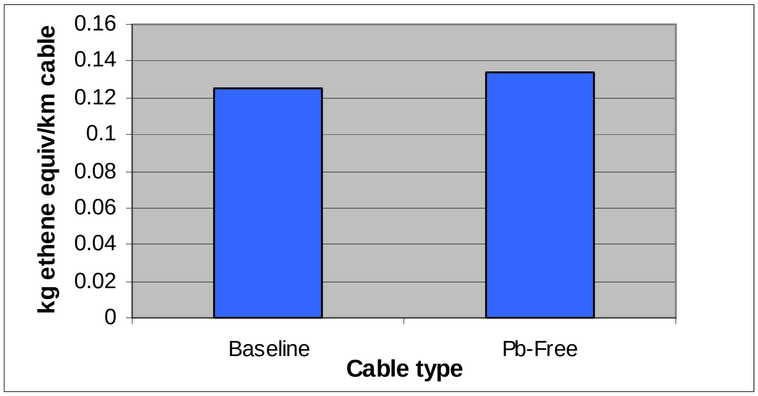

Figure 3-47. Total Photochemical Smog Impacts – CMR Full life cycle

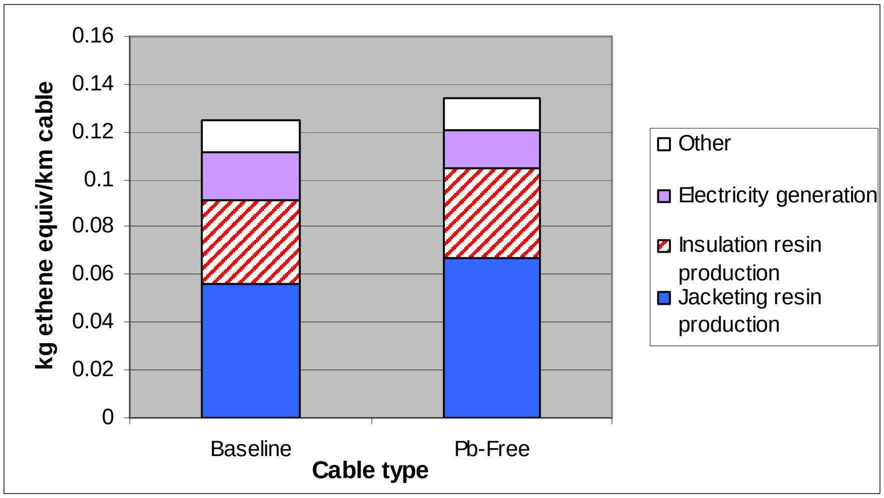

Figure 3-48. Top Contributing Processes to Photochemical Smog Impacts – CMR Full life cycle

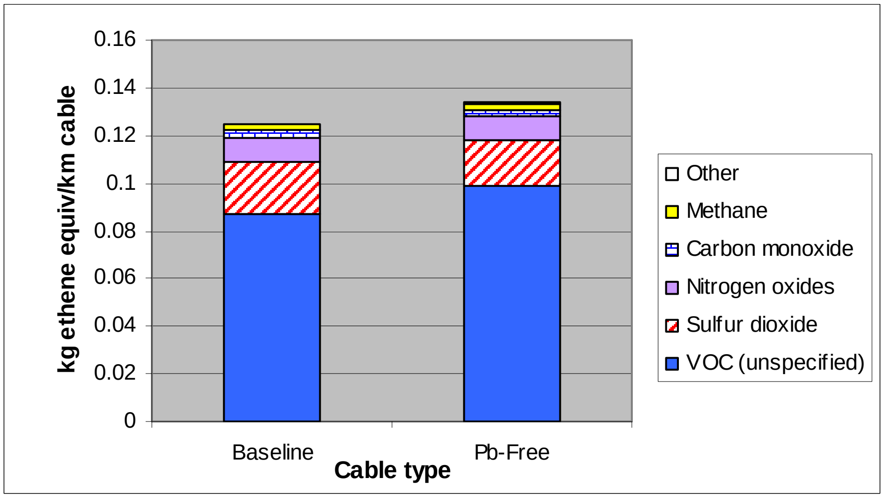

Figure 3-49. Top Contributing Flows to Photochemical Smog Impacts – CMR Full life cycle

#### 3.2.6.3 CMP results

The baseline cable has a 2 percent greater potential to form photochemical smog than the lead-free alternative, which is shown in Figure 3-50. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-51). To protect confidentiality, Figure 3-51 combines the photochemical smog formation potential impacts from all upstream electricity generation and natural gas production. The top contributing flow for both the baseline and lead-free alternatives is unspecified volatile organic compounds (Figure 3-52). Figure 3-51 includes the processes that contribute >5 percent of the total impacts, which represent 94 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-52 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total photochemical smog formation potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use offset slightly by the lead-free alternative's use of more PVC resin. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the photochemical smog formation potential impact category (see Section 3.4). However, the results do indicate that production of jacketing resin is the major contributors to photochemical smog formation potential.

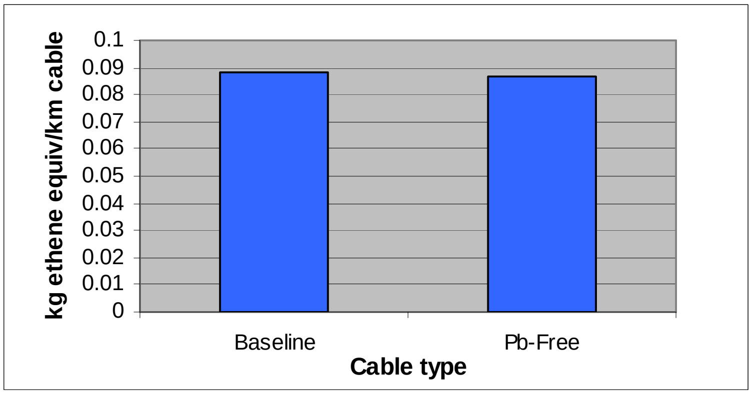

Figure 3-50. Total Photochemical Smog Impacts – CMP Full life cycle

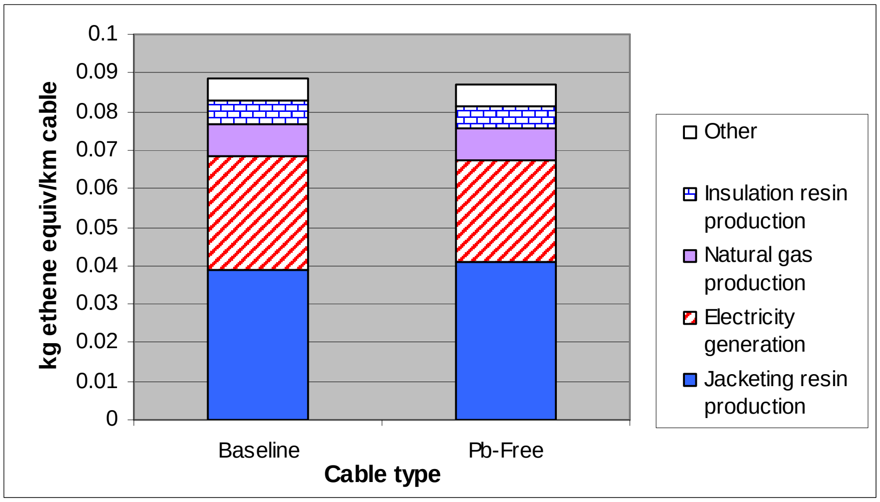

Figure 3-51. Top Contributing Processes to Photochemical Smog Impacts – CMP Full Life Cycle

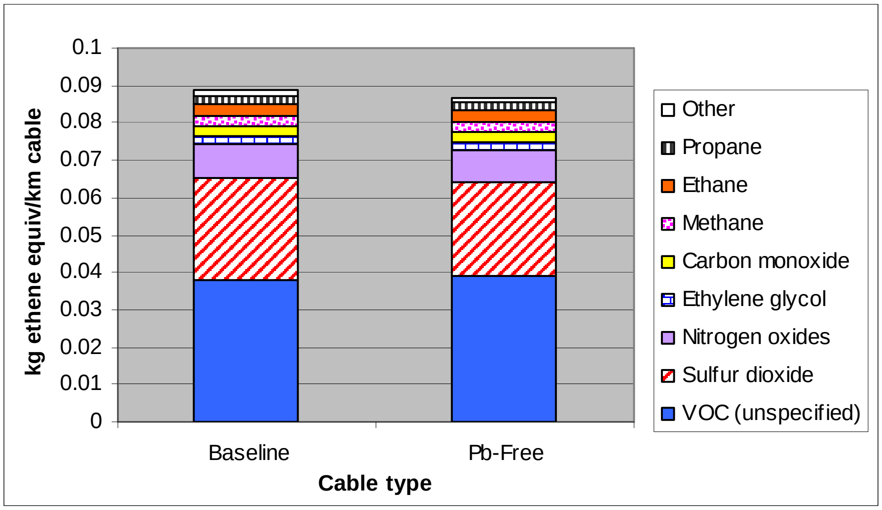

Figure 3-52. Top Contributing Flows to Photochemical Smog Impacts – CMP Full Life Cycle

#### 3.2.6.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 0.2 percent higher photochemical oxidant potential impacts than the lead-free alternative, which is shown in Figure 3-53. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-54). Unspecified volatile organic compounds (VOCs) are the greatest individual flow contributing to the impacts for both alternatives (Figure 3-55). Figure 3-54 includes the processes that contribute >5 percent of the total impacts, which represent 97 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-55 includes individual flows that contribute >1 percent to the total impacts, which represents >99 percent of the total photochemical oxidant potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC production contributes greatest to photochemical smog impacts for both alternatives could provide the opportunity to reduce these impacts if PVC jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce VOC emissions).

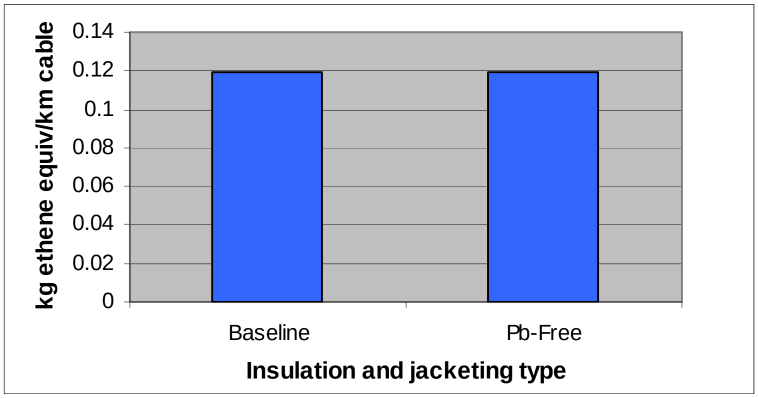

Figure 3-53. Total Photochemical Smog Impacts – NM-B Partial life cycle

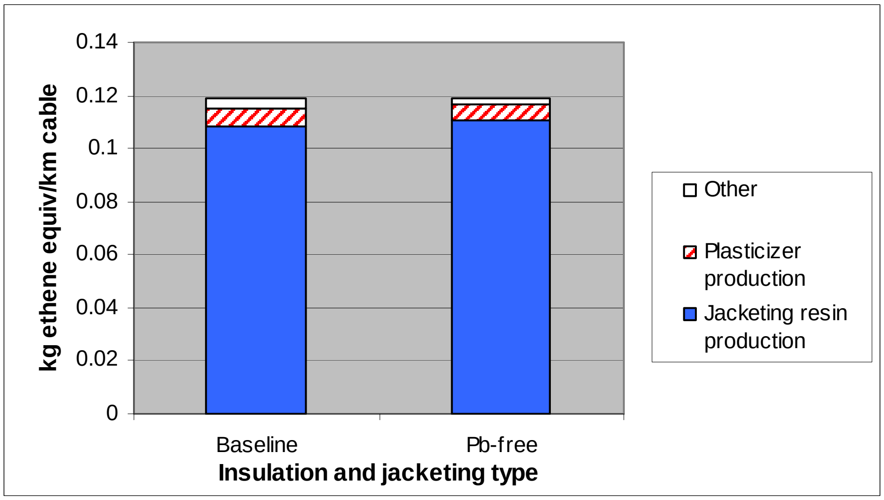

Figure 3-54. Top Contributing Processes to Photochemical Smog Impacts – NM-B Partial life cycle

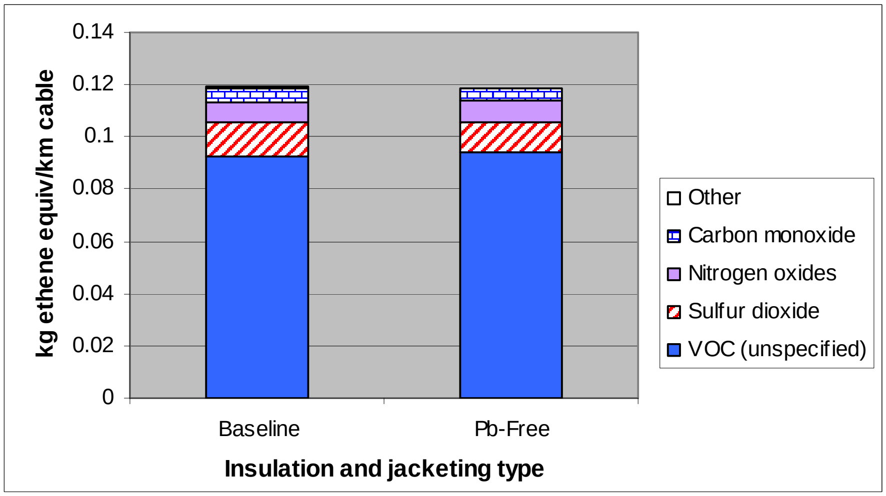

Figure 3-55. Top Contributing Flows to Photochemical Smog Impacts – NM-B Partial life cycle

### 3.2.6.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology uses the mass of a chemical released to air per functional unit and the chemical-specific partial equivalency factor. The equivalency factor is a measure of a chemical's POCP compared to the reference chemical ethene. As noted in Section 3.1.2, photochemical smog impacts are based on partial equivalency, because some chemicals cannot be converted into POCP equivalency factors (e.g., nitrogen oxide). The inability to develop equivalency factors for some chemicals is a limitation of the photochemical smog impact assessment methodology. However, the POCP equivalency factors are commonly used in LCA and are considered reliable data.

For all three cable types, results were driven by resin manufacturing (e.g., PVC, HDPE) and electricity generation (as used to fuel the manufacturing and/or upstream processes). As mentioned in the NRR and Energy impact sections (3.2.1.5 and 3.2.2.5, respectively), limitations to the PVC, HDPE, and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Photochemical Smog impact category is given an overall relative data quality rating of "medium" for all cable types.

## 3.2.7 Acidification Impacts

### 3.2.7.1 Characterization

Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the inventory amount of a chemical released to air that would cause acidification, multiplied by the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released, compared to sulfur dioxide ($SO_2$) (Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997). Appendix D lists the AP values that were used as the basis of calculating acidification impacts. The impact score is calculated by:

$$IS_{APi} = (EF_{AP} \text{ x } Amt_{AC})_i$$

where:

| | |
|---|---|
| $IS_{AP}$ | equals the impact score for acidification for chemical *i* (kg $SO_2$ equivalents) per functional unit; |
| $EF_{AP}$ | equals the AP equivalency factor for chemical *i* ($SO_2$ equivalents); and |
| $Amt_{AC}$ | equals the amount of acidification chemical *i* released to the air (kg) per functional unit. |

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the acidification impact category results.

### 3.2.7.2 CMR results

The baseline cable has an 8 percent greater acidification potential impact than the lead-free alternative, which is shown in Figure 3-56. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-57). To protect confidentiality, Figure 3-57 combines the acidification potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is sulfur dioxide (Figure 3-58). Figure 3-57 includes the processes that contribute >5 percent of the total impacts, which represent 88 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-58 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total acidification potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use, offset somewhat by greater impacts from PVC jacketing resin production for the lead-free cables. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the acidification potential impact category (see Section 3.4). However, results do indicate that generation of electricity for the cable extrusion process is the major contributor to air acidification.

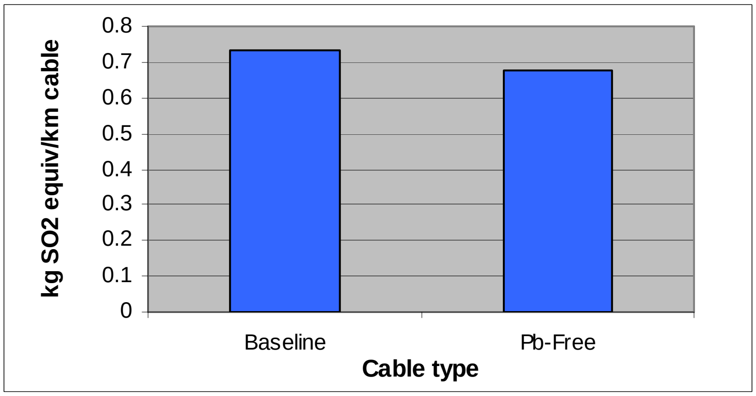

Figure 3-56. Total Air Acidification Impacts – CMR Full life cycle

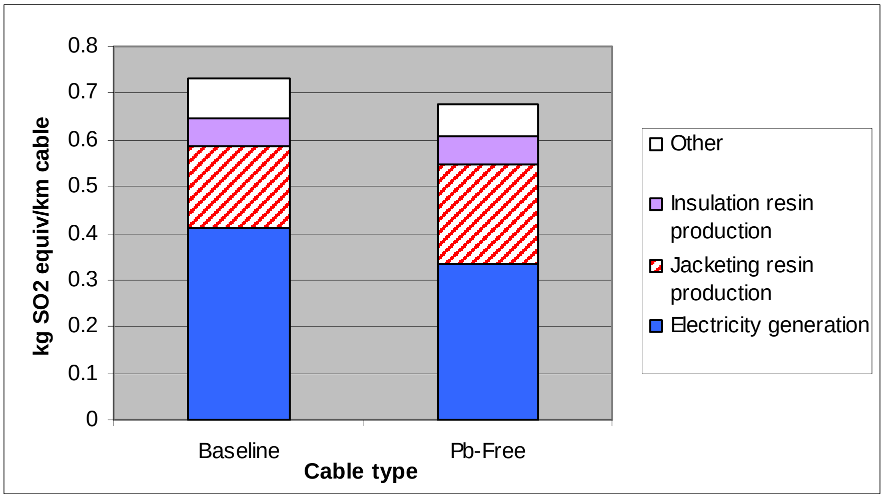

Figure 3-57. Top Contributing Processes to Acidification Impacts – CMR Full life cycle

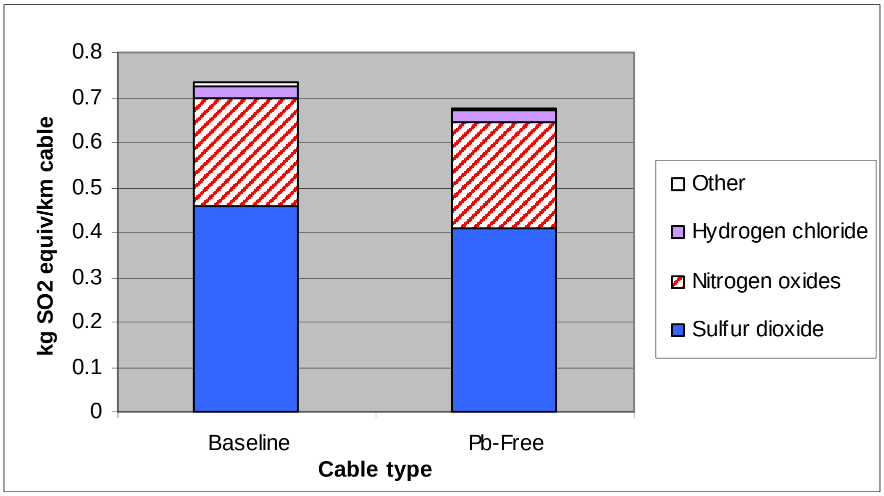

Figure 3-58. Top Contributing Flows to Acidification Impacts – CMR Full life cycle

### 3.2.7.3 CMP results

The baseline cable has a 7 percent greater potential to cause air acidification than the lead-free alternative, which is shown in Figure 3-59. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-60). To protect confidentiality, Figure 3-60 combines the acidification potential impacts from all upstream electricity generation and natural gas production. The top contributing flow for both the baseline and lead-free alternatives is sulfur dioxide (Figure 3-61). Figure 3-60 includes the processes that contribute >5 percent of the total impacts, which represents 91 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-61 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total acidification potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the acidification potential impact category (see Section 3.4). However, energy efficiency in the extrusion process could reduce impacts for both alternatives, and slightly more so for the baseline alternative.

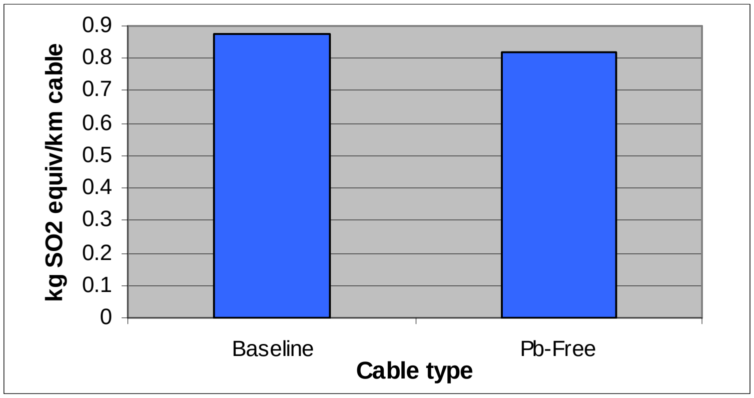

Figure 3-59. Total Air Acidification Impacts – CMP Full life cycle

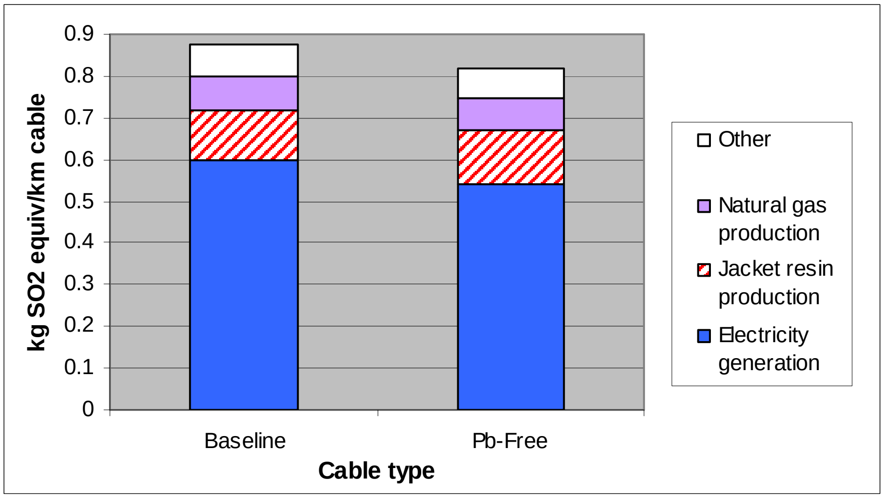

Figure 3-60. Top Contributing Processes to Air Acidification Impacts – CMP Full Life Cycle

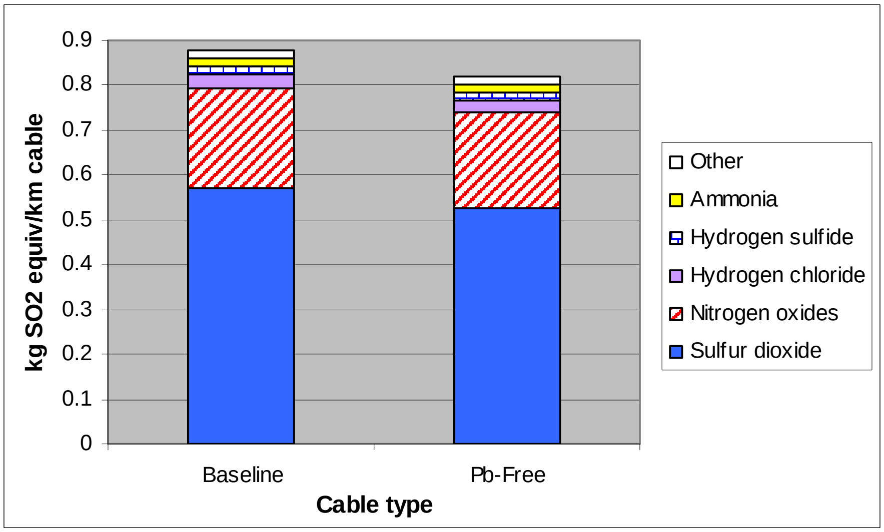

Figure 3-61. Top Contributing Flows to Air Acidification Impacts – CMP Full Life Cycle

### 3.2.7.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 7 percent higher acidification potential impacts than the lead-free alternative, which is shown in Figure 3-3-62. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-63). Sulfur dioxide is the greatest individual flow contributing to the impacts for both alternatives, followed closely by nitrogen oxides ($NO_x$) (Figure 3-64). Figure 3-63 includes the processes that contribute >5 percent of the total impacts, which represent 96 and >99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-64 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total acidification potential impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to photochemical smog impacts for both alternatives could provide the opportunity to reduce these impacts if jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., reduce sulfur dioxide and nitrogen oxide emissions).

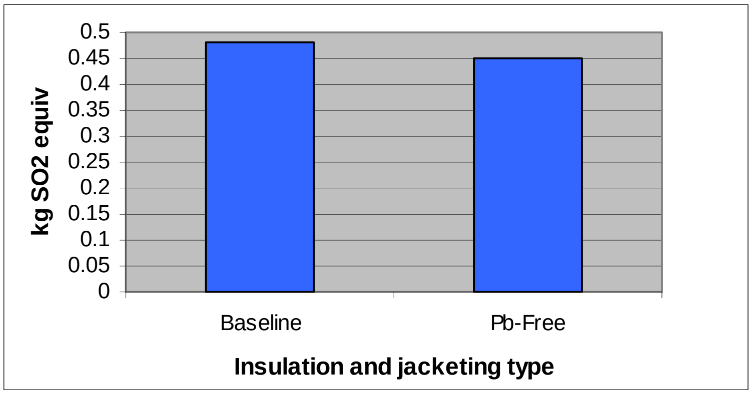

Figure 3-62. Total Air Acidification Impacts – NM-B Partial life cycle

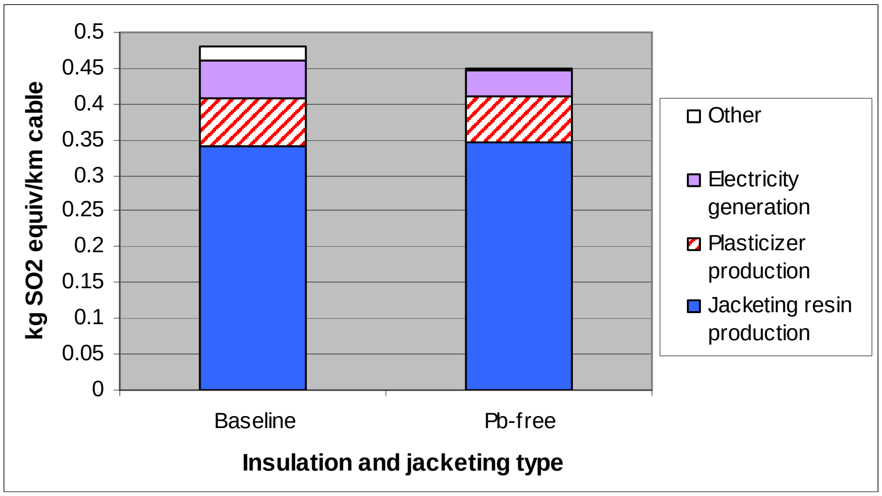

Figure 3-63. Top Contributing Processes to Air Acidification Impacts – NM-B Partial life cycle

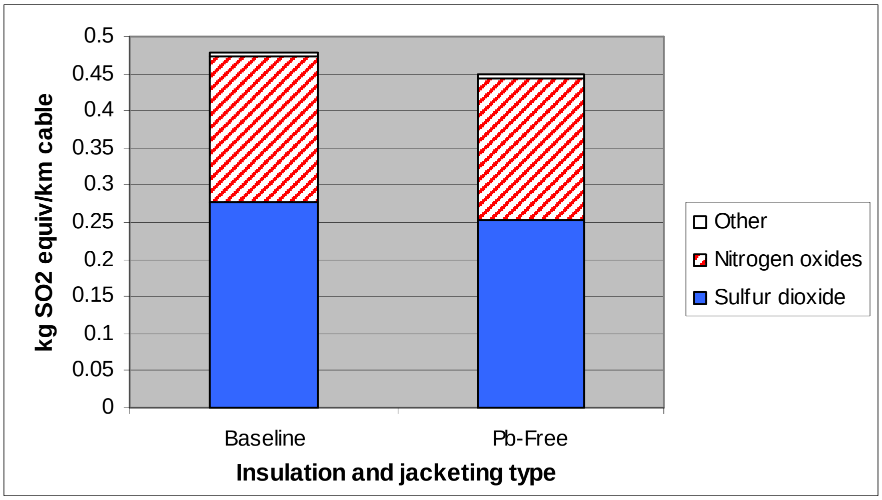

Figure 3-64. Top Contributing Flows to Air Acidification Impacts – NM-B Partial life cycle

### 3.2.7.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology characterizes acidification impact as a function of the mass of an acid-forming chemical emitted to air and the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per unit mass of the pollutant being released, compared to sulfur dioxide. This is a full equivalency approach to impact characterization, where all substances are addressed in a unified, technical model that lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.2.6). The AP equivalency factors are commonly used in LCA and are considered reliable data.

For the CMR and CMP cable types, results were driven by electricity generation (as used to fuel the manufacturing and/or upstream processes), with PVC production as the second greatest contributor, contributing to a greater extent to the CMR alternatives. The NM-B results are highly impacted by the PVC production process. As mentioned in the NRR, Energy, and Smog impact sections (3.2.1.5, 3.2.2.5, and 3.2.6.5, respectively), limitations to the PVC and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Acidification impact category is given an overall relative data quality rating of “medium” for all cable types.

## 3.2.8 Air Particulate Impacts

### 3.2.8.1 Characterization

Air particulate impacts refer to the release and build up of particulate matter primarily from combustion processes. Impact scores are based on releases to the air of particulate matter with average aerodynamic diameter less than 10 micrometers ($PM_{10}$), the size of particulate matter that is most damaging to the respiratory system. Impact characterization is simply based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

| | |
|---|---|
| $IS_{PM}$ | equals the impact score for particulate (kg $PM_{10}$) per functional unit; and |
| $Amt_{PM}$ | equals the inventory amount of particulate release ($PM_{10}$) to the air (kg) per functional unit. |

In this equation, $PM_{10}$ is used to estimate impacts; however, if only TSP data are available, these data are used. Using TSP data is an overestimation of $PM_{10}$, which only refers to the fraction of particulates in the size range below 10 micrometers. A common conversion factor (TSP to $PM_{10}$) is not available because the fraction of $PM_{10}$ varies depending on the type of particulates. The particulate matter impact category not only serves to represent potential health effects associated with particulates (e.g., respiratory impacts), but also winter smog, which consists partially of suspended particulate matter or fine dust and soot particles. Winter smog is distinguished from summer smog (e.g., photochemical smog, which is the build up of tropospheric ozone concentrations due to VOCs and nitrogen oxides in the presence of sunlight). Winter smog is a problem that occurs mainly in Eastern Europe and has been the cause of health related deaths in the past (Goedkoop, 1995).

Accounting for the inventory and the characterization method, we have assigned a “medium” data quality measure for the acidification impact category results.

#### 3.2.8.2 CMR results

The lead-free alternative has a 4 percent greater impact on particulate matter production than the baseline cable, which is shown in Figure 3-65. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-66). To protect confidentiality, Figure 3-66 combines the particulate matter production from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is dust (Figure 3-67). Figure 3-66 includes the processes that contribute >5 percent of the total impacts, which represent 94 and 95 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-67 includes individual flows that contribute >1 percent to the total impacts, and represents all of the total particulate matter production impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are a function of a number of different parameters, one of which is highly uncertain: energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the particulate matter production impact category (see Section 3.4). However, energy efficiency in the production of jacketing resin could reduce impacts for both alternatives, but more so for the lead-free alternative. In addition, any reduction in PVC use, which would be replaced with another material to reduce these impacts, would need to be evaluated for tradeoff effects in other impact categories.

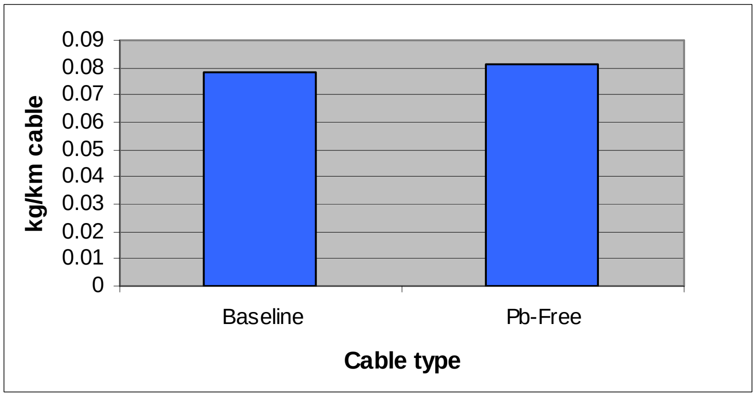

Figure 3-65. Total Air Particulate Impacts – CMR Full life cycle

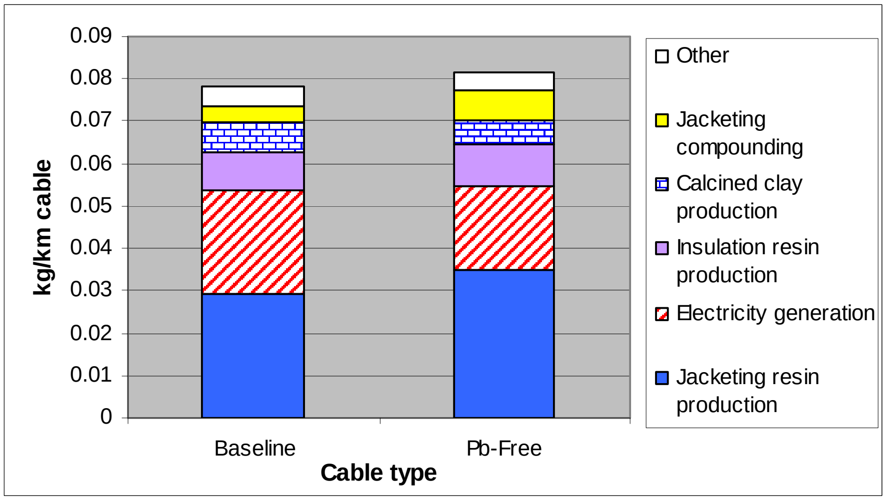

Figure 3-66. Top Contributing Processes to Air Particulate Impacts – CMR Full life cycle

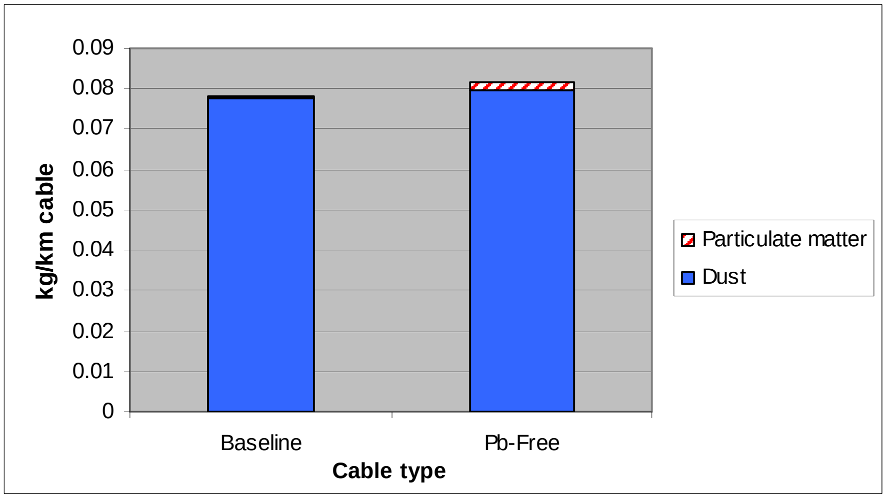

Figure 3-67. Top Contributing Flows to Air Particulate Impacts – CMR Full life cycle

### 3.2.8.3 CMP results

The baseline cable has a 3 percent greater impact on particulate matter production than the lead-free alternative, which is shown in Figure 3-68. The top contributing process for the baseline cable and lead-free alternative is the production of the PVC jacketing resin (Figure 3-69). To protect confidentiality, Figure 3-69 combines the particulate matter production impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is dust (Figure 3-70). Figure 3-69 includes the processes that contribute >5 percent of the total impacts, which represents 96 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-70 includes individual flows that contribute >1 percent to the total impacts, and represents all of the total particulate matter production impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the particulate matter production impact category (see Section 3.4). However, energy efficiency in the production of jacketing resin could reduce impacts for both alternatives.

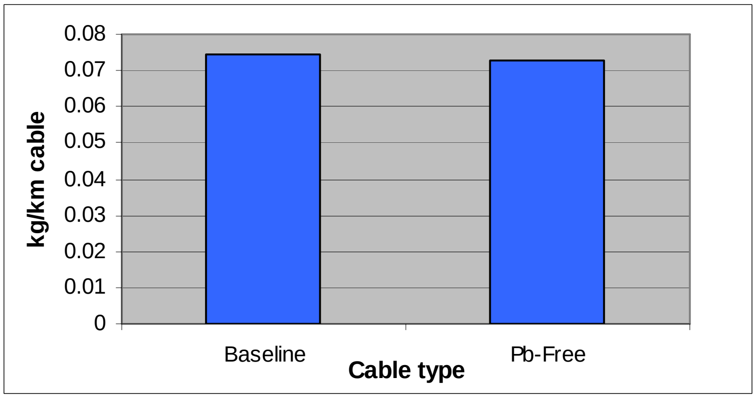

Figure 3-68. Total Air Particulate Impacts – CMP Full life cycle

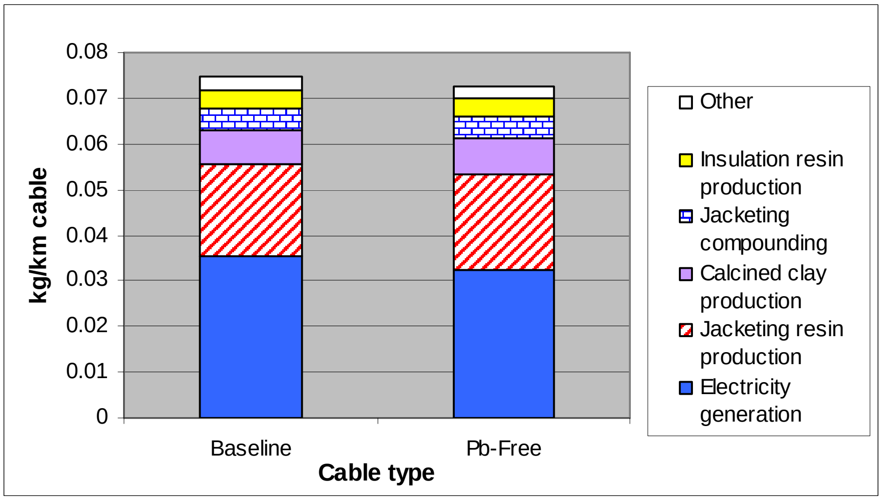

Figure 3-69. Top Contributing Processes to Air Particulate Impacts – CMP Full life cycle

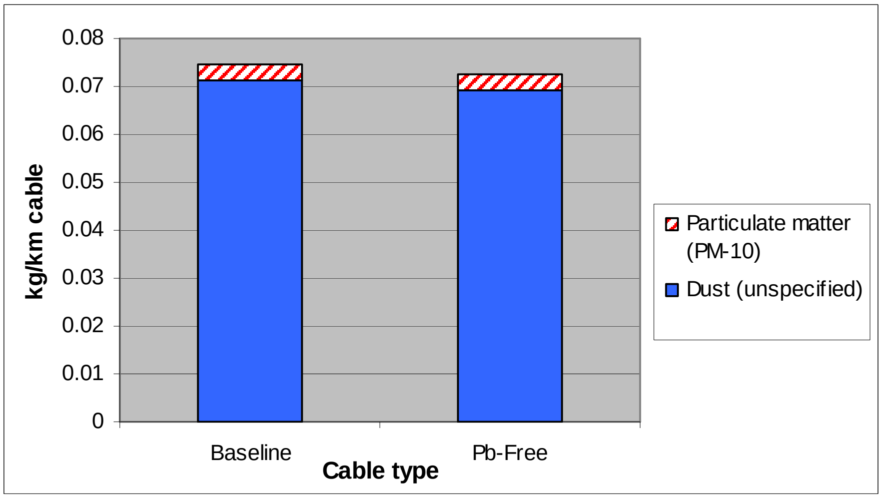

Figure 3-70. Top Contributing Flows to Air Particulate Impacts – CMP Full life cycle

#### 3.2.8.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 14 percent more particulate matter than the lead-free alternative, which is shown in Figure 3-71. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-72). Dust is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-73). Figure 3-72 includes the processes that contribute >5 percent of the total impacts, which represent 94 and 96 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-73 includes individual flows that contribute >1 percent to the total impacts, which represents all particulate matter generation impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to the particulate matter impacts for both alternatives could provide the opportunity to reduce these impacts if jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts would be to focus on reducing dust and particulate matter emissions.

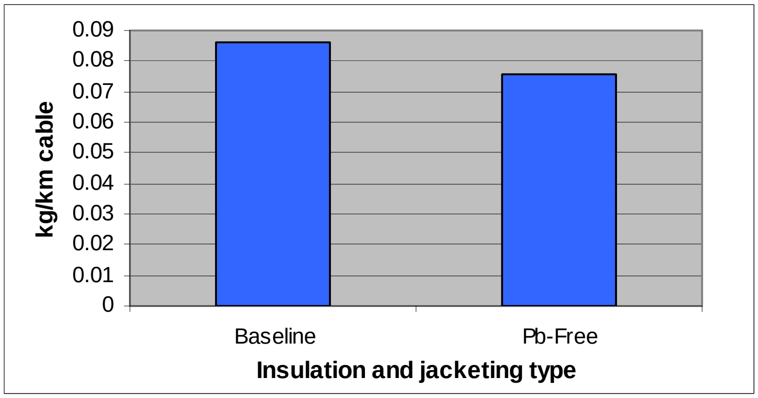

Figure 3-71. Total Air Particulate Impacts – NM-B Partial life cycle

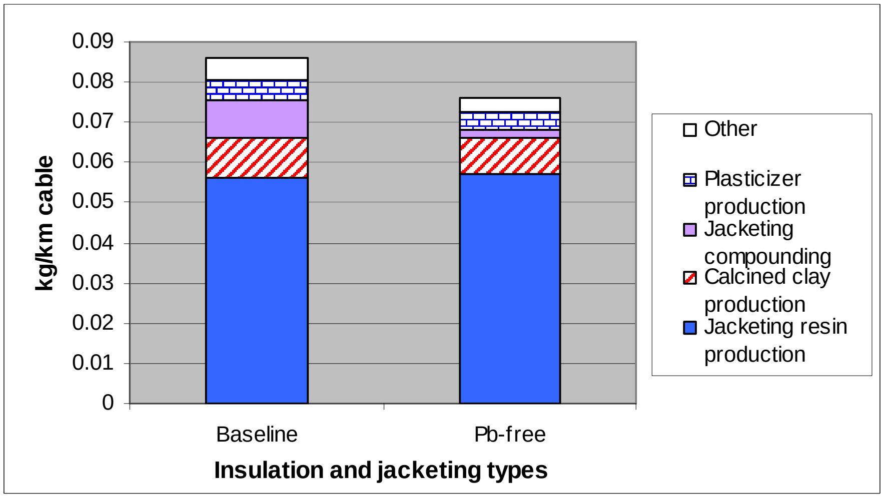

Figure 3-72. Top Contributing Processes to Air Particulate Impacts – NM-B Partial life cycle

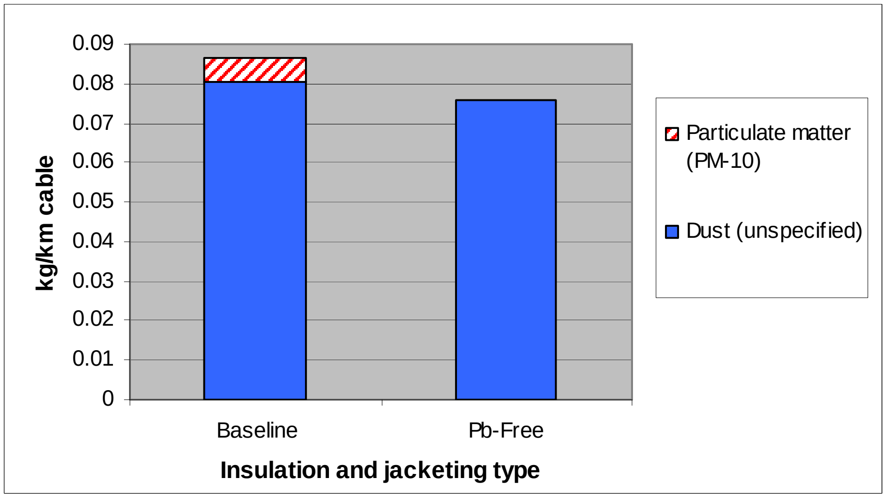

Figure 3-73. Top Contributing Flows to Air Particulate Impacts – NM-B Partial life cycle

#### 3.2.8.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology is based on the mass loading of particulate matter, which is a direct measure of the inventory; thus, few limitations to the LCIA methodology are anticipated. However, the impact characterization is intended to be based on $PM_{10}$ that is in the respirable range and considered more damaging to the respiratory system than larger particles, when considering the effects of particulate matter on human health. Because most of the inventory for this category is catalogued as unspecified “dust,” it is not known if these are $PM_{10}$ particles. If the dust includes a broader class of particulate emissions, it is likely that the results are somewhat overstated if they are to represent $PM_{10}$ only. However, similar amounts of dust impacts were found for both the baseline and lead-free alternatives, resulting in an equivalent overestimate across alternatives; thus, no great effect on the comparative results is expected.

For all three cable types, results were driven primarily by PVC manufacturing and/or electricity generation (as used to fuel the manufacturing and upstream processes). As mentioned above in several impact category limitation discussions (e.g., Photochemical Smog), limitations to the PVC and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Air Particulate impact category is given an overall relative data quality rating of “medium” for all cable types.

### 3.2.9 Water Quality (Eutrophication) Impacts

#### 3.2.9.1 Characterization

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae (($C_{106}H_{263}O_{110}N_{16}P$) compared to the reference compound phosphate ($PO_4^{3-}$) (Heijungs *et al.*, 1992; Lindfors *et al.*, 1995). If the wastewater stream is first sent to a publicly-owned treatment works (POTW), treatment is considered as a separate process, and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) (Appendix D) and the inventory amount:

$$(IS_{EUTR})_i = (EF_{EP} \ x \ Amt_{EC})_i$$

where:

| | |
|---|---|
| $IS_{EUTR}$ | equals the impact score for regional water quality impacts from chemical *i* (kg phosphate equivalents) per functional unit; |
| $EF_{EP}$ | equals the EP equivalency factor for chemical *i* (phosphate equivalents); and |
| $Amt_{EC}$ | equals the inventory mass (kg) of chemical *i* per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable. |

Accounting for the inventory and the characterization method, we have assigned a “medium” data quality measure for the water eutrophication impact category results.

### 3.2.9.2 CMR results

The baseline cable has a 19 percent greater impact in terms of eutrophication potential than the lead-free alternative, which is shown in Figure 3-74. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-75). To protect confidentiality, Figure 3-75 combines the eutrophication potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is chemical oxygen demand (Figure 3-76). Figure 3-75 includes the processes that contribute >5 percent of the total impacts, which represents 99 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-75 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total eutrophication potential impact for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the eutrophication potential impact category (see Section 3.4). However, energy efficiency in the extrusion process could reduce impacts for both alternatives, and more so for the baseline.

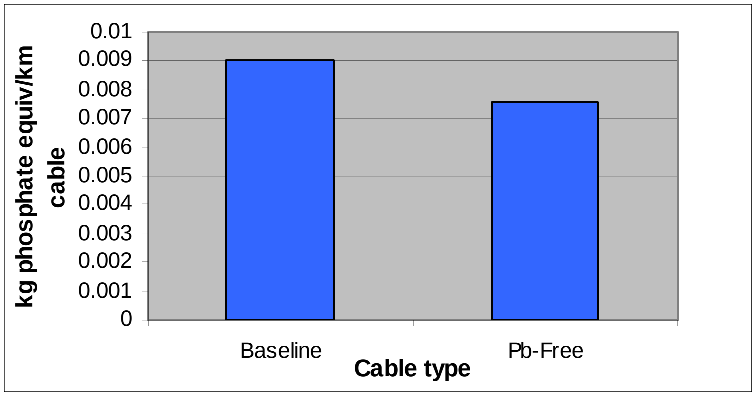

Figure 3-74. Total Water Eutrophication Impacts – CMR Full life cycle

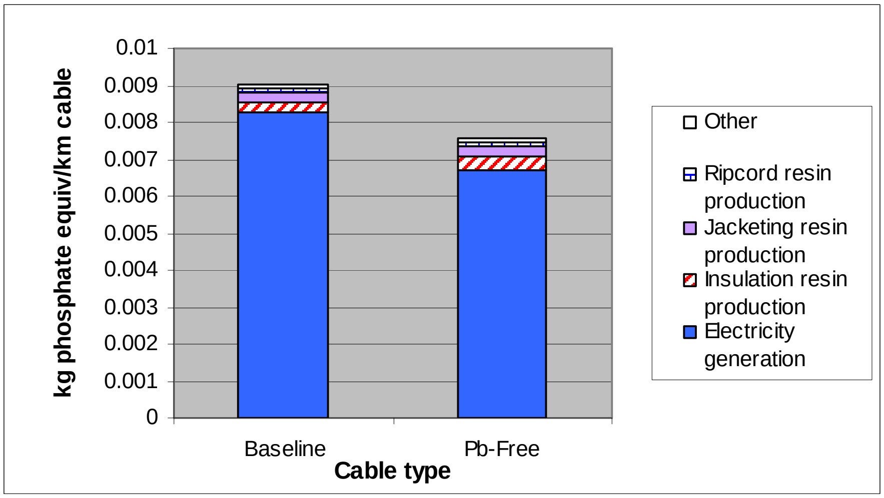

Figure 3-75. Top Contributing Processes to Eutrophication Impacts – CMR Full life cycle

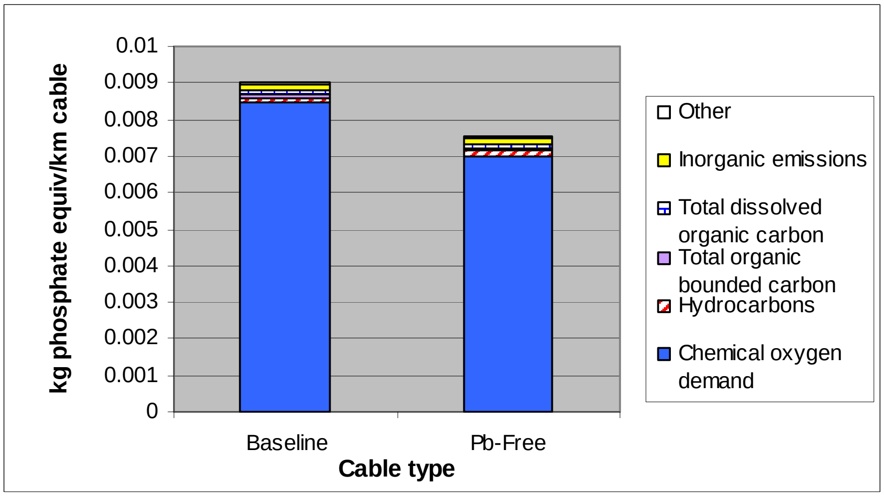

Figure 3-76. Top Contributing Flows to Eutrophication Impacts – CMR Full life cycle

### 3.2.9.3 CMP results

The baseline cable has 10 percent greater eutrophication potential impacts than the lead-free alternative, which is shown in Figure 3-77. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-78). To protect confidentiality, Figure 3-78 combines the eutrophication potential impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is chemical oxygen demand (Figure 3-79). Figure 3-78 includes the processes that contribute >5 percent of the total impacts, which represents 98 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-79 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total eutrophication potential impact for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the eutrophication potential impact category (see Section 3.4). However, energy efficiency during the cable extrusion process could offer the greatest potential to reduce impacts for both alternatives.

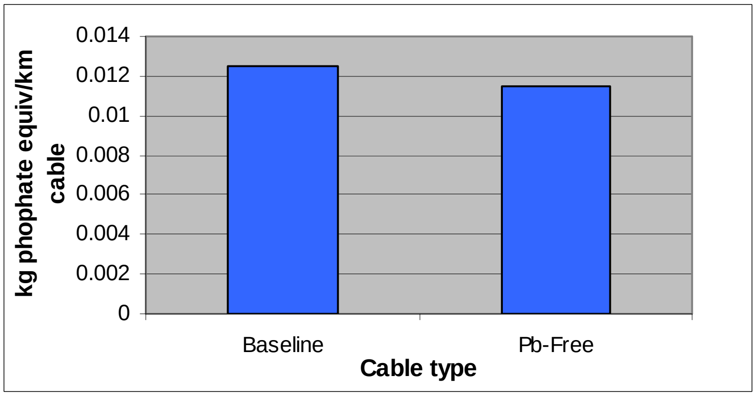

Figure 3-77. Total Water Eutrophication Impacts – CMP Full life cycle

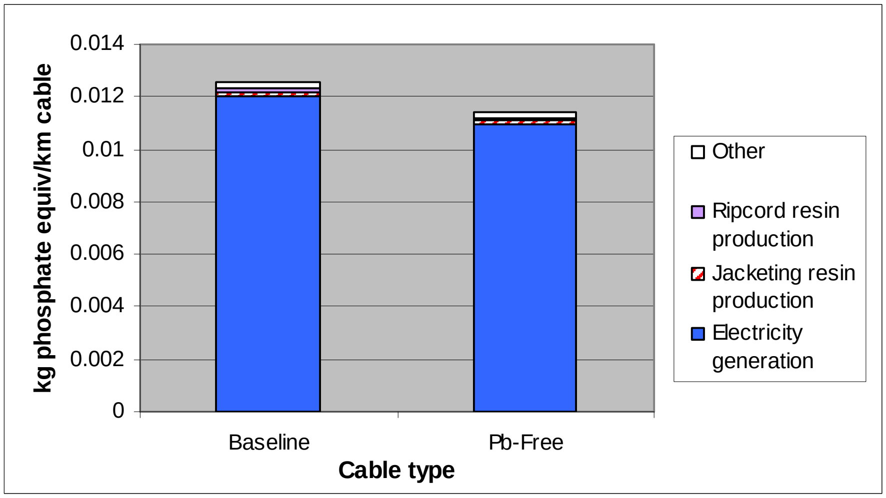

Figure 3-78. Top Contributing Processes to Water Eutrophication Impacts – CMP Full life cycle

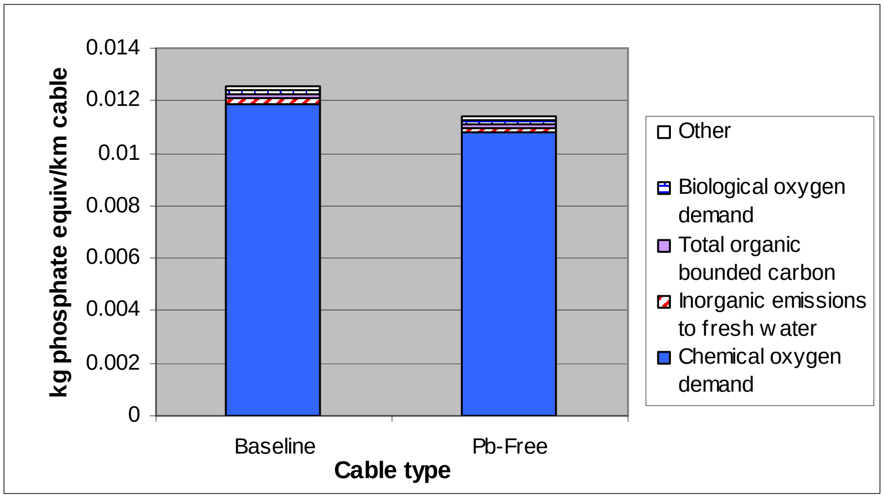

Figure 3-79. Top Contributing Flows to Water Eutrophication Impacts – CMP Full life cycle

### 3.2.9.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 25 percent higher eutrophication potential impacts than the lead-free alternative, which is shown in Figure 3-80. The top contributing process is the generation of electricity for cable compounding for both alternatives (Figure 3-81). Chemical oxygen demand is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-82). Figure 3-81 includes the processes that contribute >5 percent of the total impacts, which represent 95 and 96 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-82 includes individual flows that contribute >1 percent to the total impacts, which represent 96 percent of the total eutrophication potential impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that electricity production from compounding contributes greatest to eutrophication impacts for both alternatives could provide the opportunity to reduce these impacts if electricity use is reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., reduce chemical oxygen demand emissions).

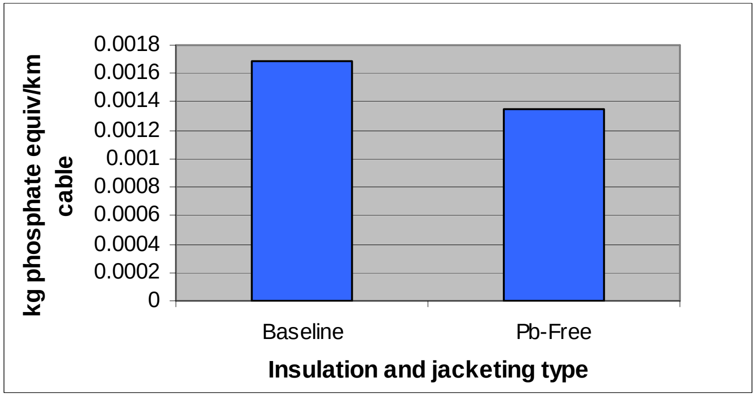

Figure 3-80. Total Water Eutrophication Impacts – NM-B Partial life cycle

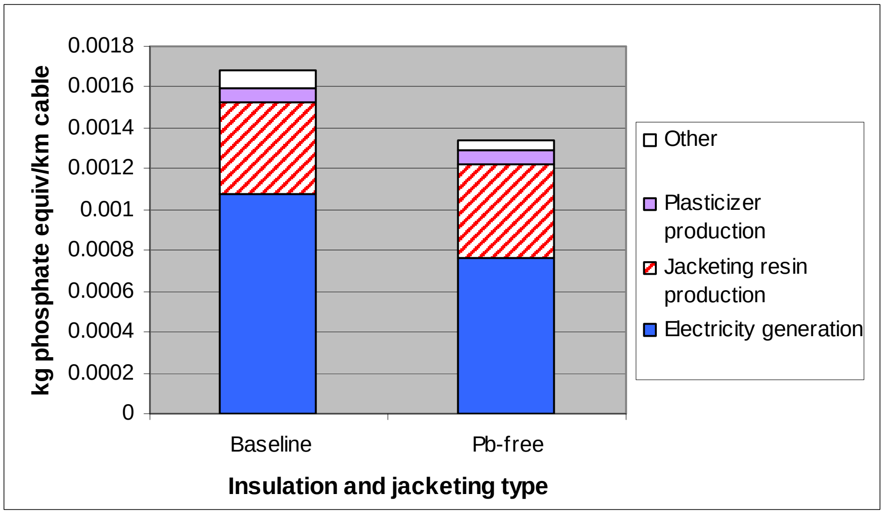

Figure 3-81. Top Contributing Processes to Water Eutrophication Impacts – NM-B Partial life cycle

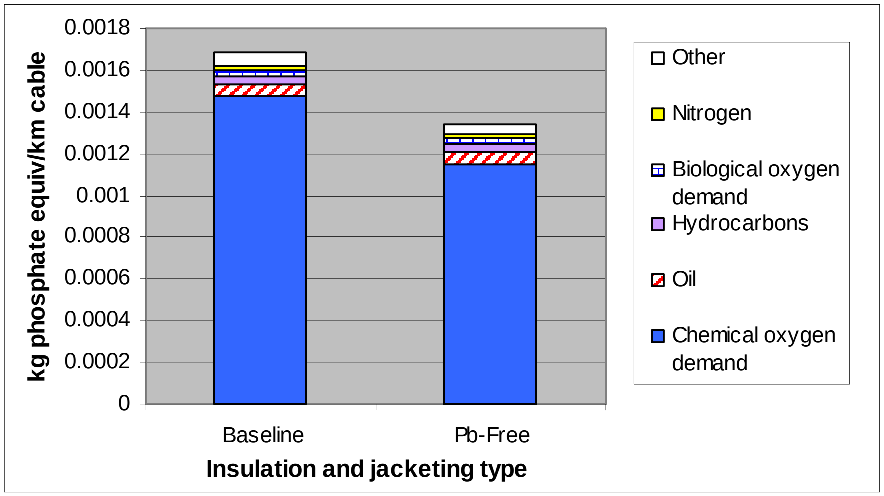

Figure 3-82. Top Contributing Flows to Water Eutrophication Impacts – NM-B Partial life cycle

### 3.2.9.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology calculates impacts from the mass of a chemical released directly to surface water, and the chemical's eutrophication potential (EP) equivalency factor. The EP is a partial equivalency factor derived from the ratio of nitrogen and phosphorus in the average composition of algae compared to the reference compound phosphate. As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. The methodology, however, does take into account nitrogen and phosphorus, which are two major limiting nutrients of importance to eutrophication, and the EPs are commonly used in LCA and are considered reliable data.

For all three cable types, results were driven primarily by electricity generation (as used to fuel the manufacturing processes). For the NM-B cables, the cradle-to-gate analysis also showed PVC to be a large contributor. As mentioned above in several impact category limitation discussions (e.g., Photochemical Smog), limitations to the electricity and PVC production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Water Eutrophication impact category is given an overall relative data quality rating of "medium" for all cable types.

## 3.2.10 Occupational Toxicity Impacts

This section presents the LCIA characterization methodology and the LCIA results for the occupational human health impact category; however, some of the discussions relate to all of the toxicity impact categories in general (e.g., occupational human health, public human health, and ecotoxicity). The occupational human health impact results presented in this section include two impact categories: occupational non-cancer impacts and occupational cancer impacts. The results for these categories are provided within each of the subsections below.

### 3.2.10.1 Characterization

***Potential Human Health Impacts***

Human health impacts are defined in the context of life-cycle assessment as relative measures of potential adverse health effects to humans. Human health impact categories included in the scope of this WCP LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects. Chronic human health effects to both workers and the public are considered. This section presents the potential occupational health impacts, and Section 3.2.11 presents the potential public health impacts.

The chemical characteristic that classifies inventory items to the human health effects (and ecotoxicity) categories is toxicity. Toxic chemicals were identified by searching lists of toxic chemicals (e.g., Toxic Release Inventory [TRI]) and, if needed, toxicity databases (e.g., Hazardous Substances Data Bank [HSDB]), and Registry of Toxic Effects of Chemical Substances (RTECS), and other literature (see Appendix E). The review was done by the DfE Workgroup for the DfE Computer Display Project (Socolof *et al.*, 2001), and remains applicable to the WCP. Materials in the WCP inventory were excluded from the toxic list if they were generally accepted as non-toxic (e.g., nitrogen, calcium). The EPA DfE Workgroup also reviewed the list of chemicals that were included in this project as potentially toxic. The final list of potentially toxic chemicals in the WCP is provided in Appendix E.

Human (and ecological) toxicity impact scores are calculated based on a chemical scoring method modified from the CHEMS-1 that is found in Swanson *et al*. (1997). To calculate impact scores, chemical-specific inventory data are required. Any chemical that is assumed to be potentially toxic is given a toxicity impact score. This involves collecting toxicity data (described in Appendix E). If toxicity data are unavailable for a chemical, a mean default toxicity score is given. This is described in detail below. Ecological toxicity is presented in Section 3.2.12.

Chronic human health effects are potential human health effects occurring from repeated exposure to toxic agents over a relatively long period of time (i.e., years). These effects could include carcinogenicity, reproductive toxicity, developmental effects, neurotoxicity, immunotoxicity, behavioral effects, sensitization, radiation effects, and chronic effects to other specific organs or body systems (e.g., blood, cardiovascular, respiratory, kidney and liver effects). Impact categories for chronic health effects are divided into cancer and non-cancer effects for both worker and public impacts. Occupational impact scores are based on inventory inputs; public impact scores are based on inventory outputs.

This section addresses chronic occupational health effects, which refer to potential health effects to workers, including cancer, from long-term repeated exposure to toxic or carcinogenic agents in an occupational setting. For possible occupational impacts, the identity and amounts of materials/constituents as input to a process are used. The inputs represent potential exposures. It could be assumed that a worker would continue to work at a facility and incur exposures over time. However, the inventory is based on manufacturing one unit length of cable and does not truly represent chronic exposure; therefore, the chronic health effects impact score is more of a ranking of the potential of a chemical to cause chronic effects than a prediction of actual effects. Also, the fact that the inputs of the model are dependent on the boundaries of the various datasets, and that chemical intermediates that might be synthesized at a plant and consumed in subsequent reactions were unavailable from secondary data sets, limit the robustness of this impact category.

Chronic occupational health effects scores are based on the identity of toxic chemicals (or chemical ingredients) found in inputs from all of the life-cycle stages. The distinction between pure chemicals and mixtures is made, if possible, by specifying component ingredients of mixtures in the inventory.

The chronic human health impact scores are calculated using hazard values (HVs) for carcinogenic and non-carcinogenic effects. Calculation of the occupational non-cancer and cancer HVs are described below, and the public non-cancer and cancer HV calculations are described in Section 3.2.11.1. Appendix E provides example calculations of toxicity impacts for two sample chemicals.

***Potential Occupational Toxicity Impact Characterization: Non-Cancer***

The non-carcinogen HV is based on either no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs). The non-carcinogen HV is the greater of the oral and inhalation HV:

$$inhalation: \qquad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

$$oral: \qquad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

where:

| | |
|---|---|
| $HV_{NC\ oral}$ | equals the non-carcinogen oral hazard value for chemical *i* (unitless); |
| $oral\ NOAEL_i$ | equals the oral NOAEL for chemical *i* (mg/kg-day); |
| $oral\ NOAEL_{mean}$ | equals the geometric mean oral NOAEL of all available oral NOAELs (mg/kg-day) (Appendix E); |
| $HV_{NC\ inhalation}$ | equals the non-carcinogen inhalation hazard value for chemical *i* (unitless); |
| $inhal\ NOAEL_i$ | equals the inhalation NOAEL for chemical *i* (mg/m$^3$); and |
| $inhal\ NOAEL_{mean}$ | equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (mg/m$^3$) (Appendix E). |

The oral and inhalation NOAEL mean values are the geometric means of a set of chemical data presented in Appendix E. If LOAEL data are available, instead of NOAEL data, the LOAEL, divided by 10, is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data for one chemical.

The non-carcinogen HVs for a particular chemical are multiplied by the applicable inventory input to calculate the impact score for non-cancer effects:

$$(IS_{CHO\text{-}NC})_i = (HV_{NC} \times Amt_{TCinput})_i$$

where:

| | |
|---|---|
| $IS_{CHO\text{-}NC}$ | equals the impact score for chronic occupational non-cancer health effects for chemical *i* (kg noncancer-toxequivalent) per functional unit; |
| $HV_{NC}$ | equals the hazard value for chronic non-cancer effects for chemical *i*; and |
| $Amt_{TC\ input}$ | equals the amount of toxic inventory input (kg) per functional unit for chemical *i*. |

***Potential Occupational Toxicity Impact Characterization: Cancer***

The cancer HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA or the International Agency for Research on Cancer (IARC). If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen; thus, given that there is a cancer slope factor (SF) for a chemical, the cancer HV for chronic occupational health effects is the greater of the following:

$$oral: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$$inhalation: \quad (HV_{CA_{inhalation}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

where:

| | |
|---|---|
| $HV_{CA\ oral}$ | equals the cancer oral hazard value for chemical *i* (unitless); |
| $oral\ SF_i$ | equals the cancer oral slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$; |
| $oral\ SF_{mean}$ | equals the geometric mean cancer slope factor of all available slope factors $(mg/kg\text{-}day)^{-1}$(Appendix E); |
| $HV_{CA\ inhalation}$ | equals the cancer inhalation hazard value for chemical *i* (unitless); |
| $inhalation\ SF_i$ | equals the cancer inhalation slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$; and |
| $inhalation\ SF_{mean}$ | equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors $(mg/kg\text{-}day)^{-1}$ (Appendix E). |

The oral and inhalation slope factor mean values are the geometric means of a set of chemical data presented in Appendix E.

Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default hazard values as follows: EPA WOE Groups D (not classifiable) and E (non-carcinogen) and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a mean slope factor) (Table 3-72). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

**Table 3-72**

**Hazard values for carcinogenicity WOE if no slope factor is available**

| EPA classification | IARC classification | Description | Hazard value |
|---|---|---|---|
| Group A | Group 1 | Known human carcinogen | 1 |
| Group B1 | Group 2A | Probable human carcinogen (limited human data) | 1 |
| Group B2 | N/A | Probable human carcinogen (from animal data) | 1 |
| Group C | Group 2B | Possible human carcinogen | 1 |
| Group D | Group 3 | Not classifiable | 0 |
| Group E | Group 4 | Non-carcinogenic or probably not carcinogenic | 0 |

N/A=not applicable

The cancer HV for a particular chemical, whether it is from a slope factor or WOE, is then multiplied by the applicable inventory amount to calculate the impact score for cancer effects:

$$(IS_{CHO\text{-}CA})_i = (HV_{CA} \times Amt_{TCinput})_i$$

where:

| | |
|---|---|
| $IS_{CHO\text{-}CA}$ | equals the impact score for chronic occupational cancer health effects for chemical *i* ( kg cancertox-equivalents) per functional unit; |
| $HV_{CA}$ | equals the hazard value for carcinogenicity for chemical *i*; and |
| $Amt_{TC\ input}$ | equals the amount of toxic inventory input (kg) per functional unit for chemical *i*. |

Accounting for the inventory and characterization methodology and data, the occupational chronic non-cancer toxicity impact category is given a “medium” data quality measure. Occupational cancer toxicity is 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.

### 3.2.10.2 CMR results

***Potential Occupational Non-cancer Toxicity Impacts (CMR)***

The lead-free alternative has an 8 percent greater impact on potential occupational non-cancer toxicity than the baseline cable, which is shown in Figure 3-83. The top contributing process for the baseline cable and lead-free alternative is the cable jacketing compounding process (Figure 3-84). To protect confidentiality, Figure 3-84 combines the occupational non-cancer toxicity impact from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is a non-halogen flame retardant (Figure 3-85). Figure 3-84 includes the processes that contribute >3 percent of the total impacts, which represent 96 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-85 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total potential occupational non-cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in figure 3-85, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in the amount of the non-halogen flame retardant used in the cable jacketing. As the uncertainty analysis did not take into consideration differences in product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the differences between the cables remained for the potential occupational non-cancer toxicity impact category (see Section 3.4).

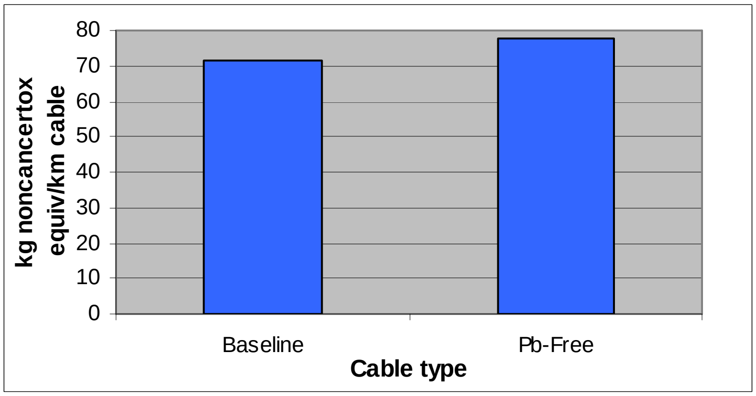

Figure 3-83. Total Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

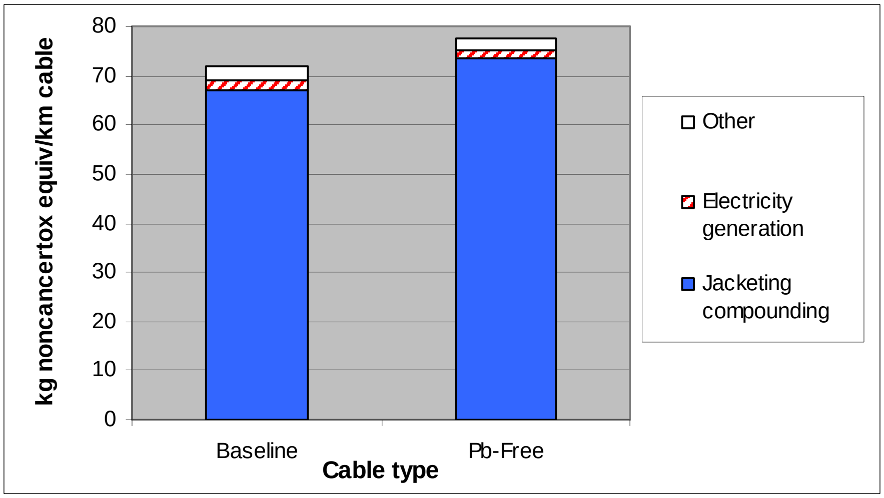

Figure 3-84. Top Contributing Processes to Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

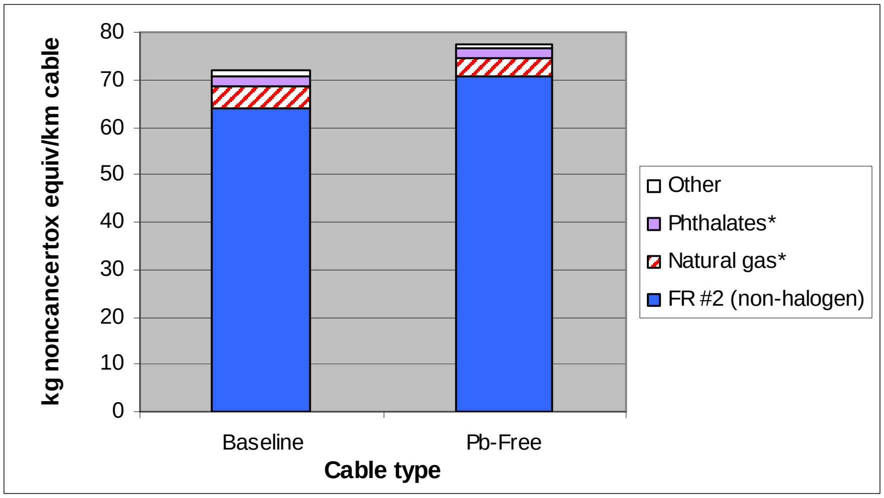

Figure 3-85. Top Contributing Flows to Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

***Potential Occupational Cancer Toxicity Impacts (CMR)***

The lead-free alternative has a 5 percent greater impact on potential occupational cancer toxicity than the baseline cable, which is shown in Figure 3-86. The top contributing process for the baseline cable and lead-free alternative is the cable jacketing compounding process (Figure 3-87). The top contributing flow for both the baseline and lead-free alternatives is phthalates (Figure 3-88). Figure 3-87 includes the processes that contribute >3 percent of the total impacts, which represent 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-88 includes individual flows that contribute >3 percent to the total impacts, and represents 97 and 94 percent of the total potential occupational cancer toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-88, some material flow has been given a default hazard value due to lack of toxicological data

The overall differences between the cables are primarily a function of the differences in jacketing compounding and non-lead stabilizer production. An uncertainty analysis was conducted to address the uncertainty in extrusion and EOL data (Section 3.4). As that analysis did not take into consideration differences in jacket compounding or product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained for the potential occupational cancer toxicity impact category (see Section 3.4). Modifications to the jacket compounding process could have the largest potential to reduce impacts for both alternatives.

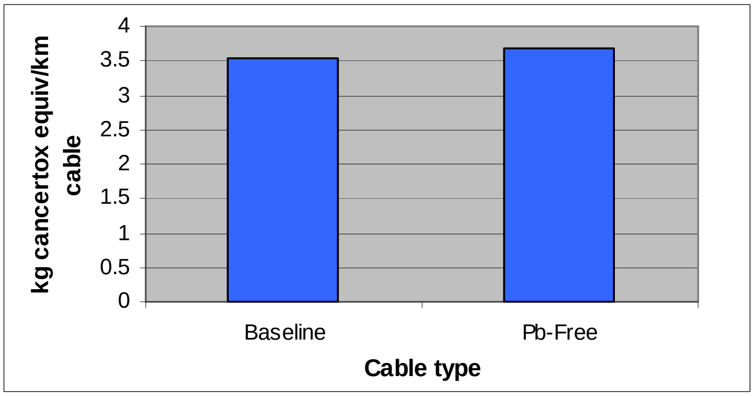

Figure 3-86. Total Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

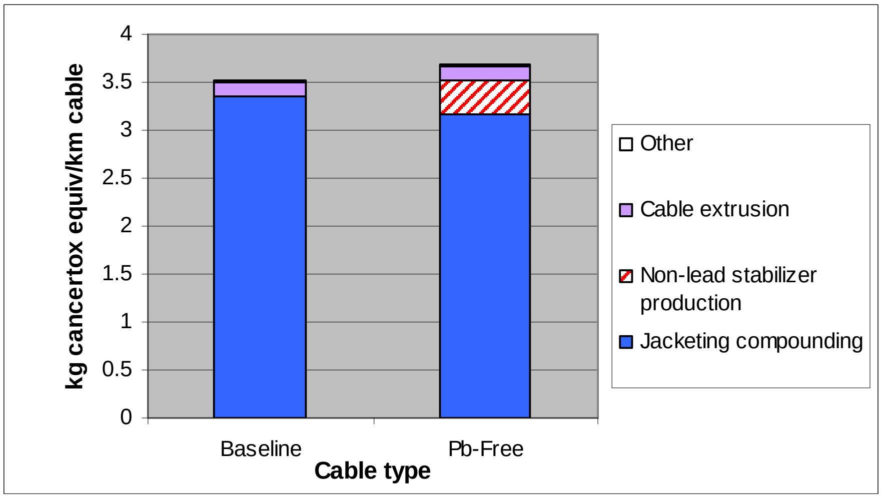

Figure 3-87. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

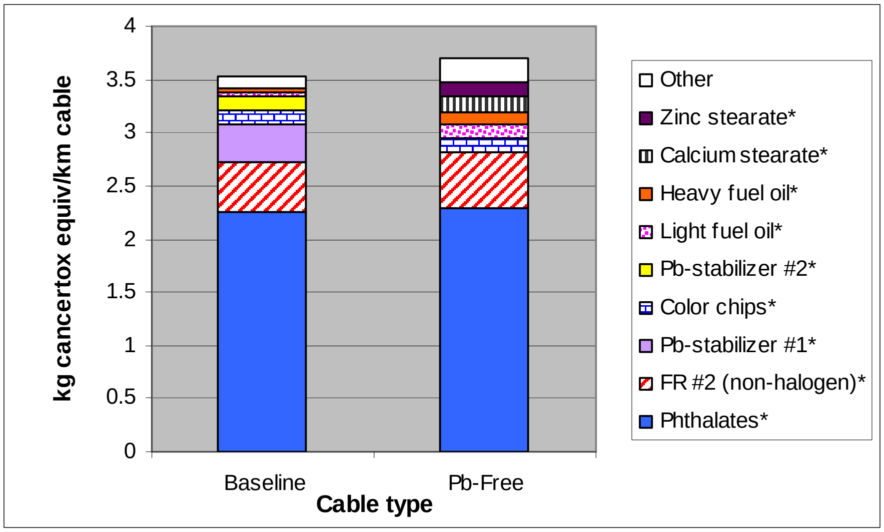

Figure 3-88. Top Contributing Flows to Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.10.3 CMP results

*Potential Occupational Non-cancer Toxicity Impacts (CMP)*

The baseline cable has a 5 percent greater impact on potential occupational non-cancer toxicity than the lead-free alternative, which is shown in Figure 3-89. The top contributing process for the baseline cable and lead-free alternative is the production of natural gas (Figure 3-90). To protect confidentiality, Figure 3-90 combines the potential occupational non-cancer toxicity impacts from all upstream natural gas production. The top contributing flow for both the baseline and lead-free alternatives is natural gas (Figure 3-91). Figure 3-90 includes the processes that contribute >5 percent of the total impacts, which represent 89 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-91 includes individual flows that contribute >0.5 percent to the total impacts, and represents 98 percent of the total potential occupational non-cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in Figure 3-91, natural gas was given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in insulation (FEP) production and natural gas production. As the uncertainty analysis did not take into consideration uncertainties in these processes, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained for the potential occupational non-cancer toxicity impact category (see Section 3.4).

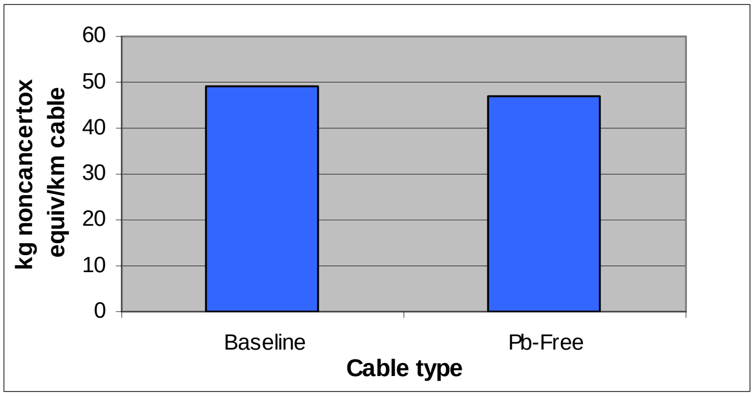

Figure 3-89. Total Potential Occupational Non-cancer Toxicity Impacts – CMP Full life cycle

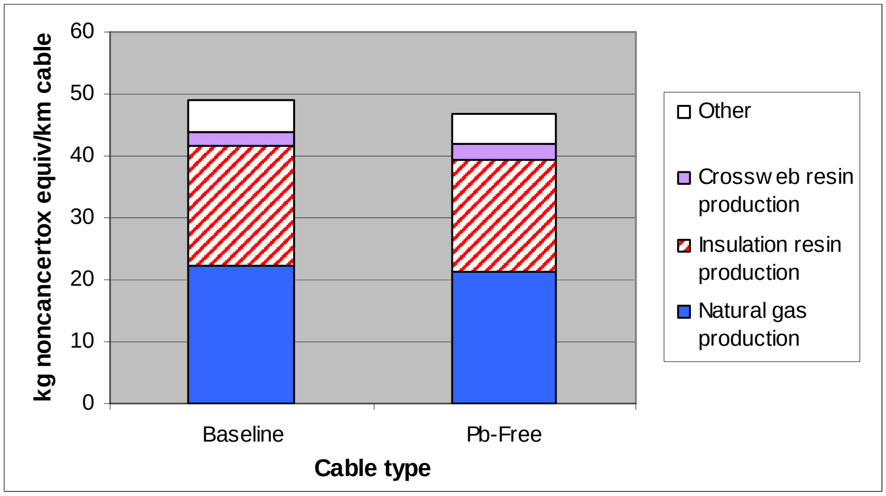

Figure 3-90. Top Contributing Processes to Potential Occupational Non-cancer Toxicity Impacts – CMP Full life cycle

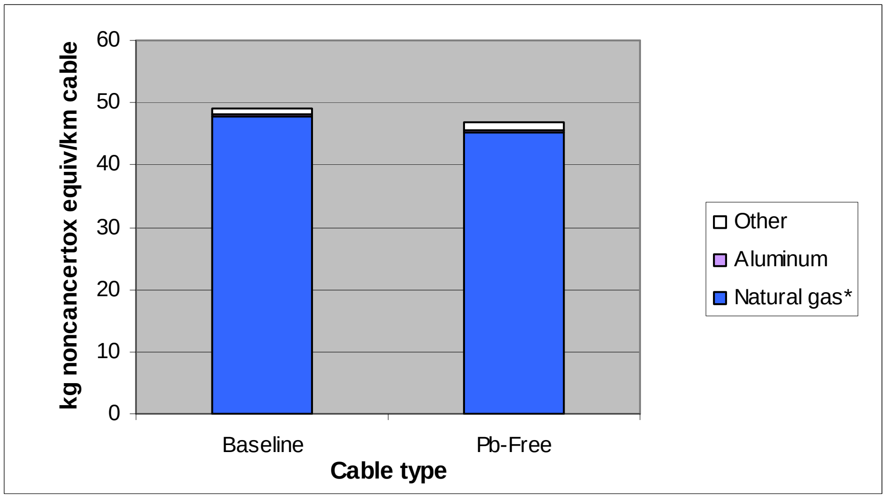

Figure 3-91. Top Contributing Flows to Potential Occupational Non-cancer Toxicity – CMP full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### *Potential Occupational Cancer Toxicity Impacts (CMP)*

The lead-free cable has a 3 percent greater impact on potential occupational cancer toxicity than the lead-free alternative, which is shown in Figure 3-92. The top contributing process for the baseline cable and lead-free alternative is the compounding of the cable jacketing (Figure 3-93). The top contributing flow for both the baseline and lead-free alternatives is fire retardant #3 (Figure 3-94). Figure 3-93 includes the processes that contribute >5 percent of the total impacts, which represents 96 and 91 percent of the total impact for the baseline and lead-free alternatives, respectively. Figure 3-94 includes individual flows that contribute >5 percent to the total impacts, and represents 89 and 81 percent of the total potential occupational cancer toxicity impact for the baseline and lead-free alternatives, respectively. As noted in figure 3-94, all of the material flows have been given a default hazard value due to lack of toxicological data.

The greatest contributor to occupational cancer toxicity impacts is jacketing compounding. An uncertainty analysis was conducted to address the uncertainty in extrusion and EOL data (Section 3.4). As that analysis did not take into consideration differences in jacket compounding, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained distinguishable for the potential occupational cancer toxicity impact category (see Section 3.4). Modifications to the jacket compounding process could have the largest potential to reduce impacts for both alternatives.

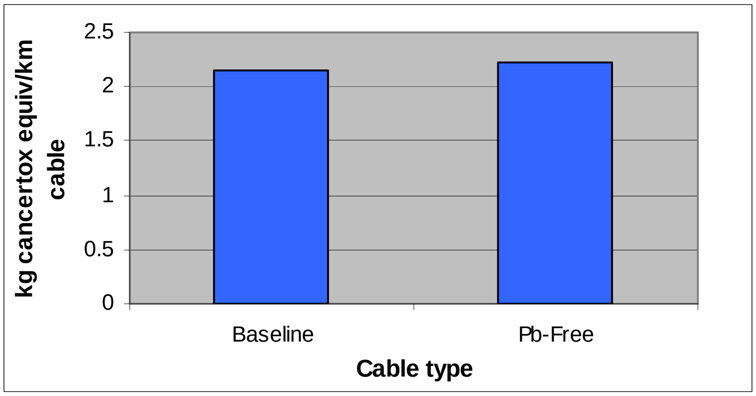

Figure 3-92. Total Potential Occupational Cancer Toxicity Impacts – CMP Full life cycle

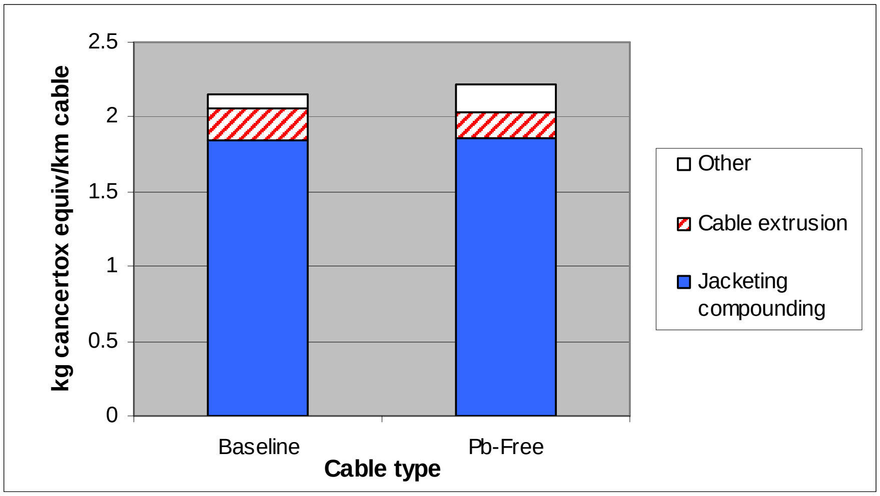

Figure 3-93. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – CMP Full life cycle

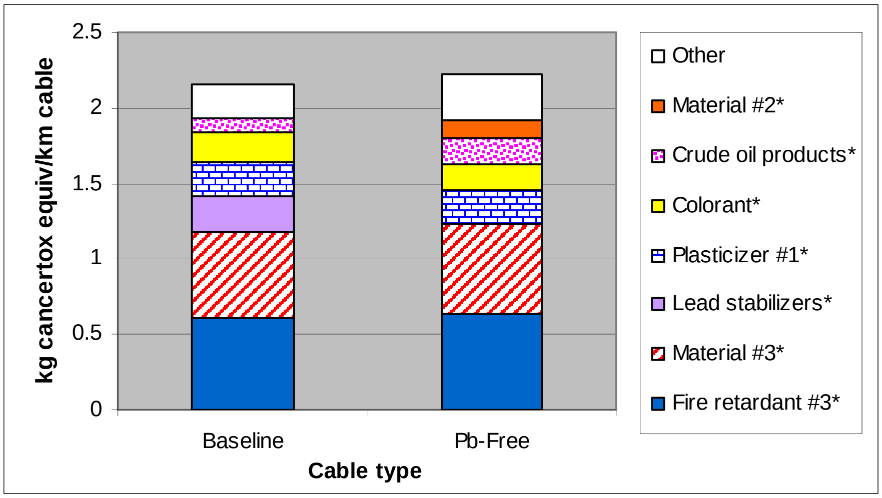

Figure 3-94. Top Contributing Flows to Potential Occupational Cancer Toxicity – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.10.4 NM-B results

***Occupational Non-cancer Toxicity Impacts (NM-B)***

In the NM-B cradle-to-gate analysis, the lead-free alternative generates 33 percent greater occupational non-cancer toxicity impacts than the baseline (leaded) cable, which is shown in Figure 3-95. The top contributing process is cable insulation compounding for both alternatives (Figure 3-96). Non-halogenated fire retardant #2 is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-97). Figure 3-96 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-97 includes individual flows that contribute >1 percent to the total impacts, which represent 99 and 98 percent of the total occupational non-cancer impacts for the baseline and lead-free alternatives, respectively.

The flow primarily responsible for causing the lead-free cable to have greater impacts than the baseline cable is a phthalate plasticizer. In addition, the greater amount of the non-halogenated flame retardant #2 (name withheld to protect confidentiality) contributed to greater burden on occupational toxicity for the lead-free cable. As noted in figure 3-97, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that insulation compounding contributes greatest to occupational non-cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts if insulation and plasticizers are reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., non-halogenated flame retardants).

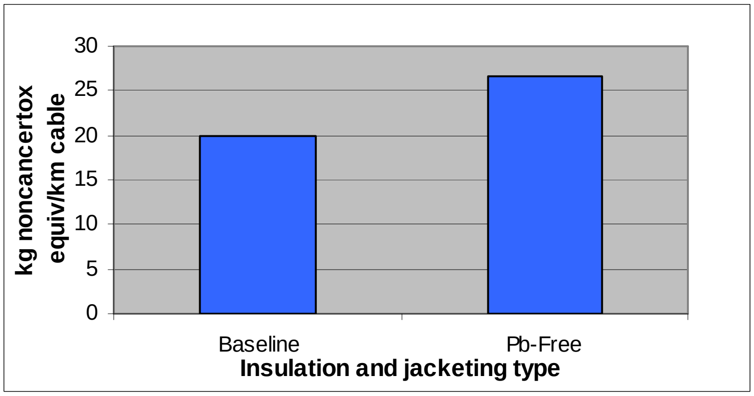

Figure 3-95. Total Potential Occupational Non-Cancer Impacts – NM-B Partial life cycle

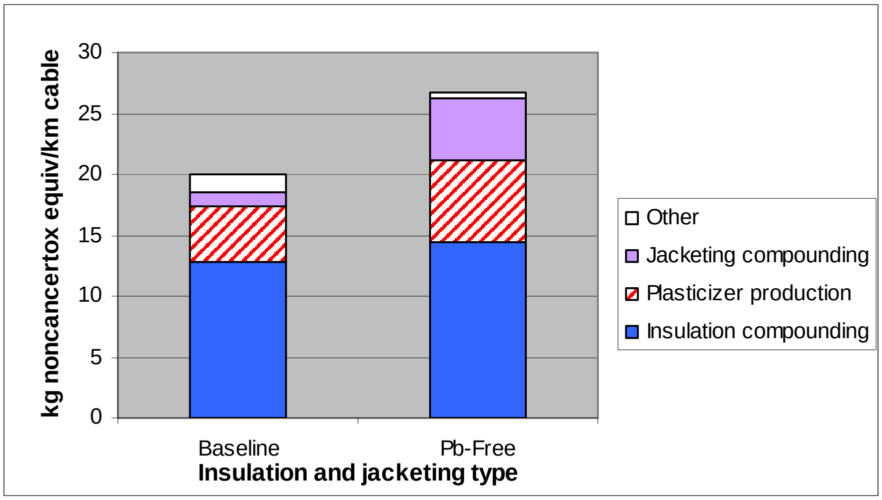

Figure 3-96. Top Contributing Processes to Potential Occupational Non-Cancer Toxicity Impacts – NM-B Partial life cycle

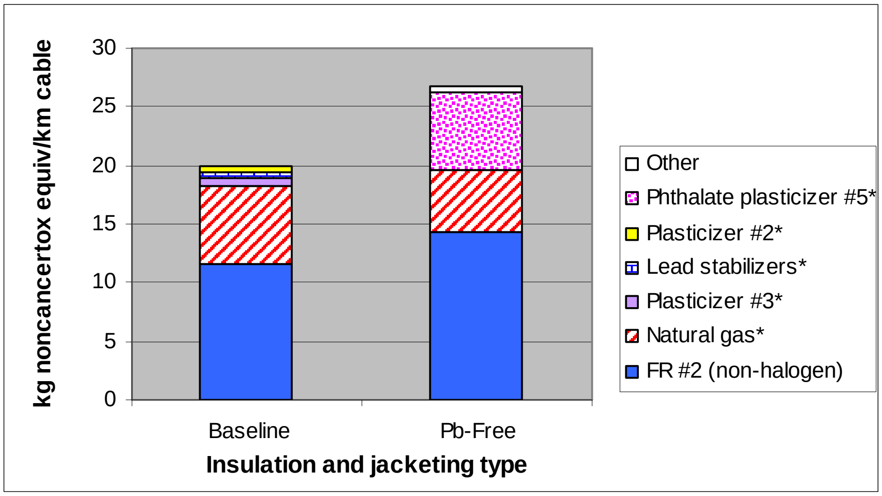

Figure 3-97. Top Contributing Flows to Potential Occupational Non-Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### *Potential Occupational Cancer Toxicity Impacts (NM-B)*

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 16 percent higher potential occupational cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-98. The top contributing process is cable jacketing compounding for both alternatives (Figure 3-99). The top contributing flow for the baseline cable is plasticizer #2, and for the lead-free alternative it is phthalate plasticizer #5 (Figure 3-100). Figure 3-99 includes the processes that contribute >5 percent of the total impacts, which represent >99 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-100 includes individual flows that contribute >1 percent to the total impacts, which represent >99 and 98 percent of the total potential occupational cancer impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-100, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that jacketing compounding contributes greatest to potential occupational cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts if electricity use is reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., plasticizers).

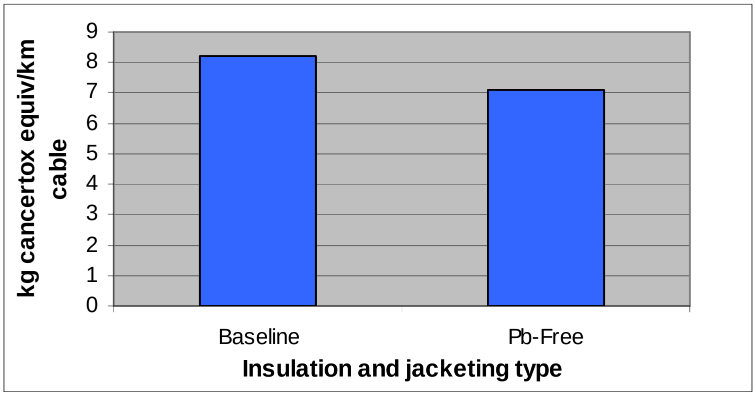

Figure 3-98. Total Potential Occupational Cancer Impacts – NM-B Partial life cycle

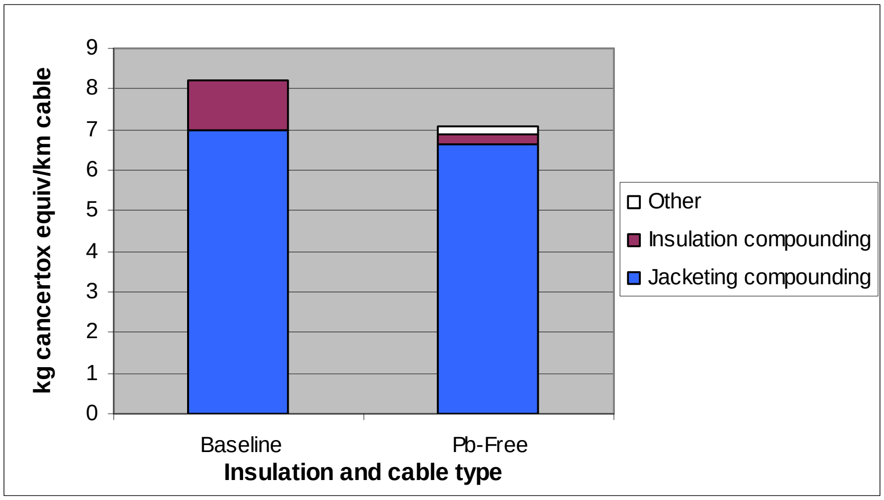

Figure 3-99. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – NM-B Partial life cycle

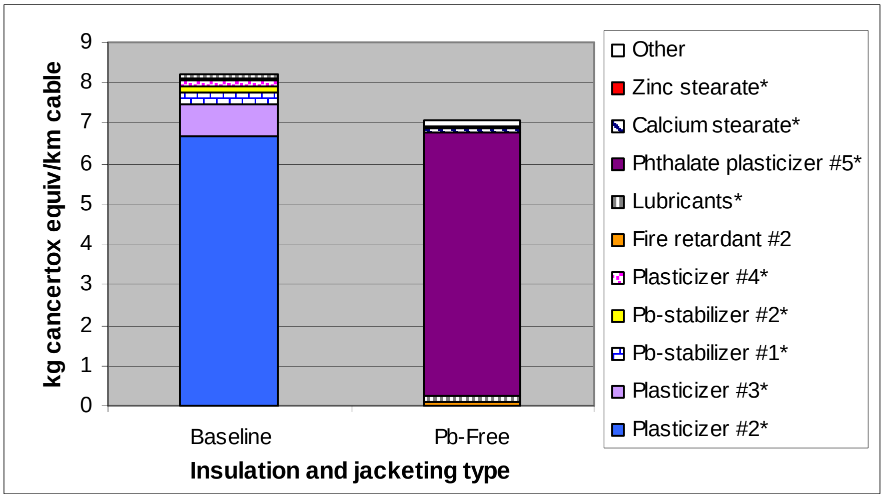

Figure 3-100. Top Contributing Flows to Potential Occupational Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.10.5 Limitations and uncertainties

Most of the limitations and uncertainties associated with the chronic human health results presented here and in Section 3.2.12 can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent potential human health effects.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

Each of these is discussed below:

Structural or modeling limitations and uncertainties. The chemical scoring method used in the human health effects impact characterization is a screening tool to identify chemicals of potential concern, not to predict actual effects or characterize risk. A major limitation in the method is that it only measures relative toxicity combined with inventory amount. It does not take chemical fate, transportation, or degradation into account. In addition, it uses a simple surrogate value (e.g., inventory amount) to evaluate the potential for exposure, when actual exposure potential involves many more factors, some of which are chemical-specific. The LCIA method for toxicity impacts also takes the most toxic endpoint to calculate a hazard value, regardless of the route of exposure (e.g., inhalation or ingestion); therefore, this approach does not model true potential exposures, but rather the relative toxicity as compared to other chemicals, to compare life-cycle results among alloys. This is addressed further in Section 3.2.11.5 with respect to public health impacts.

Other sources of uncertainty include possible omissions by the WCP researchers in the impact classification process (e.g., potentially toxic chemicals not classified as such) or misrepresentation of chemicals in the impact characterization method itself (e.g., misrepresenting a chemical as a small contributor to total impacts, because of missing or inaccurate toxicity data). Some of these limitations and uncertainties also may be considered limits in the toxicity data which are discussed further below.

It should be noted, however, that because LCA involves analyzing many processes over the entire life cycle of a product, a comprehensive, quantitative risk assessment of each chemical input or output cannot be done. Rather, LCA develops relative impacts that often lack temporal or spatial specificity, but can be used to identify materials for more detailed evaluation.

Toxicity data limitations and uncertainties. Major uncertainties in the impact assessment for potentially toxic chemicals result from missing toxicity data and from limitations of the available toxicity data. Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- Using dose-response data from laboratory animals to represent potential effects in humans.
- Using data from homogenous populations of laboratory animals or healthy human populations to represent the potential effects on the general human populations with a wide range of sensitivities.
- Using dose-response data from high dose toxicity studies to represent potential effects that may occur at low levels.
- Using data from short-term studies to represent the potential effects of long-term exposures.
- Assuming a linear dose-response relationship.
- Possibly increased or decreased toxicity resulting from chemical interactions.

Uncertainty is associated with using a default HV (i.e., assuming average toxicity for that measure when a chemical could be either more or less toxic than average) for missing toxicity data; however, the use of neutral default values for missing data reduces the bias that typically favors chemicals with little available information. Use of a data-neutral default value to fill data gaps is consistent with principles for chemical ranking and scoring (Swanson and Socha, 1997). Of the top contributing flows to the occupational *non-cancer* toxicity impacts, only a few chemicals had toxicity data (flame retardant #2, chlorine, aluminum, and plasticizer #2). All the others used the default HV of unity to represent potential relative toxicity. For the occupational *cancer* toxicity impacts, all top contributing flows represented in previous figures were based on default hazard values where no toxicity data were available (e.g., WOE classification or slope factor). Therefore, none of the top material contributors to the occupational cancer impacts that are known or suspected human carcinogens have slope factors. The occupational cancer impacts, therefore, are largely distributed among the material inputs used in the greatest quantity in the cable life cycles, but the relative carcinogenicity of these materials is uncertain.

LCI data limitations and uncertainties. For the CMR results, jacketing compounding followed by electricity generation (as used to fuel the manufacturing processes) were the major contributing processes to both non-cancer and cancer toxicity. The compounding process for the baseline CMR cables had the largest number of primary data sets (i.e., 3) and is believed to be of good quality. The compounding process for the lead-free CMR cables were averaged from 2 primary datasets, which are believed to be of good quality, but somewhat more limited by the smaller sample size. Any limitations resulting from selection bias (e.g., companies choosing to provide data might represent more progressive health and environmental protection activities) would be consistent across alternatives being compared; therefore, this is not considered a large limitation.

The CMP results were mostly affected by the FEP production process, which was derived from 2 companies providing data, and are also believed to be of good quality, however, are limited by the small sample size and the fact that the dataset had different boundaries than other modeled resins. As a result of secondary dataset boundaries, PVC and HDPE were modeled as coming from ground (i.e., all inputs were mined, bulk precursors), whereas FEP was modeled with industrial chemical intermediates as inputs. This discrepancy may limit the utility of comparisons between the impacts of FEP and the other resins, especially in impact categories that utilize inputs rather than outputs (e.g., energy use). Natural gas production and electricity production (used in manufacturing processes) were the second and third greatest contributors to CMP results and used secondary data (see Section 2.1.2.6).

NM-B results were highly impacted by the compounding process and to a lesser degree the plasticizer production process. Compounding of insulation and jacketing for NM-B was based on 2 or 3 data sets (refer to Table 2-9), and are expected to be of good quality, again limited by the small sample size. The plasticizer production process was based on secondary data, which were averaged data for several plasticizers, introducing a limitation to these data.

Based on the LCIA methodology and the LCI data, the occupational non-cancer toxicity category is given an overall relative data quality rating of “medium” for all cable types, and the cancer toxicity category is given a “medium to low” since the results are primarily based on chemicals without toxicity data (and were thus given default values).

### 3.2.11 Public Toxicity Impacts

This section presents the LCIA characterization methodology and the LCIA results for the public human health impact category. General information that is common to all the toxicity impact categories (i.e., occupational human health, public human health, and ecological toxicity) was presented in Section 3.2.10 and is applicable to this section. For chronic public health effects, the impact scores represent surrogates for potential health effects to residents living near a facility from long-term repeated exposure to toxic or carcinogenic agents. Impact scores are calculated for both cancer and non-cancer effects, and are based on the identity and amount of toxic chemical outputs with dispositions to air, soil and water.[16] As stated previously, inventory items do not truly represent long-term exposure, instead impacts are relative toxicity weightings of the inventory.

The scores for impacts to the public differ from occupational impacts in that inventory outputs are used as opposed to inventory inputs. This basic screening level scoring does not incorporate the fate and transport of the chemicals. The public human health impact results presented in this section include two impact categories: public non-cancer impacts and public cancer impacts.

#### 3.2.11.1 Characterization

Section 3.2.10.1 (Potential Human Health Impacts) provides a general discussion of the human health characterization approach in this LCIA. Below are the specific equations used to calculate impact scores for potential public non-cancer and cancer impacts.

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[16] Disposition to soil includes direct, uncontained releases to soil as could occur from unregulated disposal. It does not include solid or hazardous waste disposal in a regulated landfill. Disposition to water, however, could include groundwater if a landfill model shows releases to groundwater, for example.

***Potential Public Toxicity Impact Characterization: Non-cancer***

The chronic public health effects impact score for non-cancer effects is calculated by:

$$(IS_{CHP\text{-}NC})_i = (HV_{NC} \times Amt_{TCoutput})_i$$

where:

| | |
|---|---|
| $IS_{CHP\text{-}NC}$ | equals the impact score for chronic non-cancer effects to the public for chemical *i* (kg non-cancertox-equivalent) per functional unit; |
| $HV_{NC}$ | equals the hazard value for chronic non-cancer effects for chemical *i* (based on either inhalation or oral toxicity, see Section 3.2.10.1); and |
| $Amt_{TC\ output}$ | equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit. |

More detail on the $HV_{NC}$ is provided in Section 3.2.10.1. Accounting for the inventory and characterization methodology and data, the potential public chronic non-cancer toxicity impact category is given a "medium" data quality measure.

***Potential Public Toxicity Impact Characterization: Cancer***

The chronic public health effects impact score for cancer effects is calculated as follows:

$$(IS_{CHP\text{-}CA})_i = (HV_{CA} \times Amt_{TCoutput})_i$$

where:

| | |
|---|---|
| $IS_{CHP\text{-}CA}$ | equals the impact score for chronic cancer health effects to the public for chemical *i* (kg cancertox-equivalent) per functional unit; |
| $HV_{CA}$ | equals the hazard value for carcinogenicity for chemical *i* (based on either inhalation or oral carcinogenicity, see Section 3.2.10.1); and |
| $Amt_{TC\ output}$ | equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit. |

Potential public cancer toxicity is 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.

### 3.2.11.2 CMR results

***Potential Public Non-cancer Toxicity Impacts (CMR)***

The baseline cable has a five-fold greater impact on the potential public chronic non-cancer toxicity than the lead-free alternative, which is shown in Figure 3-101. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the electricity used during cable extrusion (Figure 3-102). To protect confidentiality, Figure 3-102 combines the public non-cancer toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is sulfur dioxide (Figure 3-103). Figure 3-102 includes the processes that contribute >5 percent of the total impacts, which represent 97 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-103 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 99 percent of the total potential public non-cancer toxicity impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are primarily a function of the differences in composition: The use of lead in the baseline cable potentially increases the public non-cancer risk substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential public non-cancer toxicity impact category (see Section 3.4).

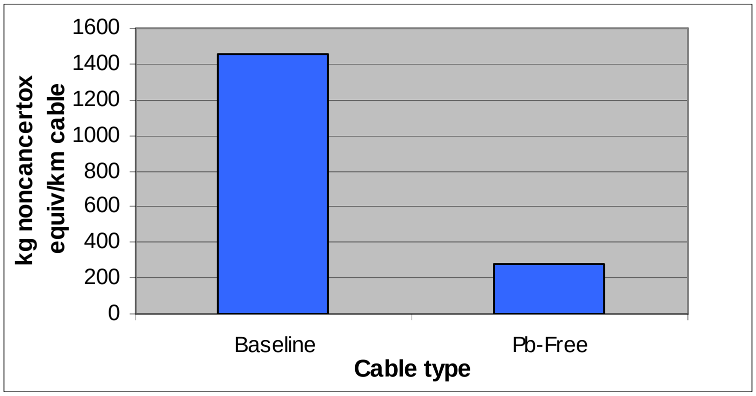

Figure 3-101. Total Potential Public Non-cancer Toxicity Impacts – CMR Full life cycle

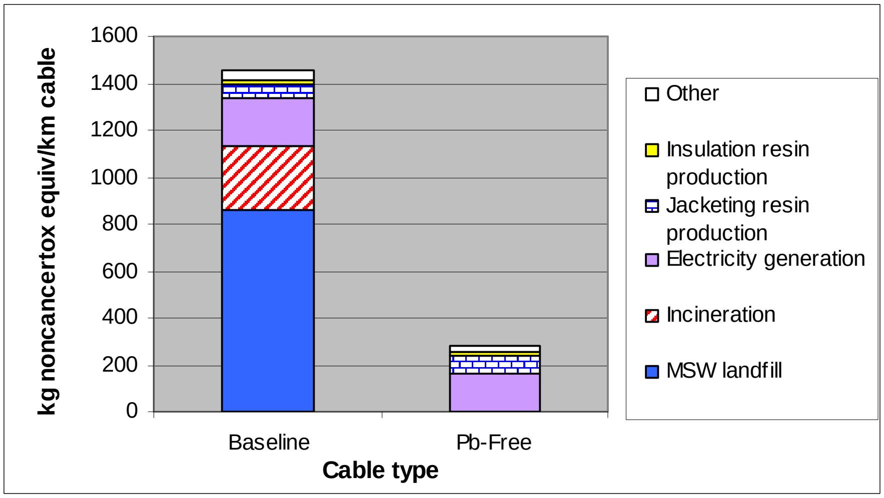

Figure 3-102. Top Contributing Processes to Potential Public Non-Cancer Toxicity Impacts – CMR Full life cycle

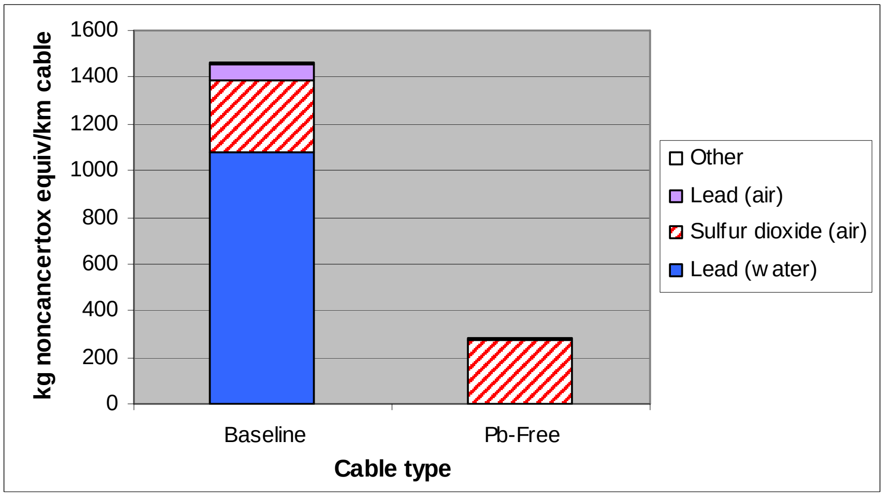

Figure 3-103. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – CMR Full life cycle

### *Potential Public Cancer Toxicity Impacts (CMR)*

The lead-free alternative has a 1 percent greater impact on the potential public cancer toxicity than the baseline cable, which is shown in Figure 3-104. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the production of jacketing resin (Figure 3-105). To protect confidentiality, Figure 3-105 combines the public cancer toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable and the lead-free alternative is methane (Figure 3-106). Figure 3-105 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-106 includes individual flows that contribute >1 percent to the total impacts and represents 97 percent of the total potential public cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in figure 3-106, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are a result of a number of factors including energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the potential public cancer toxicity impact category (see Section 3.4).

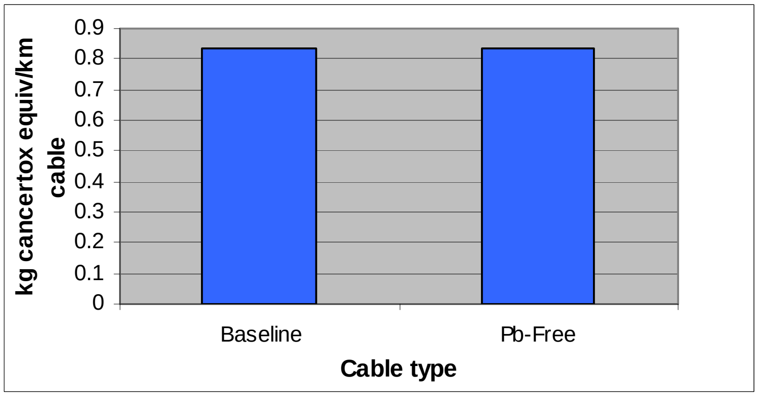

Figure 3-104. Total Potential Public Cancer Toxicity Impacts – CMR Full life cycle

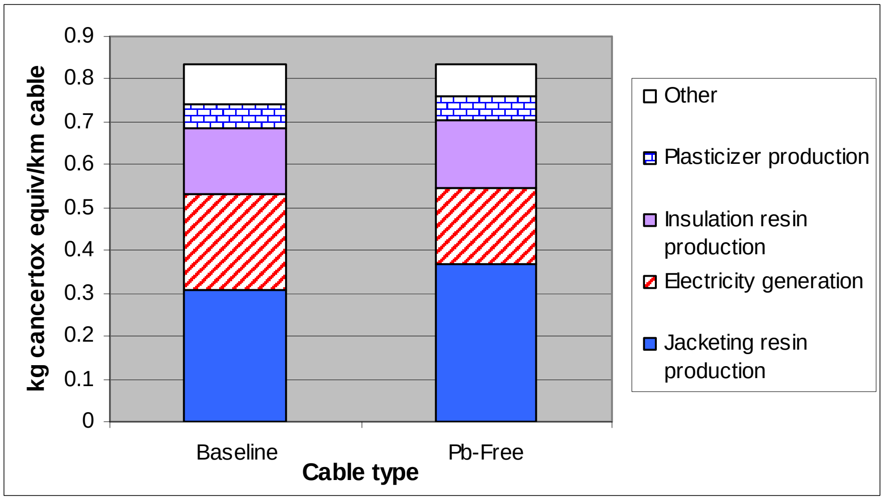

Figure 3-105. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – CMR Full life cycle

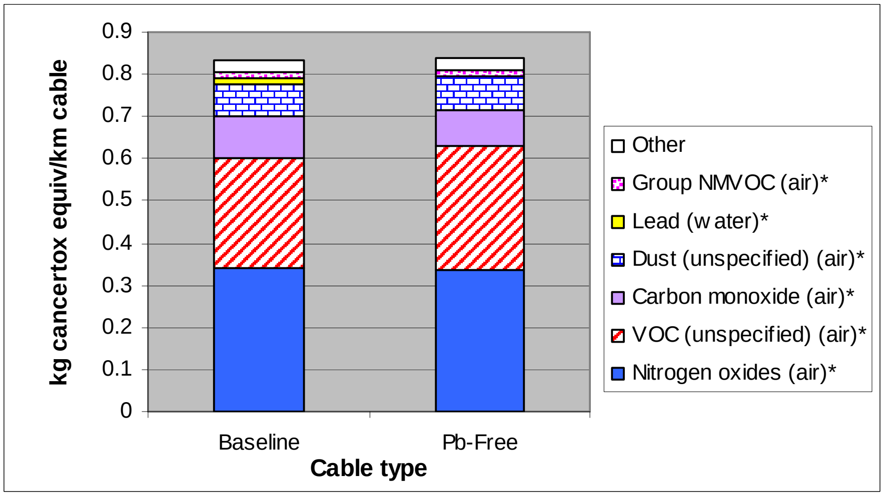

Figure 3-106. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.11.3 CMP results

***Potential Public Non-cancer Toxicity Impacts (CMP)***

The baseline cable has an approximately 2.5-fold greater impact on the potential public chronic non-cancer toxicity as the lead-free alternative, which is shown in Figure 3-107. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the electricity used during cable extrusion (Figure 3-108). To protect confidentiality, Figure 3-108 combines the public non-cancer toxicity from all upstream electricity generation and natural gas production. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is sulfur dioxide (Figure 3-109). Figure 3-108 includes the processes that contribute >5 percent of the total impacts, which represents 97 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-109 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 99 percent of the total potential public non-cancer toxicity impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the public non-cancer risk substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential public non-cancer toxicity impact category (see Section 3.4).

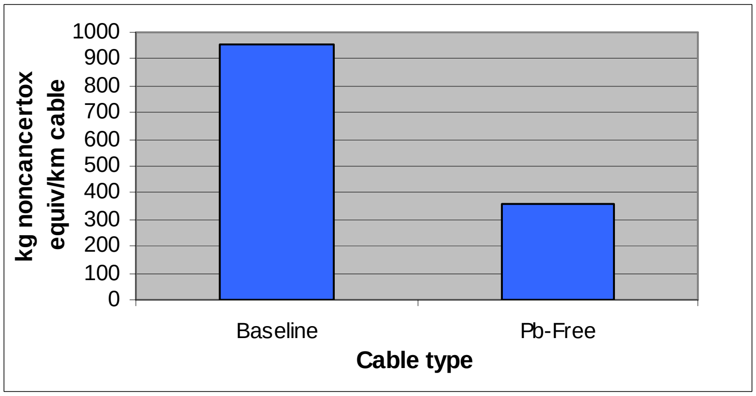

Figure 3-107. Total Potential Public Non-cancer Toxicity Impacts – CMP Full life cycle

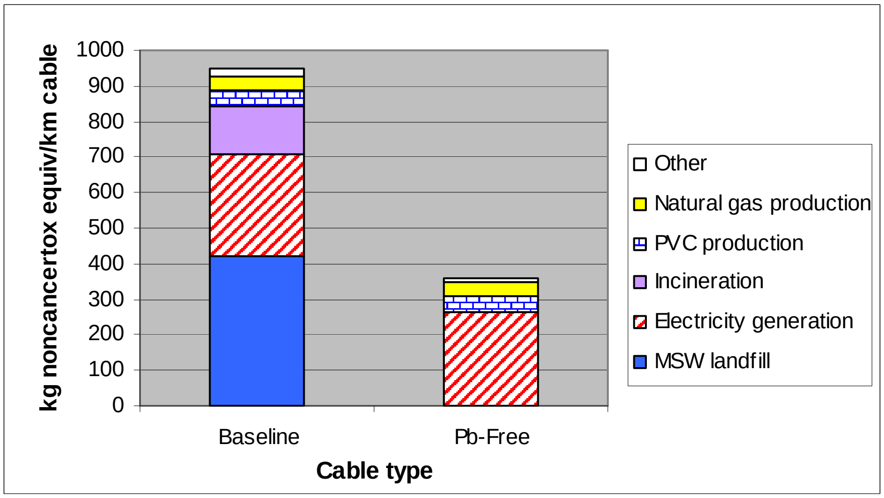

Figure 3-108. Top Contributing Processes to Potential Public Non-cancer Toxicity Impacts – CMP Full life cycle

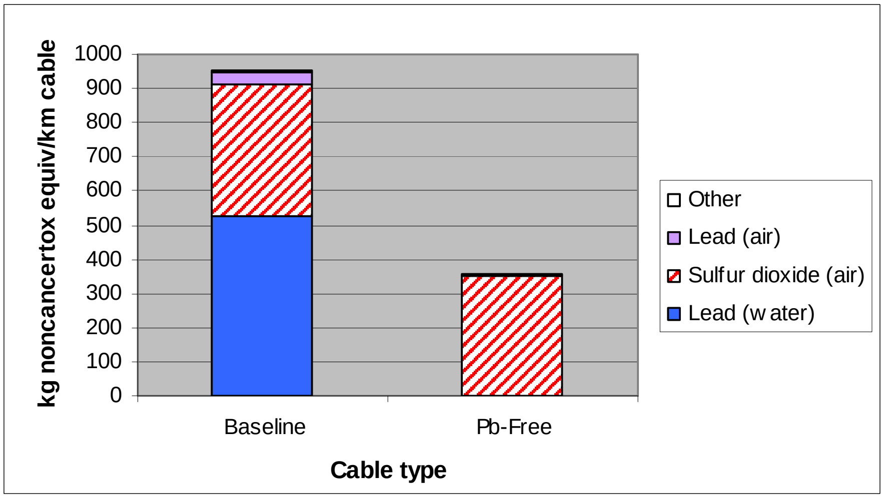

Figure 3-109. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – CMP Full life cycle

### *Potential Public Cancer Toxicity Impacts (CMP)*

The baseline cable has a 5 percent greater impact on the potential public cancer toxicity than the lead-free alternative, which is shown in Figure 3-110. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for cable extrusion (Figure 3-111). To protect confidentiality, Figure 3-111 combines the public cancer toxicity impacts from all upstream electricity generation. The top contributing flow for both alternatives is nitrogen oxides ($NO_x$) (Figure 3-112). Figure 3-111 includes the processes that contribute >5 percent of the total impacts, which represent 85 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-112 includes individual flows that contribute >1 percent to the total impacts and represents 93 and 94 percent of the total potential public cancer toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-112, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the potential public cancer toxicity impact category (see Section 3.4).

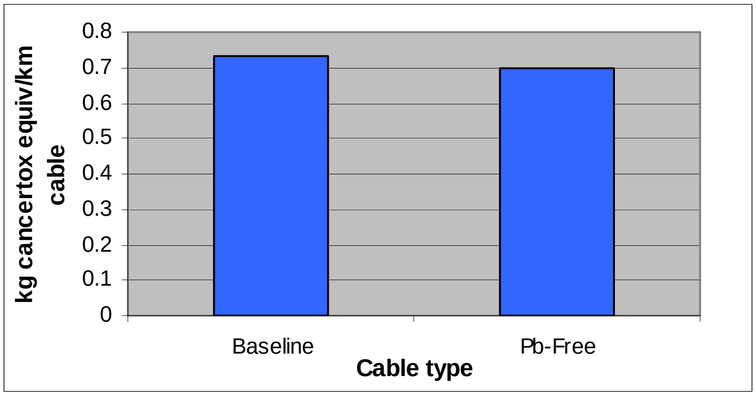

Figure 3-110. Total Potential Public Cancer Toxicity Impacts – CMP Full life cycle

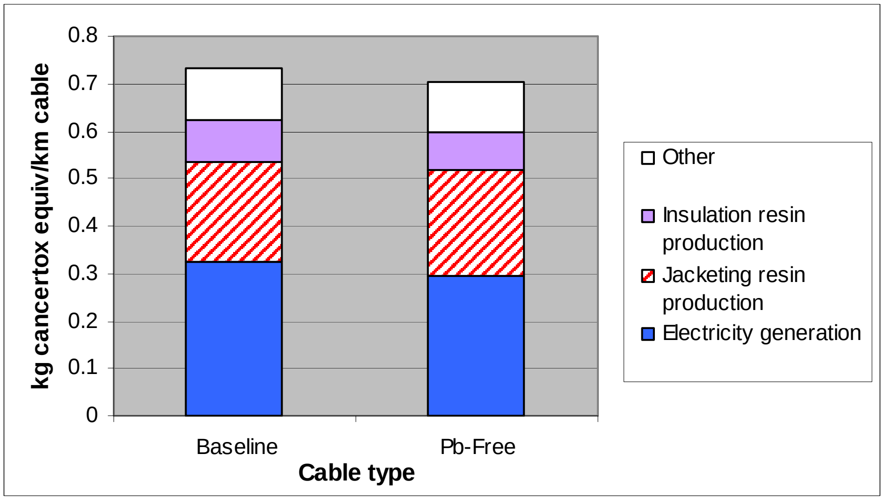

Figure 3-111. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – CMP Full life cycle

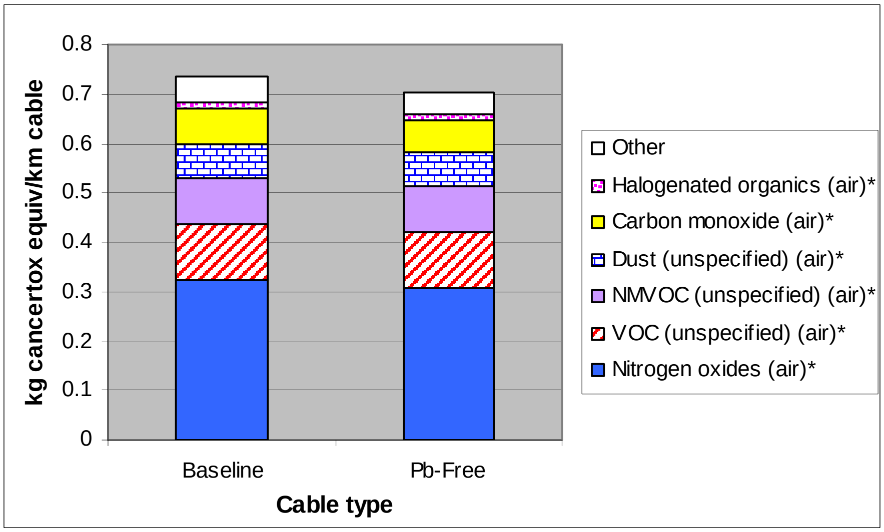

Figure 3-112. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.11.4 NM-B results

***Potential Public Non-cancer Toxicity Impacts (NM-B)***

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 11 percent higher potential public chronic non-cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-113. The top contributing process is jacketing resin production for both alternatives (Figure 3-114) and sulfur dioxide is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-115). Figure 3-114 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-115 includes individual flows that contribute >1 percent to the total impacts, which represent 98 and 99 percent of the total potential public non-cancer impacts for the baseline and lead-free alternatives, respectively.

Of note is that the impacts for both the leaded and lead-free constructions are driven by sulfur dioxide, which is in contrast to the CMR and CMP results, which included EOL. When EOL was included, the leaded cables had much greater burdens due to lead released to the environment primarily at the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B these results would be driven by other processes and chemicals. Since we expect EOL to be a large driver of impacts to this category, the potential public non-cancer toxicity category for NM-B is given a “medium-to-low” quality rating (ratings are summarized in Chapter 4, Table 4-6).

As alluded to, care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to potential public non-cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of PVC used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce sulfur dioxide emissions).

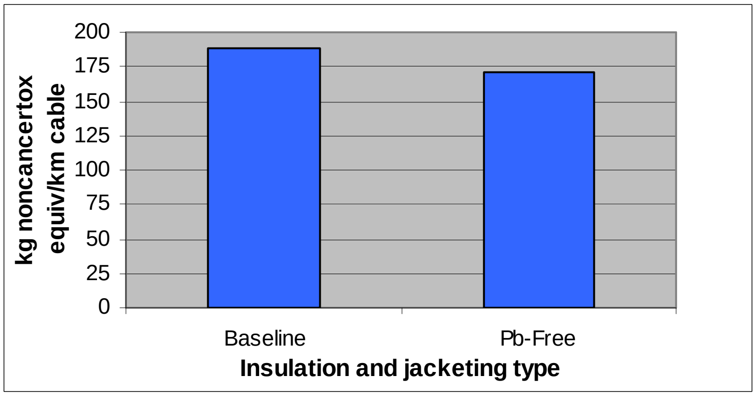

Figure 3-113. Total Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

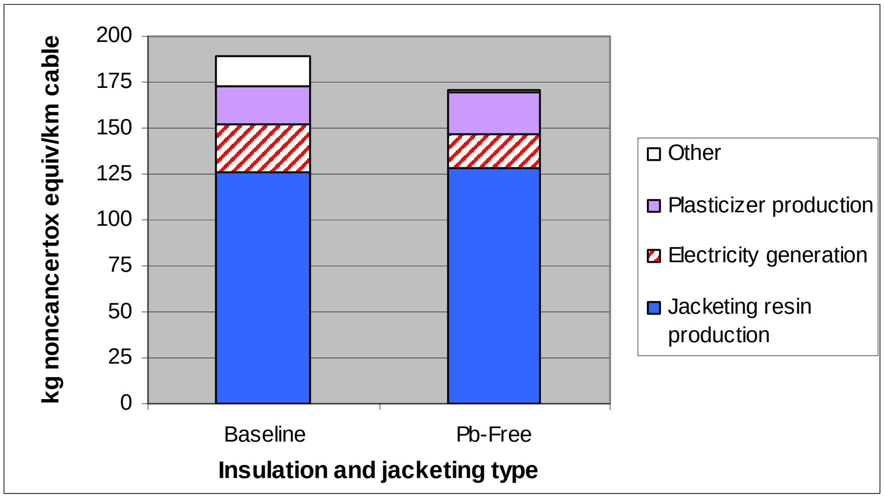

Figure 3-114. Top Contributing Processes to Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

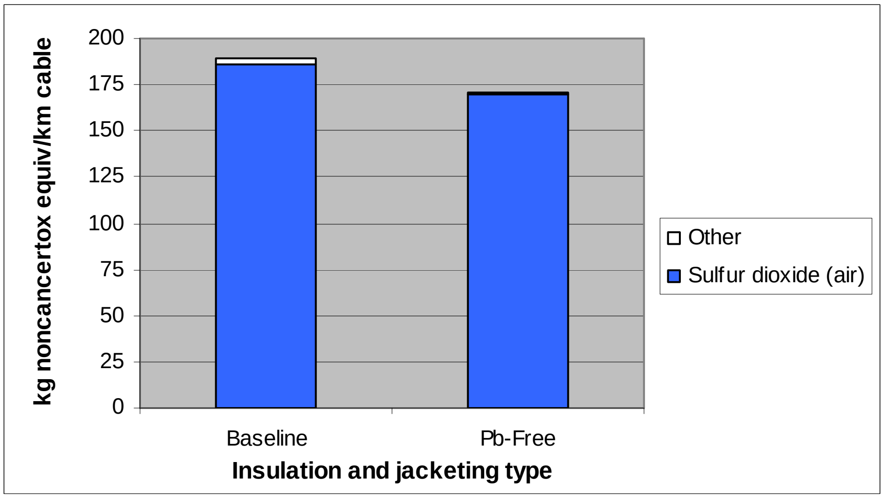

Figure 3-115. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

***Potential Public Cancer Toxicity Impacts (NM-B)***

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 4 percent higher potential public cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-116. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-117). Nitrogen oxides ($NO_x$) is the greatest individual flow contributing to the impact of the baseline cable, and unspecified volatile organic compounds (VOCs) are the greatest individual flow contributing to the impact of the lead-free alternative (Figure 3-118). Figure 3-117 includes the processes that contribute >5 percent of the total impacts, which represent 96 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-118 includes individual flows that contribute >1 percent to the total impacts, which represent 96 and 98 percent of the total potential public cancer impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-118, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to potential public cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of PVC used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce nitrogen oxide emissions). It should also be noted that the output flows contributing to the potential public cancer toxicity category are not any known carcinogens. Chemicals lacking data on carcinogenicity remain in the analysis as potential carcinogens.

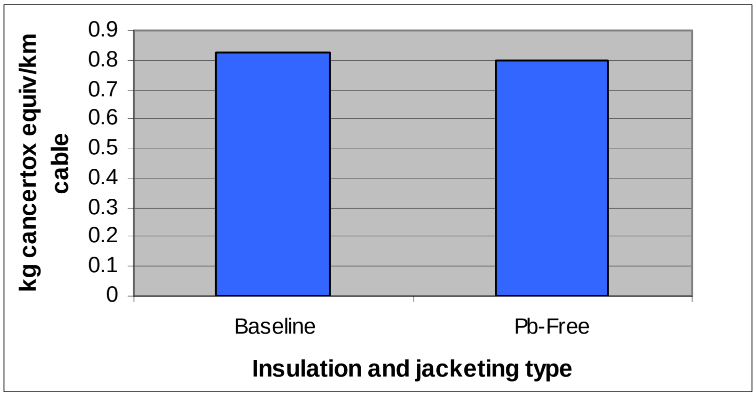

Figure 3-116. Total Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

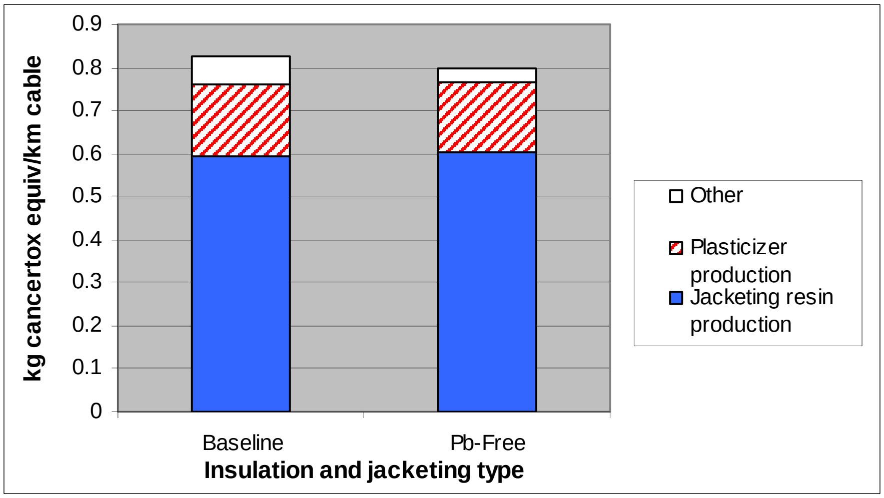

Figure 3-117. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

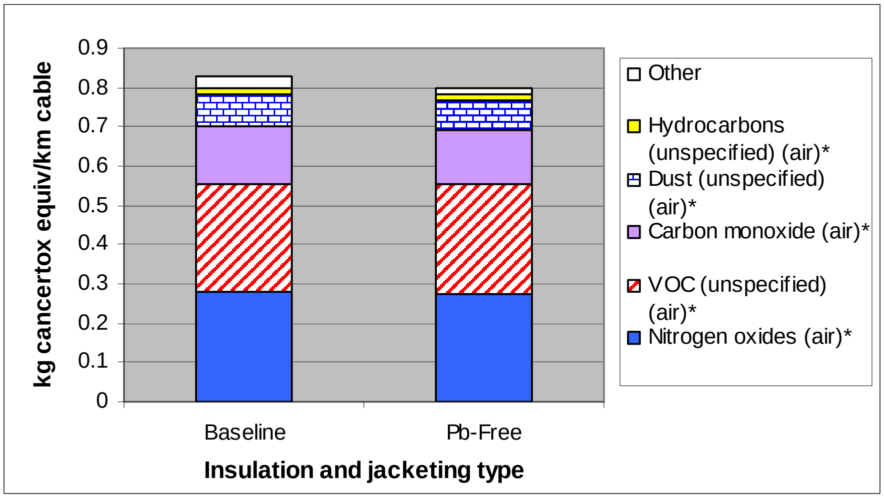

Figure 3-118. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

#### 3.2.11.5 Limitations and uncertainties

This section summarizes the limitations and uncertainties associated with public non-cancer and cancer health impacts. The public health LCIA limitations and uncertainties that address (1) structural or modeling limitations and (2) toxicity data limitations, are identical to those for occupational health impacts. For a detailed discussion, refer to Section 3.2.10.5. For example, much of the public *cancer* impact results are driven by a lack of toxicity data, rather than known carcinogenic hazards. Of the top contributing flows to the public *non-cancer* toxicity impacts presented in preceding figures, all the chemicals had HVs based on available toxicity data. For the occupational *cancer* toxicity impacts, all top contributing flows except for lead (in CMR public cancer toxicity results) were based on default hazard values where no toxicity data were available (e.g., WOE classification or slope factor). Therefore, most of the public cancer impacts are based on materials that lack data on their carcinogenicity, and similar to the occupational impact results, the public cancer impacts are largely distributed among the material inputs used in the greatest quantity in the cable life cycles, but the relative carcinogenicity of these materials is uncertain.

The LCI data limitations for public health impacts in many cases are similar to those described in Section 3.2.10.5. LCI data limitations pertinent to public health impacts are summarized below.

For the CMR and CMP results, the baseline results were driven by landfilling (e.g., lead leaching from the landfill), followed by incineration and then electricity production (for manufacturing processes). The impacts from the lead-free alternative, however, were driven by the electricity production. There is uncertainty in the leachate estimate used in the analysis, which was therefore varied in the multivariate uncertainty analysis (Section 3.4). As the uncertainty analysis revealed, a significant difference between the alternatives is likely, even given the defined range of uncertainty (see Section 3.4). Since the landfill leachate data were an important aspect of the public toxicity impacts, further refinement of the potential exposure, through more sophisticated exposure analysis and fate and transport analysis, as well as leachability studies, are warranted. In addition to lead output uncertainties, there are EOL uncertainties related to the assumptions about EOL dispositions (e.g., 4 percent of cables go directly to landfilling, and 73 percent go to landfilling after chopping for copper recovery). This is discussed in greater detail in Chapter 2. For incineration, secondary literature was used to estimate outputs and additional secondary sources were reviewed to make assumptions about lead releases and partitioning to various environmental media, which introduces uncertainty into the incineration outputs.

The NM-B analysis, which did not include EOL modeling were driven by PVC production for both non-cancer and cancer toxicity impacts. As explained in previous sections, PVC production data are secondary data. It is also important to note that the secondary data set that was used for this process does not include any vinyl chloride monomer inputs or outputs. As discussed in Chapter 1, vinyl chloride is a known carcinogen. Given that there is potential occupational exposure to the vinyl chloride monomer during production, and potential public exposure from any environmental releases of the monomer, the cancer impact results are further limited. Therefore, the differences in PVC use across alternatives could drive cancer impacts in the same direction. Because PVC production was a large contributor to NM-B results, the M-B results would likely be affected to the greatest extent. However, CMR and CMP results would also be affected as PVC is used in both of these cables as well.

As lead released to water (via landfill leaching) is a large proportion of impacts, further investigation into the hazard and exposure to lead from landfills is warranted. And although lead-free constructions are gaining market share, further investigation into the exposure and risk from landfill disposal is important to address existing leaded-cables that have not yet reached their end-of-life dispositions.

Based on the LCIA methodology and the LCI data, the public non-cancer toxicity category is given an overall relative data quality rating of “medium” for all cable types, and the cancer toxicity category is given a “medium to low” rating since the results are primarily based on chemicals without toxicity data (and were thus given default values), and there is no consideration for vinyl chloride in the PVC production process.

### 3.2.12 Potential Aquatic Ecotoxicity Impacts

#### 3.2.12.1 Characterization

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. Impact categories could include both ecotoxicity impacts to aquatic and terrestrial ecosystems. The method for calculating terrestrial toxicity, however, would be the same as for the chronic, non-cancer public toxicity impacts described above, which is based on mammalian toxicity data. As the relative ranking approach of the LCIA toxicity method does not modify the toxicity data for different species or for fate and transport, both human and terrestrial LCIA impacts are the same; therefore, only aquatic toxicity, which uses a different methodology, is presented below.

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts comprise the aquatic ecotoxicity term. The HVs for acute and chronic toxicity are based on $LC_{50}$ (the lethal concentration to 50 percent of the exposed fish population) and NOEL (no-observed-effect level) (or NOEC [no-observed-effect concentration]) toxicity data, respectively, mostly from toxicity tests in fathead minnows (Pimephales promelas) (Swanson *et al*., 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

$HV_{FA}$ equals the hazard value for acute fish toxicity for chemical *i* (unitless);

$LC_{50}$ equals the lethal concentration to 50 percent of the exposed fish population for chemical *i*; and

$LC_{50\ mean}$ equals the geometric mean $LC_{50}$ of available fish $LC_{50}$ values in Appendix E (mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/\ NOEL_i}{1/\ NOEL_{mean}}$$

where:

$HV_{FC}$ equals the hazard value for chronic fish toxicity for chemical *i*;

*NOEL* equals the no-observed-effect level for fish for chemical *i*; and

$NOEL_{mean}$ equals the geometric mean NOEL of available fish NOEL values in Appendix E (mg/L).

For chemicals that do not have chronic fish toxicity data available, but do have $LC_{50}$ data, the $LC_{50}$ and the log $K_{ow}$ of the chemical are used to estimate the NOEL. Based on studies comparing the $LC_{50}$ to the NOEL (Kenega, 1982; Jones and Schultz, 1995, and Call *et al.*, 1985) as reported in Swanson *et al.* (1997), NOEL values for organic chemicals within a certain range of log $K_{ow}$ values are calculated using the following continuous linear function:

For organics with 2 # log $K_{ow}$ < 5:

$$\mathrm{NOEL} = \mathrm{LC}_{50}/(5.3\ x \log \mathrm{K}_{ow} - 6.6)$$

Organic chemicals with high log $K_{ow}$ values (i.e., greater than 5) are generally more toxic to fish and are not expected to follow a continuous linear function with $K_{ow}$, thus, they are estimated directly from the $LC_{50}$. In addition, inorganic chemicals are poorly fat soluble and their fish toxicity does not correlate to log $K_{ow}$. The NOEL values of the inorganic chemicals were, therefore, also based on the fish $LC_{50}$ values.

For inorganics or organics with log $K_{ow}$ ∃5:

$$\mathrm{NOEL} = 0.05\ x\ (\mathrm{LC}_{50})$$

For organics with log $K_{ow}$<2, which are poorly fat soluble but assumed to have a higher NOEL value than those with higher $K_{ow}$ values or than inorganics, the NOEL is estimated as follows:

For organics with log $K_{ow}$ <2:

$$\mathrm{NOEL} = 0.25\ x\ (\mathrm{LC}_{50})$$

Once the HVs are calculated, whether from NOEL data or estimated from the $LC_{50}$ and the $K_{ow}$, the aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC})\ x\ Amt_{TCoutput,water}]_i$$

Accounting for the inventory and the characterization method, we have assigned a “medium” data quality measure for the aquatic ecotoxicity impact category results.

### 3.2.12.2 CMR results

The baseline cable has an approximately 150-fold greater impact on the potential aquatic toxicity than the lead-free alternative, which is shown in Figure 3-119. The top contributing process for the baseline cable is the landfilling of chopped cable, and for the lead-free alternative it is the generation of electricity for cable extrusion (Figure 3-120). To protect confidentiality, Figure 3-120 combines the aquatic toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is dissolved chlorine (Figure 3-121). Figure 3-120 includes the processes that contribute >5 percent of the total impacts, which represent 99 and 91 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-121 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 97 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-121, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the aquatic toxicity impact substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential aquatic toxicity impact category (see Section 3.4).

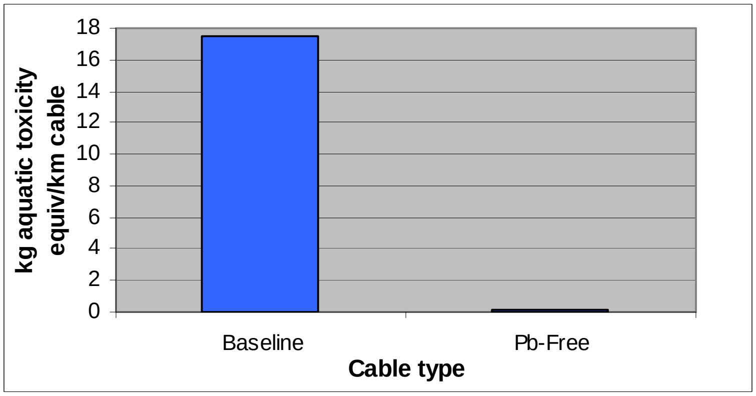

Figure 3-119. Total Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

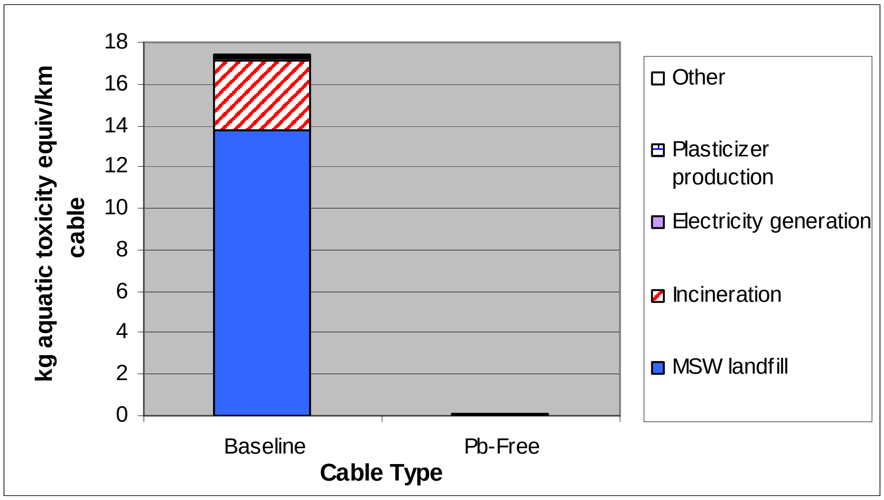

Figure 3-120. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

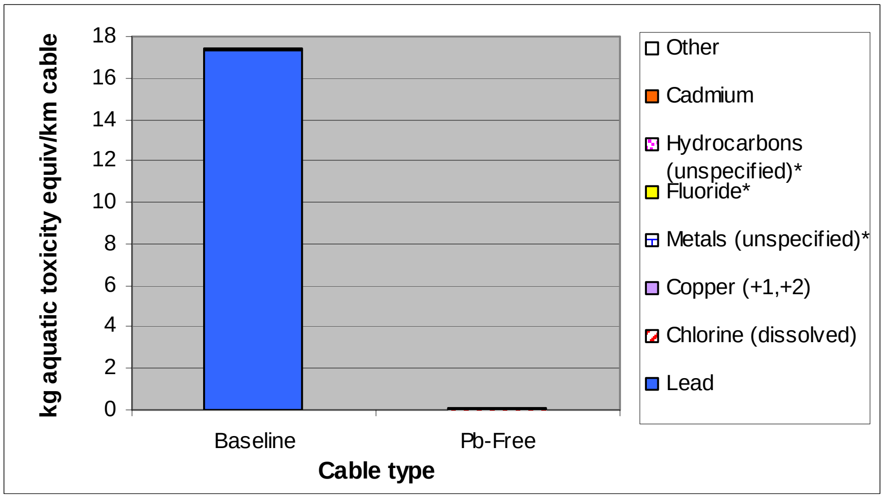

Figure 3-121. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.12.3 CMP results

The baseline cable has an approximately 55-fold greater impact on the potential aquatic toxicity than the lead-free alternative, which is shown in Figure 3-122. The top contributing process for the baseline cable is the landfilling of chopped cable, and for the lead-free alternative it is the generation of electricity for cable extrusion (Figure 3-123). To protect confidentiality, Figure 3-123 combines the aquatic toxicity impacts from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is dissolved chlorine (Figure 3-124). Figure 2-123 includes the processes that contribute >5 percent of the total impacts, which represent 99 and 94 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-124 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 96 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-124, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the aquatic toxicity impact substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential aquatic toxicity impact category (see Section 3.4).

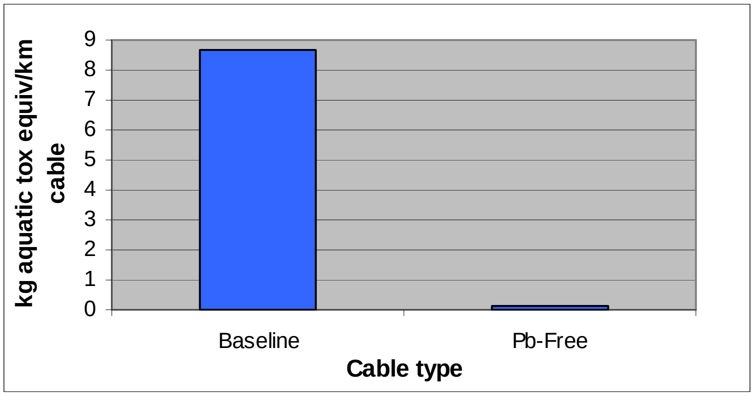

Figure 3-122. Total Potential Ecotoxicity Impacts – CMP Full life cycle

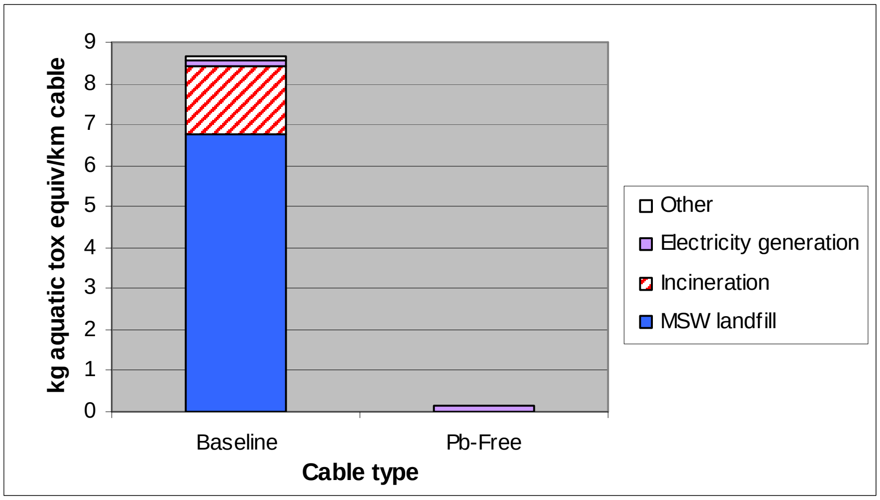

Figure 3-123. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – CMP full life cycle

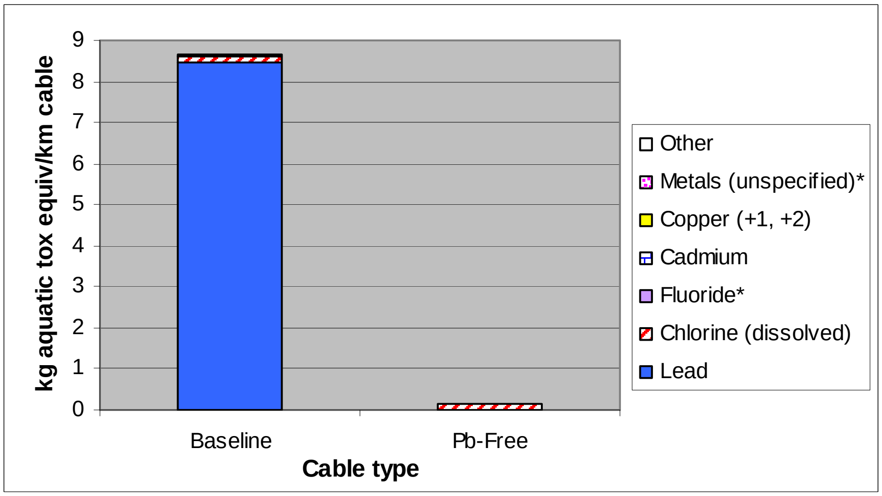

Figure 3-124. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

### 3.2.12.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 43 percent higher potential aquatic toxicity impacts than the lead-free alternative, which is shown in Figure 3-125. The top contributing process is phthalate plasticizer production for both alternatives (Figure 3-126) and copper (1+, 2+) is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-127). Figure 3-126 includes the processes that contribute >5 percent of the total impacts, which represent 96 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-127 includes individual flows that contribute >1 percent to the total impacts, which represent 99 and 98 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in Figure 3-127, some material flow has been given a default hazard value due to lack of toxicological data.

Of note is that the impacts for both the leaded and lead-free constructions are driven by plasticizer production process, and the top contributing flow was copper ions. This is in contrast to the CMR and CMP results, which included EOL. When EOL was included, the leaded telecommunication cables had much greater burdens due to lead released to the environment primarily at the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B these results would be driven by other processes and chemicals. Since we expect EOL to be a large driver of impacts to this category, the potential aquatic ecotoxicity category for NM-B is given a "medium-to-low" quality rating (ratings are summarized in Chapter 4, Table 4-6).

As alluded to, care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that phthalate production contributes greatest to potential aquatic ecotoxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of phthalates used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce copper emissions).

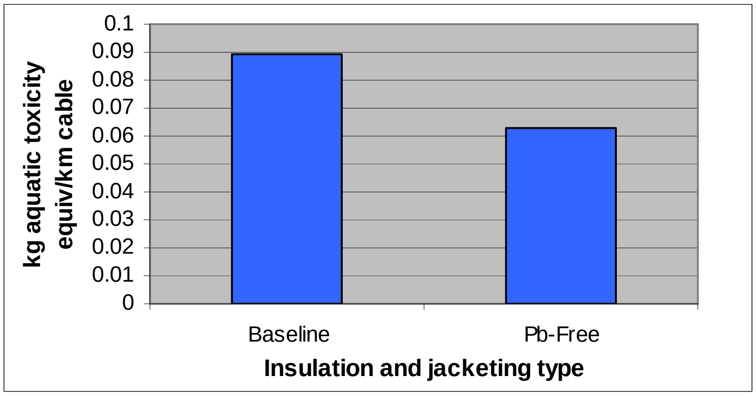

Figure 3-125. Total Potential Aquatic Ecotoxocity Impacts – NM-B Partial life cycle

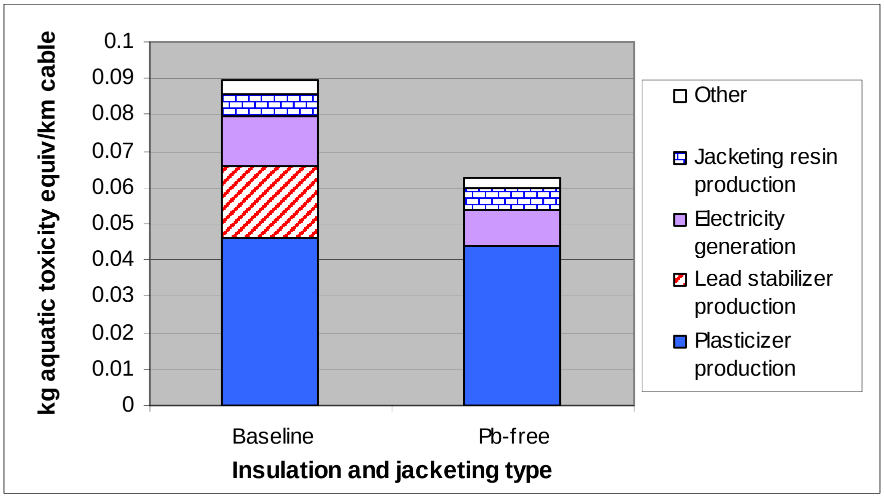

Figure 3-126. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – NM-B Partial life cycle

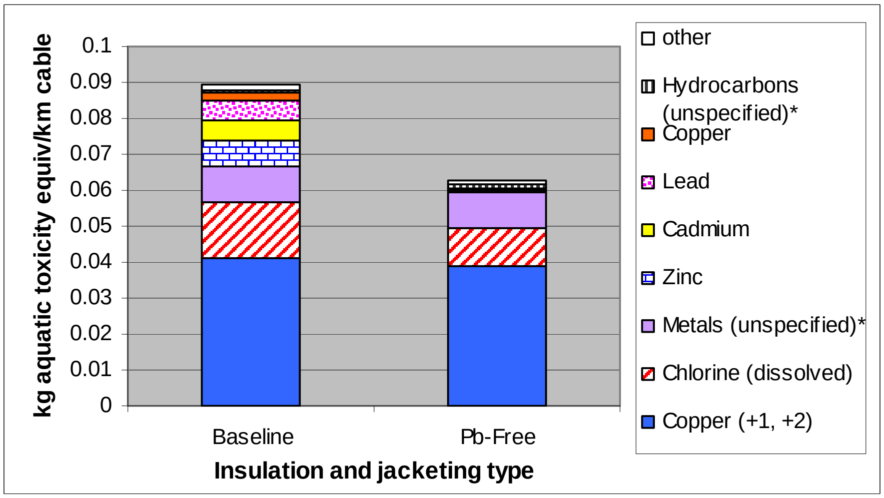

Figure 3-127. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – NM-B Partial life cycle
* Material flow has been given a default hazard value due to lack of toxicological data

#### 3.2.12.5 Limitations and uncertainties

The LCIA methodology for potential aquatic ecotoxicity impacts is subject to the same structural or modeling limitations and toxicity data limitations discussed previously for the occupational and public health impact categories. For a detailed discussion, refer to the *Structural or modeling limitations and uncertainties* subsection of Section 3.2.10.5. One important distinction is that more toxicity data tend to be available for aquatic effects than for human carcinogenic effects. Specifically, toxicity data were available for lead outputs, which drive the aquatic ecotoxicity differences between CMR and CMP alternatives. For NM-B, the top contributing flows differed from the CMR/CMP results; however, ecotoxicity data were also available for those chemicals.

The LCI data limitations also are similar to those described in preceding sections. For the CMR and CMP results, the baseline results were driven by landfilling (e.g., lead leaching from the landfill), followed primarily by incineration and then electricity production (for manufacturing processes). The impacts from the lead-free alternative, however, were driven by the electricity production. There is uncertainty in the leachate estimate used in the analysis, and this estimate was varied in the multivariate uncertainty analysis (Section 3.4). As the uncertainty analysis revealed, a significant difference between the alternatives is likely, even given the defined range of uncertainty (see Section 3.4). Since the landfill leachate data were an important aspect of the public toxicity impacts, further refinement of the potential exposure, through more sophisticated exposure analysis and fate and transport analysis are warranted.

The NM-B analysis, which did not include EOL modeling was driven by phthalate plasticizer production, which used secondary data. Based on the LCIA methodology and the LCI data, the aquatic ecotoxicity category is given an overall relative data quality rating of “medium” for all cable types.

## 3.3 Summary of Life-Cycle Impact Analysis Characterization

This section presents an overview of the characterization methods and the life-cycle impact results for the different cable types. Section 3.3.1 provides the equations for each impact category that are used to calculate impact scores; Section 3.3.2 describes the LCIA data sources and data quality; and Section 3.3.3 provides the limitations and uncertainties associated with the LCIA methodology.

The WCP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (scoring and possibly ranking of indicators across categories), or weighting (converting indicator results based on importance and possibly aggregating them across impact categories). Grouping and weighting, in particular, are subjective steps that depend on the values of different individuals, organizations, or societies performing the analysis. Since the WCP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the WCP LCIA methodology. Normalization also was intentionally not included as there are not universally accepted normalization reference values for all the impact categories included in this study. Furthermore, one of the primary purposes of this research is to identify the relative differences in the potential impacts among cable alternatives, and normalization within impact categories would not affect the relative differences among alternatives within the impact categories.

### 3.3.1 Impact Score Equations

Table 3-112 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations is a loading estimate. For a more detailed discussion of loading estimates, refer to Section 3.1.2.

**Table 3-112**

**Summary of natural resources impact scoring**

| Impact category | Impact score approach | Data required from inventory (per functional unit) | |
|---|---|---|---|
| | | Inputs | Outputs |
| Use/depletion of non-renewable resources | $IS_{NRR} = Amt_{NRR} \times (1 - RC)$ | Material mass (kg) | None |
| Energy use, general energy consumption | $IS_E = Amt_E$ or $(Amt_F \times H/D)$ | Energy (MJ) (electricity, fuel) | None |
| Landfill space use | $IS_L = Amt_W / D$ | None | Mass of waste (hazardous and solid waste combined) (kg) and density (e.g., volume, $m^3$) |

Abbreviations: RC=recycled content; H=heat value of fuel *i*; D=density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-113 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

**Table 3-113**

**Summary of atmospheric resource impact scoring**

| Impact category | Impact score approach | Data required from inventory (per functional unit) | |
|---|---|---|---|
| | | Inputs | Outputs |
| Global warming | $IS_{GW} = EF_{GWP} \times Amt_{GG}$ | None | Amount of each greenhouse gas chemical released to air |
| Stratospheric ozone depletion | $IS_{OD} = EF_{ODP} \times Amt_{ODC}$ | None | Amount of each ozone depleting chemical released to air |
| Photochemical smog | $IS_{POCP} = EF_{POCP} \times Amt_{POC}$ | None | Amount of each smog-creating chemical released to air |
| Acidification | $IS_{AP} = EF_{AP} \times Amt_{AC}$ | None | Amount of each acidification chemical released to air |
| Air quality (particulate matter) | $IS_{PM} = Amt_{PM}$ | None | Amount of particulates: $PM_{10}$ or TSP released to air [a] |

[a] Assumes $PM_{10}$ and TSP are equal; however, using TSP will overestimate $PM_{10}$.

Table 3-114 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

**Table 3-114**

**Summary of water resource impact scoring**

| Impact category | Impact score approach | Data required from inventory (per functional unit) | |
|---|---|---|---|
| | | Inputs | Outputs |
| Water eutrophication | $IS_{EUTR} = EF_{EP} \times Amt_{EC}$ | None | Amount of each eutrophication chemical released to water |

Table 3-115 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization. For a more detailed discussion of characterization methods, refer to Section 3.1.2.

**Table 3-115**

**Summary of human health and ecotoxicity impact scoring**

| Impact category | Impact score equations | Data required from inventory (per functional unit) | | Chemical properties data required |
|---|---|---|---|---|
| | | Inputs | Outputs | |
| Chronic human health effectsC occupational, cancer | $IS_{CHO\text{-}CA} = HV_{CA} \times Amt_{TCinput}$ | Mass of each primary and ancillary toxic chemical | None | WOE or SF |
| Chronic human health effectsC occupational, noncancer | $IS_{CHO\text{-}NC} = HV_{NC} \times Amt_{TCinput}$ | Mass of each primary and ancillary toxic chemical | None | Mammal NOAEL or LOAEL |
| Chronic human health effectsC public, cancer | $IS_{CHP\text{-}CA} = HV_{CA} \times Amt_{TCoutput}$ | None | Mass of each toxic chemical released to air and surface water | WOE or SF |
| Chronic human health effectsC public, noncancer | $IS_{CHP\text{-}NC} = HV_{NC} \times Amt_{TCoutput}$ | None | Mass of each toxic chemical released to air and surface water | Mammal NOAEL or LOAEL |
| Aquatic ecotoxicity | $IS_{AQ} = (HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}$ | None | Mass of each toxic chemical released to surface water | Fish $LC_{50}$ and/or fish NOEL |

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., $CO_2$ releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a functional unit of a cable).

### 3.3.2 LCIA Data Sources and Data Quality

Data that are used to calculate impacts come from: (1) equivalency factors or other parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values presented in this methodology include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, fish $LC_{50}$, and fish NOEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, and EP (see Appendix D). The other parameters may exist for a large number of chemicals, and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., Health Effects Assessment Summary Tables [HEAST], Integrated Risk Information System [IRIS], Hazardous Substances Data Bank [HSDB]), next other databases (e.g., Registry of Toxic Effects of Chemical Substances [RTECS]), then other studies or literature, and finally estimation methods (e.g., structure-activity relationships [SARs] or quantitative structure-activity relationships [QSARs]). More details are provided in Appendix E.

The sources of each parameter presented in this report and the basis for their values are presented in Table 3-116. Data quality is affected by the data source itself, the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.2, LCIA Results.

**Table 3-116**

**Data sources for equivalency factors and hazard values**

| Parameter | Basis of parameter values | Source |
|---|---|---|
| Global warming potential | Atmospheric lifetimes and radiative forcing compared to $CO_2$ | IPCC, 2001 (see Appendix D) |
| Ozone depletion potential | The change in the ozone column in the equilibrium state of a substance compared to CFC-11 | UNEP, 2003; WMO 1999 (see Appendix D) |
| Photochemical oxidant creation potential | Simulated trajectories of ozone production with and without VOCs present compared to ethene | Heijungs *et al.*, 1992;<br>EI, 1999 (see Appendix D) |
| Acidification potential | Number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to $SO_2$ | Heijungs *et al.*, 1992;<br>Hauschild and Wenzel, 1997 (see Appendix D) |
| Nutrient enrichment/eutrophication potential | Ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate ($PO_4^{3-}$) | Heijungs *et al.*, 1992;<br>Lindfors *et al.*, 1995 (see Appendix D) |
| Weight-of-evidence | Classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data | EPA, 1999; IARC, 1998 (see Appendix E) |
| Slope factor | Measure of an individual=s excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data | IRIS and HEAST as cited in RAIS online database (see Appendix E) |
| Mammalian: LOAEL/NOAEL | Mammalian (primarily rodent) toxicity studies | IRIS, HEAST and various literature sources (see Appendix E) |

**Table 3-116**

**Data sources for equivalency factors and hazard values**

| Parameter | Basis of parameter values | Source |
|---|---|---|
| Fish lethal concentration to 50 percent of the exposed population ($LC_{50}$) | Fish (primarily fathead minnow) toxicity studies | Various literature sources and Ecotox database (see Appendix E) |
| Fish NOEL | Fish (primarily fathead minnow) toxicity studies | Literature sources and Ecotox database (see Appendix E) |

IRIS = Integrated Risk Information System; HEAST = Health Effects Assessment Summary Tables; RAIS = Risk Assessment Information System.

### 3.3.3 General LCIA methodology limitations and uncertainties

This section summarizes some of the limitations and uncertainties in the LCIA methodology in general. Specific limitations and uncertainties in each impact category are discussed in Sections 3.2.2 through 3.2.12 with the LCIA results for the WCP.

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.

In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA also is limited by the availability and quality of the inventory data. Data collection can be time-consuming and expensive, and confidentiality issues may inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-112 through 3-115. 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.

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. Uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, thus introducing uncertainty. 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 potentially toxic materials in the inventory.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires 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;
- measurement uncertainty;

- estimation uncertainty;
- allocation uncertainty/working with aggregated data; and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is assured that some missing data still exist. The remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

## 3.4 Uncertainty and Sensitivity Analyses

As was stated in Section 3.3.3, uncertainty is inherent in all of the parameters involved in the calculation of product life-cycle impacts. Uncertainty and sensitivity analysis were both used to examine the effect that parameter uncertainty had on the impact category results. Uncertainty analysis addressed the magnitude of the sum of parameter uncertainty, and sensitivity analysis was used to address each parameter's contribution to the overall uncertainty. Uncertainty and sensitivity analysis were performed on the CMR and CMP full life-cycle comparisons, and not on the CMR three-way (baseline/lead-free/halogen-free) and NM-B cradle-to-gate comparisons.

### 3.4.1 Uncertainty Analysis

#### 3.4.1.1 Methodology

Monte Carlo statistical methods were used to examine the contribution of uncertainty in various life-cycle processes to each impact category result. Monte Carlo methods describe the generation of a distribution of model results based on the specification of one or more distributions to represent model parameters. As values are iteratively chosen from uncertain model parameters, a distribution of outcomes is created that represents the effect of this uncertainty. A built-in Monte Carlo function found in the GaBi4 software package (PE & IKP, 2003), which provides two built-in distributions, Gaussian and uniform, was used to generate probabilistic impact results.

Four parameters within the life-cycle processes were chosen as highly uncertain and given uniform distributions representing the degree of uncertainty surrounding them. The majority of the parameters selected as highly uncertain came from end-of-life processes. Uniform distributions were chosen to represent these parameters as they allow parameters to assume extreme bounds without presuming any more knowledge about the actual parameter distribution. Choosing a Gaussian distribution to represent the parameter uncertainty would have expressed the highest confidence in values surrounding the mean, something justifiable only in the presence of a larger number of parameter data points.

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 in the case of CMP and CMR). A number of factors complicate this picture. Communication cables are contained behind fire resistant walls and are protected by sprinkler systems. They are formulated using effective flame retardants. Finally, out of all of the fires reported in the U.S., it is likely that a high proportion are minor and do not cause extensive damage to the whole structure. Thus, the extreme values stated above do not reflect an accurate bounding of the likely value of the percentage of cable consumed in fire. The bounding values chosen were 0 percent and 20 percent of the cable contained in buildings that have fires being burned. These values were chosen as somewhat arbitrary reductions of the natural extreme bounds in response to the recognition that fire protection methods would skew actual burn percentages toward the lower end.

The percentage of cable resins going to recycling was another source of substantial uncertainty in the end-of-life. As noted previously, a report for the European Commission stated that 20 percent of thermoplastics going to recycling was a justifiable high-end estimate. Using this European estimate as a surrogate for U.S.-specific data, 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). As there was no other information to narrow the uncertainty bounds, the natural extreme bounds were used to model parameter uncertainty.

The final uncertainty distribution represented a data discrepancy for extruding energy data for the CMR and CMP cables. Inconsistent and highly divergent energy values used in the cable extrusion process led to high uncertainty for the extruding data. Large inter-company variation in extrusion energy combined with small numbers of data sets for each cable type resulted in a need to create proxy values for the energy of extrusion of the CMR and CMP baseline cable types, which both had only one contributing data point. Thus, the range of the data sets collected as primary data, or, in cases where there was only one data point, the range spanning the data point and the proxy data point, was used to set the bounds of the uncertainty analysis, given that none of the data could be identified as anomalous. 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 parameters described above were varied simultaneously, to observe the distribution of the LCIA indicator results given the ranges of uncertainties in all four parameters. The parameters varied were only applicable to the CMR and CMP full life-cycle analyses. Five thousand simulations were run (i.e., five thousand combinations of uncertain parameter values were chosen) to generate a distribution of the LCIA indicator results represented as the mean and various percentile ranges around the mean.

#### 3.4.1.2 Uncertainty Analysis Results

Tables 3-117 through 3-120 present the uncertainty analysis results for the CMR and CMP lead and lead-free cable alternative analyses. Results are presented as means and 10th/90th percentiles of the impact distribution (i.e., the values below which 10 percent and 90 percent of the Monte Carlo iterative results fell). These results give a sense of the magnitude of uncertainty in the impact categories resulting from model parameter uncertainty. The majority of the impact categories' 10th and 90th percentile ranges overlap for both the CMP and CMR lead versus lead-free comparisons, revealing few major differences between the alternatives. An example of this can be seen in the non-renewable resources impact category from the CMR comparison. The baseline cable 10th-90th percentile range is 98.6-185 kg of non-renewable resources used/km of cable, which overlaps the lead-free range of 87.1-155 kg of non-renewable resources used/km of cable. The overlap implies that, given the lack of precision in the uncertain parameters, it cannot definitively be stated that the lead-free cable alternative uses less non-renewable resources. Chapter 4 summarizes these results in terms of the overall LCA results.

**Table 3-117**

**CMR Baseline LCIA Uncertainty Analysis Results**

| LCIA Results | Units per km Cable | Mean | 10th Percentile | 90th Percentile |
|---|---|---|---|---|
| NRR | kg | 141 | 98.6 | 185 |
| Energy | MJ | 2410 | 2020 | 2820 |
| Landfill space | $m^3$ | 0.0166 | 0.0163 | 0.0168 |
| Global warming | kg $CO_2$-equiv. | 90.1 | 69.3 | 111 |
| Ozone depletion | kg CFC 11-equiv. | 5.89E-06 | 3.55E-06 | 8.26E-06 |
| Smog | kg ethene-equiv. | 0.125 | 0.117 | 0.133 |
| Acidification | kg $SO_2$-equiv. | 0.730 | 0.563 | 0.899 |
| Air particulates | kg | 0.0781 | 0.0682 | 0.0881 |
| Eutrophication | kg phosphate-equiv. | 0.00899 | 0.00564 | 0.0124 |
| Pot. occ. non-ca | kg cancertox-equiv. | 71.8 | 70.8 | 72.8 |
| Pot. occ. cancer | kg noncancertox-equiv. | 3.53 | 3.52 | 3.54 |
| Pot. public non-ca | kg noncancertox-equiv. | 1470 | 770 | 2170 |
| Pot. public cancer | kg cancertox-equiv. | 0.832 | 0.741 | 0.923 |
| Pot. Aq. ecotox | kg aqtox-equiv. | 17.7 | 6.44 | 28.7 |

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

**Table 3-118**

**CMR Lead-free LCIA Uncertainty Analysis Results**

| LCIA Results | Units per km Cable | Mean | 10th Percentile | 90th Percentile |
|---|---|---|---|---|
| NRR | kg | 121 | 87.1 | 155 |
| Energy | MJ | 2360 | 2050 | 2680 |
| Landfill space | $m^3$ | 0.0181 | 0.0179 | 0.0183 |
| Global warming | kg $CO_2$-equiv. | 83.7 | 67.3 | 100 |
| Ozone depletion | kg CFC 11-equiv. | 4.98E-06 | 3.11E-06 | 6.81E-06 |
| Smog | kg ethene-equiv. | 0.134 | 0.127 | 0.140 |
| Acidification | kg $SO_2$-equiv. | 0.680 | 0.547 | 0.810 |
| Air particulates | kg | 0.0816 | 0.0737 | 0.0893 |
| Eutrophication | kg phosphate-equiv. | 0.00760 | 0.00492 | 0.0102 |
| Pot. occ. non-ca | kg cancertox-equiv. | 77.6 | 76.9 | 78.4 |
| Pot. occ. cancer | kg noncancertox-equiv. | 3.69 | 3.69 | 3.70 |
| Pot. public non-ca | kg noncancertox-equiv. | 280 | 216 | 343 |
| Pot. public cancer | kg cancertox-equiv. | 0.836 | 0.765 | 0.908 |
| Pot. aq. ecotox | kg aqtox-equiv. | 0.113 | 0.0786 | 0.148 |

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

The results from the uncertainty analysis for the CMR baseline and lead-free cable alternatives display substantial variability in a number of the impact categories. For the leaded cable results, the categories with high variability were non-renewable resource use, potential public chronic non-cancer toxicity, potential 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 (not reported in Tables 3-117 and 3-118). For the lead-free cables, the results also show substantial variability in a number of impacts: non-renewable resources, potential aquatic ecotoxicity, ozone depletion potential, and eutrophication potential, whose standard deviations were 20 percent, 22 percent, 27 percent, and 25 percent of their means, respectively.

**Table 3-119**

**CMP Baseline LCIA Uncertainty Analysis Results**

| LCIA Results | Units per km Cable | Mean | 10th Percentile | 90th Percentile |
|---|---|---|---|---|
| NRR | kg | 237 | 200 | 273 |
| Energy | MJ | 3940 | 3600 | 4280 |
| Landfill space | $m^3$ | 0.0132 | 0.0124 | 0.0140 |
| Global warming | kg $CO_2$-equiv. | 181 | 163 | 198 |
| Ozone depletion | kg CFC 11-equiv. | 1.16E-03 | 1.16E-03 | 1.16E-03 |
| Smog | kg ethene-equiv. | 0.0885 | 0.0814 | 0.0956 |
| Acidification | kg $SO_2$-equiv. | 0.877 | 0.732 | 1.02 |
| Air particulates | kg | 0.0746 | 0.0660 | 0.0830 |
| Eutrophication | kg phosphate-equiv. | 0.0125 | 0.00961 | 0.0154 |
| Pot. occ. non-ca | kg cancertox-equiv. | 49.2 | 48.3 | 50.0 |
| Pot. occ. cancer | kg noncancertox-equiv. | 2.16 | 2.15 | 2.17 |
| Pot. public non-ca | kg noncancertox-equiv. | 951 | 606 | 1300 |
| Pot. public cancer | kg cancertox-equiv. | 0.736 | 0.658 | 0.813 |
| Pot. aq. ecotox | kg aqtox-equiv. | 8.63 | 3.22 | 14.1 |

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

**Table 3-120**

**CMP Lead-free LCIA Uncertainty Analysis Results**

| LCIA Results | Units per km Cable | Mean | 10th Percentile | 90th Percentile |
|---|---|---|---|---|
| NRR | Kg | 219 | 187 | 252 |
| Energy | MJ | 3740 | 3440 | 4050 |
| Landfill space | $m^3$ | 0.0144 | 0.0137 | 0.0150 |
| Global warming | kg $CO_2$-equiv. | 171 | 155 | 187 |
| Ozone depletion | kg CFC 11-equiv. | 0.00110 | 0.00110 | 0.00111 |
| Smog | kg ethene-equiv. | 0.0869 | 0.0807 | 0.0932 |
| Acidification | kg $SO_2$-equiv. | 0.819 | 0.693 | 0.947 |
| Air particulates | Kg | 0.0726 | 0.0651 | 0.0802 |
| Eutrophication | kg phosphate-equiv. | 0.0114 | 0.00890 | 0.0140 |
| Pot. occ. non-ca | kg cancertox-equiv. | 46.8 | 46.0 | 47.5 |
| Pot. occ. cancer | kg noncancertox-equiv. | 2.22 | 2.21 | 2.23 |
| Pot. public non-ca | kg noncancertox-equiv. | 358 | 297 | 420 |
| Pot. public cancer | kg cancertox-equiv. | 0.702 | 0.633 | 0.771 |
| Pot. aq. ecotox | kg aqtox-equiv. | 0.151 | 0.118 | 0.185 |

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

The CMP baseline and lead-free cable alternatives display less relative variability (measured as standard deviation normalized by the mean) than those of the CMR cable alternatives overall. However, the potential public chronic non-cancer toxicity and potential aquatic ecotoxicity indicators still display substantial variability in the baseline case (standard deviations are 27 percent and 47 percent of their means, respectively; not shown in Tables 3-119 and 3-120). The lead-free cable results show substantially less relative variability than those of the baseline cable, with no impact indicators' standard deviations exceeding 20 percent of their mean.

### 3.4.2 Sensitivity Analysis

The variance of results from the Monte Carlo analysis emanated from the concurrent variation of 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 software was used to determine the amount of variance in each impact category attributable to each of the dynamic parameters.

The sensitivity analysis was used to probe the contributions to overall impact uncertainty from each of the stochastic parameters. Results of the analysis, shown in Table 3-121, give the largest contributing parameter along with the percent variance in the impact result attributable to this dominant parameter.

It is evident from Table 3-121 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 public chronic non-cancer toxicity and the aquatic ecotoxicity categories are dominated by the landfill leachate parameter, and for all cables, thermoplastic recycling dominates the landfill space use indicators.

**Table 3-121**

**LCIA Sensitivity Analysis Results [a,b]**

| Impact Category | CMR | | CMP | |
|---|---|---|---|---|
| | Baseline | Lead-free | Baseline | Lead-free |
| NRR | 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-ca | E (97) | E (96) | E (96) | E (95) |
| Pot. occ. cancer | E (98) | E (97) | E (97) | E (97) |
| Pot. public non-ca | L (83) | E (98) | L (78) | E (97) |
| Pot. public cancer | 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] TR = Percentage of cable going to thermoplastics recycling; L = percentage of lead lost from landfill; E = Variance of extrusion energy; NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity

[c] Actual percentage withheld to protect confidentiality.

# CHAPTER 4 SUMMARY OF RESULTS

Life-cycle impact indicators were calculated for 14 impact categories to compare leaded and lead-free cable resin constructions for Category 6 CMR, 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 model parameters that possessed a large degree of uncertainty, a Monte Carlo-based uncertainty analysis was conducted to identify the likelihood that observed differences are real. For NM-B cables, extrusion data were not obtained and therefore, only a cradle-to-gate analysis (materials extraction to resin compounding) was conducted. Similarly, complete extrusion data were not obtained for the CMR zero-halogen alternative. Therefore, to conduct a comparable analysis, only the compounding process and the production of fuels and electricity needed to power the compounding process were included in the 3-way CMR analysis of leaded, lead-free, and zero-halogen cables.

Within this chapter, CMR, CMP, and NM-B results are presented in Sections 4.1, 4.2 and 4.3, respectively. Summary tables in each section list the total impact indicators for each impact category for the baseline and alternative cables, followed by the percent change for each category. The differences in the indicator scores within an impact category simply represent relative differences between the alternatives. The scores are not normalized to determine if they present a significant environmental impact. The scores for one category have no bearing on scores for another, which is evidenced by the differing units used in each category. Further, the percent change in one category is independent of the percent change in another category, and any difference does not indicate that one category is of greater or lesser concern than another category.

The summary results tables also provide relative quality ratings for each impact category. These are based on the quality of data used to quantify the LCI and LCIA, and the models used for each LCIA methodology. The basis for these ratings, as well as overall limitations and uncertainties are described in Chapter 5 (Section 5.3). Finally, the summary results tables in Section 4.1 and 4.2 indicate which impact categories have likely significant differences between the lead and lead-free alternative. These are only relevant to the CMR and CMP full life-cycle comparisons for which uncertainty analyses were conducted.

Additional summary tables are also presented in the following sections (4.1, 4.2, and 4.3), which indicate the process and individual flow responsible for the greatest percent of the total impact indicator. This information is provided to assist in identifying potential improvement opportunities, and should be used in conjunction with the information given in Section 5.2 (“Opportunities for Improvement”).

## 4.1 CMR Results Summary

The full life-cycle comparative analysis of leaded (baseline) and lead-free cables are summarized in Table 4-1. The point estimate results from the CMR impact assessment showed mixed results for both leaded and lead-free cable types, though the disparities for most impact categories were minimal. In eight impact categories, the lead-free cable construction had less environmental impacts; however, six of those categories generated inconclusive results due to the large uncertainty (i.e., the 10th and 90th percentiles of the two alternatives overlap, which eliminates the possibility of statistically significant differences). The remaining two categories that had less environmental burden and that were significantly different (at 80 percent confidence) were potential public chronic non-cancer toxicity and potential aquatic ecotoxicity. Both categories had a medium data quality rating.

**Table 4-1**

**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 alternatives were significantly different at 80% 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.

Of the six categories that showed lower burden for the leaded cable, three displayed potential statistical significance (i.e., did not have overlapping 10th and 90th percentile results due to model parameter uncertainty): landfill space use, potential occupational non-cancer toxicity, and potential occupational cancer toxicity. Potential occupational non-cancer and landfill space use were assigned a medium quality rating, while potential occupational cancer toxicity was assigned a medium-low quality rating due to the scarcity of quantitative toxicity data (i.e., cancer slope factors).

The sensitivity analysis results (Section 3.4.2) revealed that the large uncertainty ranges were mostly attributable to the uncertainty in the energy needed for cable extrusion. For the leaded cable, this was the case for all categories except potential public non-cancer toxicity and potential aquatic ecotoxicity, where leachate uncertainty dominated, and landfill space use, where the percent of resins recycled after chopping had more effect on the results. For the lead-free cable, the uncertainty in all impact result categories was driven by extrusion energy, except for the landfill space use, which was most sensitive to the percent of resins recycled after chopping. These results indicate that the highly uncertain EOL parameters (e.g., percent of cables burned in a fire) did not greatly affect most of the overall comparative life-cycle CMR results.

As shown in Table 4-2, the top contributing process for several impact categories 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).

**Table 4-2**

**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] Flows given default toxicity hazard values due to lack of toxicological data

The 3-way CMR analysis (leaded versus lead-free versus zero-halogen) showed that for the cradle-to-gate analysis, the zero-halogen alternative required greater energy. This was a function of more energy required per mass of compounded resin produced, as well as the halogen-free 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 does not provide full life-cycle information and should not be construed to represent a full life-cycle analysis.

These results also demonstrate that only looking at one manufacturing process, even on a functionally equivalent basis, does not adequately estimate impacts over the full life cycle. This is evidenced by comparing the full 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 impacts 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.

## 4.2 CMP Results Summary

The full life-cycle comparative analysis of leaded (baseline) and lead-free cables are summarized in Table 4-3. The point estimates from the CMP cable comparisons showed all categories except for landfill space use 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: ozone depletion, potential occupational non-cancer toxicity, potential occupational cancer toxicity, potential public chronic non-cancer toxicity, and potential aquatic ecotoxicity, suggesting greater confidence in these results.

The sensitivity analysis results (Section 3.4.2) revealed that, as was the case with the CMR cable alternatives, the large uncertainty ranges were mostly attributable to the uncertainty in the extrusion energy. For the leaded cable, this was the case for all categories except potential public non-cancer toxicity and potential aquatic ecotoxicity, where leachate uncertainty dominated, and landfill space use, where the percent of resins recycled after chopping had more effect on the results. For the lead-free cable, the uncertainty in all impact result categories was driven by extrusion energy, except for the landfill space use, which was most sensitive to the percent of resins recycled after chopping. These results indicate that the highly uncertain EOL parameters (e.g., percent of cables burned in a fire) did not greatly affect most of the overall comparative life-cycle CMP results.

**Table 4-3**

**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% 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.

Table 4-4 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 landfill space use impact category was also dominated by the municipal solid waste landfilling process. 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).

**Table 4-4**

**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] Flows 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.

## 4.4 NM-B Results Summary

The NM-B results are based on cradle-to-gate data and therefore life-cycle conclusions cannot be made. The processes modeled are presented in Chapter 2 (Section 2.5.3). For the NM-B cradle-to-gate results, all categories had reduced environmental burdens for lead-free cables compared to the baseline, except potential occupational non-cancer toxicity. Since CMR and CMP full life-cycle analyses showed little impact from EOL (except landfill space use, potential public non-cancer toxicity, and potential aquatic ecotoxicity), those relevant impact categories may also not appreciably change if the entire life cycle were considered. However, impact categories with more impact from EOL processes are more likely to have differing outcomes than determined by the cradle-to-gate analysis. Therefore, landfill space use, potential public non-cancer toxicity, and potential aquatic ecotoxicity are given a lower quality rating for the NM-B partial life-cycle analysis. No uncertainty or sensitivity analyses were run for this comparison as cable extrusion, use, and end-of-life processes were excluded from the analysis.

**Table 4-5**

**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; equiv. = equivalents.

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 4-6). 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 4-6**

**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] Flows given default toxicity hazard values due to lack of toxicological data

# CHAPTER 5 CONCLUSIONS

The general conclusions (Section 5.1) of this chapter have been divided into three sub-sections: upstream materials and their production processes; energy sources; and end-of-life disposition. Section 5.2 details the opportunities for improvement, and is divided in the same manner in order to maximize the efficiency of use by interested parties in the wire and cable industry. Section 5.3 details the limitations and uncertainties of the LCIA results. Finally, Section 5.4 lists potential areas for future research, both to enhance future LCIs and LCIAs, and to conduct more exhaustive and targeted investigations into material flows, processes, or impacts of concern.

## 5.1 General Conclusions

Across all cable types examined in this study, the lead-free cable formulations had lower environmental impacts for the majority of impact categories. In the CMR cable alternatives, the lead-free formulation had lower mean impacts in 8 out of 14 impact categories. In the CMP cable alternatives, the difference was even more substantial, as the lead-free formulation showed lower average environmental burden in 12 of the 14 impact categories. The results from the NM-B cable were similar, with the lead-free formulation showing less environmental burden in all categories except for potential occupational non-cancer toxicity. However, results for CMR and CMP cable were complicated by parameter uncertainty. After factoring in parameter uncertainty, CMR lead-free cable only showed significantly reduced burden in 2 impact categories instead of 8, and baseline CMR cable showed significantly reduced burden in 3 impact categories instead of 6. Similarly, CMP lead-free cable only showed significantly reduced burden in 3 impact categories instead of 12 after factoring in parameter uncertainty; and significantly increased burden in one category. Thus, for most impacts, overall disparities between cable alternatives after the factoring in of parameter uncertainty were small to minimal.

The uncertainty analysis shows that several impact categories are sensitive to the variation of model parameters described earlier. 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 can not 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.

### 5.1.1 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 burdens are, in order of decreasing impact, lead heat stabilizers, jacketing and insulation resins, phthalate plasticizers, and filler materials (e.g., calcined clay and limestone). The various burdens due to material choices and production processes are detailed below.

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 resulted in 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. 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 and 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 in Section 5.1.3 (“EOL”).

The production and use of a number of other upstream materials results in substantial environmental burden. Resins used in jacketing and insulation make up not only in a large proportion of the cable mass but also use a large proportion of the energy input. When combined, the energy inputs for jacketing and insulation resin production are approximately equivalent to the energy inputs required for all grid electricity generation (the top contributor to energy use) for both CMR and CMP cables.

Insulation and especially jacketing resin production processes also represent many of the top contributors for potential public cancer toxicity for CMR, CMP, and NM-B alternatives. The toxicological burden is primarily a result of NOx and unspecified VOC air emissions during resin production, with a small contribution from particulate matter. Though these compounds have all been given default cancer hazard values, the potential for human health impacts warrants further inspection. NOx emissions from resin production also contribute considerably to the air acidification impact category, and particulate matter emissions contribute to air particulate production.

There are a number of hazardous chemicals that appear in the cable jacketing and supply chain during the production of CMP cable. Natural gas is the top contributor to the potential occupational non-cancer toxicity impact category. It is not clear if there is any potential for worker exposure during their upstream process use; however, as this is a screening-level assessment, their use may warrant further inspection. Due to the fact that the other major resin used in the production of CMP cable (PVC) was modeled as starting with mined inputs (low-toxicity precursors) rather than industrial precursor chemicals, we removed the industrial precursor chemicals from the insulation resin production to produce a more consistent occupational toxicity comparison across resin types. This does not, however, obviate the fact that industrial precursor chemicals are present during the manufacture of both resin types, and that possible additional occupational toxicity impacts contributed by these precursor chemicals are not included in these results. The potential occupational non-cancer toxicity for the CMR and NM-B cable alternatives is dominated by fire retardant #2, a proprietary chemical to which a default non-cancer hazard value was applied. Though the toxicity of this chemical has not been unequivocally confirmed, the degree to which it dominates other contributors to this impact category may indicate the usefulness of further inquiry.

Another interesting finding was that within the CMR cable alternatives, the lead-free cable has more potential occupational non-cancer toxicity burden than the baseline cable, while within the CMP cable alternatives the opposite is true. This is due, in the case of CMR cable, to the use of more compounded jacketing in the lead-free cable; and, in the case of CMP cable, to the use of less insulation resin.  These material use differences had no uncertainty applied to them, as it was unclear how to implement this in the life-cycle model, while reflecting the current wire and cable market.  It is possible, however, that the significant findings are an artifact of the small primary/secondary data sample size and/or asymmetric upstream data.

In all cable types, carbon dioxide was found to be the biggest contributor to global warming; however, other emissions were determined to contribute substantially to this impact, as well.  In the CMP cable alternatives, HCFCs produced primarily during insulation and jacketing resin production were found to be a sizeable contributor (>40 percent) to the overall burden.  These compounds are also implicated as top contributors to photochemical smog formation.

Within the jacketing compounding processes of both the baseline and lead-free CMR cable alternatives, phthalate plasticizers constitute a sizeable material input.  Phthalates also represent greater than 60 percent of the potential occupational cancer toxicity impact for the overall life cycle.  As is the case with most of the top contributors to the cancer toxicity impact categories, this material received a default cancer toxicity hazard value.  Like fire retardant #2, the toxicity of this suite of chemicals has not been unequivocally confirmed, though the degree to which it dominates this impact category potentially warrants further inquiry into issues of chronic toxicity in workers.

### 5.1.2 Energy Sources

Energy sources throughout the wire and cable life cycle, particularly the generation of electricity 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.  Other energy sources such as natural gas showed up as top contributing flows in two CMR impact categories, but played a far more minor role in overall environmental burden than that of electricity generation.

The sensitivity analysis results (Table 3-121) revealed that the large impact uncertainty ranges in 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 compelling reminder that the sample size of the primary/secondary datasets used, and the product or material market share represented by these datasets are important in determining the accuracy of the life-cycle modeling effort.

### 5.1.3 EOL

This study demonstrated that the EOL stage generates the most sizeable impact differences between baseline leaded cable and lead-free cable. For both the CMR and CMP cable types, the difference between the two cables was most pronounced in the potential public chronic non-cancer (CMR: 1,459 versus 279; CMP: 952 versus 358 kg noncancertox-equivalent) and potential aquatic ecotoxicity impacts (CMR: 17 versus 0.11; CMP: 8.6 versus 0.15 kg aqtox-equivalent), with the lead-free cables displaying much lower impacts in these categories. The other factors affecting these impacts, most of which were present in both cable alternatives, were dwarfed by the contribution of lead from the end-of-life disposition of baseline cable to landfilling and incineration. The sensitivity analysis showed that the lead leachability assumptions are responsible for the majority of the uncertainty in these impact results. However, even with the parameter representing the proportion of lead leachate escaping the landfill subject to a high degree of uncertainty, the cable alternative impact differences were significant.

Cable incineration is another major contributor to the potential public non-cancer toxicity and potential aquatic ecotoxicity impact categories, due to both landfilled lead-containing byproducts and lead air emissions. The contribution of landfilled lead-containing waste to both toxicity categories is highly uncertain, as has been mentioned throughout this report. The contributions from lead air emissions, on the other hand, are less uncertain, and human exposure through inhalation or other pathways is clearly possible.

In all cable types, carbon dioxide was found to be the biggest contributor to global warming; however, other emissions were determined to contribute substantially to this impact, as well. In the CMR cable alternatives, methane produced primarily in the landfill was found to be a sizeable contributor (~10 percent) to the overall burden. The production of methane during landfilling functions as a reminder that sequestration of waste can have unintended adverse environmental consequences.

The top contributing material flow to landfill space use was found to be PVC waste. Over long periods of time, or under more extreme environmental conditions, the degradation of PVC waste might result in emissions of deleterious compounds. This is a reminder that the results of the study should be understood in the context of geographic, temporal, and material boundaries. Another finding related to the landfilling of cable scrap was that the thermoplastics recycling process modeled in this study produced a substantial amount of landfilled waste (second largest contributor to landfill space use in both CMR and CMP cable alternatives).

## 5.2 Opportunities for Improvement

Conclusions about opportunities for improvement throughout the wire and cable life cycle should be understood solely within the context of the study boundaries. A prime example of this is the role of copper conductor in the cable and its associated environmental burden. Copper was excluded from this study in order to focus on materials and processes where the cables might be substantially different. This being the case, it is important to keep in mind that copper represents a large part of the cable mass and, had it been included, copper and the processes associated with its production and drawing would likely be counted among the top contributing processes and flows for a number of impact categories if only one cable were being evaluated in isolation (Krieger *et al.*, 2007).

One general opportunity for improvement relates to the gathering of data from different life-cycle stages. The EOL disposition is difficult to model, given the scarcity of data and the rapidly fluctuating markets for recycled materials. The feasibility of new recycling technologies, along with market incentives such as the growth of secondary Asian markets, is changing the economics of wire and cable scrap. Interestingly, the EOL disposition seems to drive far fewer impacts than processes on the upstream side (e.g., electricity generation and resin production). This is probably due to the high combustion efficiency of incinerators, the sequestration of hazardous waste byproducts in landfills, and the fairly low rate of energy-intensive polymer recycling. This suggests that refining the upstream data, which could be available via company participation, might be more valuable than refining EOL scenarios, where data are currently difficult to obtain.

### 5.2.1 Materials

The 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 cable. This is the most substantive difference between the baseline and lead-free cable with regards to any of the impact categories. The results are highly uncertain and dependent on parameters which have not been well studied, such as the proportion of lead that leaches out of landfilled resins and landfill failure rates, but the potential for human and ecological risk is not negligible. It is important to attempt understand the potential hazards inherent in the use of lead stabilizers; however, this study cannot provide definitive findings about actual risk or relative risk between cable alternatives due to differences in stabilizer formulation.

This study has identified a number of areas where potential improvements could be made in resin production. As indicated in Section 5.1.1, the overall proportion of energy used by the jacketing and insulation resin production processes is high. Increasing energy efficiency in the resin production processes, or using resins that require less energy input but meet all other specifications, would therefore lead to substantial reductions in energy use overall, and decrease other environmental impacts. Resin production might also be improved through the minimization of NOx, VOC, HCFC, and particulate matter emissions, or through the use of resins that produce fewer emissions during production. Substantial reduction of VOC emissions would not only reduce the potential human health burden, but would also reduce the potential for photochemical smog formation, and reduction of NOx emissions would reduce both the potential human health and air acidification burden. The generation of HCFCs during resin production is implicated in both global warming potential and photochemical smog formation impacts. The reduction of these emissions, therefore, would substantially reduce the burden in these impact categories for both baseline and lead-free cable. Reductions in particulate matter emissions would also have a multi-impact effect by reducing the potential public cancer toxicity and air particulate emissions burdens. The use of toxic chemicals, such as hydrofluoric acid and chlorine gas in the CMP cable jacketing and supply chain, and likely use of similar industrial precursors in the production of other resins, calls attention to potential issues of plant safety and worker health, especially with regards to the use of closed systems and consistent monitoring of indoor air quality.

The jacketing compounding processes of the baseline and lead-free CMR cable alternatives contribute substantial burden in the potential occupational cancer toxicity impact category through the use of fairly large quantities of phthalates (>10 percent). Due to phthalates' high 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.

### 5.2.2 Energy Sources

This study indicates that the life-cycle results are sensitive to changes in extrusion energy, which varied greatly across different manufacturers. Therefore, identifying opportunities for reducing extrusion energy inputs would likely have a notable effect on the results. Note that the CMR results were slightly more sensitive to the extrusion energy uncertainty than the CMP data, since the extrusion energy contributes a larger percent to the total life-cycle energy for CMR than for CMP. Other sources of energy throughout the wire and cable life cycle, especially electricity generation for use in a number of upstream and EOL processes, were top contributors to many of the impact categories. This reflects the importance of focusing on energy efficiency in all stages of the wire and cable life cycle to reduce overall environmental burden.

### 5.2.3 EOL

The results of this study suggest that potential public non-cancer toxicity and potential aquatic ecotoxicity impact results are extremely sensitive to the ability of lead to leach out of cable jacketing and then escape landfills linings and drainage systems. The implication is that if lead is contained in impermeable landfills, it will not cause harm; however, any potential for landfill failure means a non-negligible human health and ecotoxicity risk. Opportunities for improvement exist, therefore, in the reduction of the quantities of lead entering the landfills (while recognizing potential tradeoffs if alternatives are needed to replace the reduced amounts of lead) or management of municipal solid waste and construction and demolition landfills, by ensuring that permeation of lead-containing landfill leachate is minimized. As indicated in Section 5.1.3, although it is highly uncertain whether landfilled lead residue is a public health and ecotoxicity hazard, airborne lead from baseline cable incineration that escapes collection is a sure hazard. Ensuring that incineration facilities deal properly with air emissions during cable burning would also reduce the potential human health and ecological burdens from such processes.

EOL disposition choices for wire and cable products are complicated by the trade-offs inherent in the processes themselves. As mentioned in the preceding paragraph, the sequestration of wire and cable waste by landfilling is not without its source of hazards; and incineration, while advantageous from a landfill space use perspective, creates airborne lead emissions, which are problematic from a public health standpoint. Thermoplastic recycling is energy-intensive and creates new waste streams, which must be landfilled. Thus, the choices are not straightforward, and depend, among other things, on economic incentives and the value placed on different environmental burdens.

## 5.3 Limitations and Uncertainties

Limitations and uncertainties in the WCP LCIA results are due to limitations and uncertainties inherent in LCIA methodology itself, as well as limitations and uncertainties in the project LCI data. General limitations and uncertainties in the LCIA methodology were discussed in Section 3.3.3, and limitations and uncertainties in the project inventory were discussed in Chapter 2 (Sections 2.1.3, 2.2.5, 2.3.4, and 2.4.5.3). In addition, particular limitations and uncertainties as they pertain to individual impact category results are presented in Sections 3.2.1 through 3.2.12.

The overall limitations and uncertainties associated with the results of each impact category are summarized in Tables 4-1, 4-3, and 4-5 as relative data quality ratings. The data quality ratings are qualitative indicators representing a high (H), medium (M), or low (L) level of overall quality, or some combination thereof.

In general, the number of data sets available for the upstream and manufacturing primary data was quite limited (Table 2-9). The greatest number of data sets collected for a particular process was 3 (e.g., CMR jacketing compounding). Where primary data could not be obtained, secondary data were used for some of the upstream processes. In the case where a small number of samples possess majority market share for a specific product, this limitation would not be highly influential on the accuracy of life-cycle impact results. Data suppliers indicated this is likely the case with the wire and cable product manufacturing and associated upstream processes, although we cannot quantitatively confirm this given proprietary concerns of participating companies. Further investigation into the proportion of the market modeled in this LCA is necessary to understand the potential magnitude of the uncertainty in the material and energy inputs derived from the primary and secondary data used in this study.

EOL data relied on limited primary and secondary data, and was also modeled based on assumptions or default values where data were not available to make representative assumptions. Given the high uncertainty in EOL assumptions, uncertainty and sensitivity analyses were conducted. The sensitivity analysis results showed that most impact categories were not greatly affected by the EOL assumptions. For example, varying the percent of cables burned from zero to a maximum upper bound did not appreciably affect any of the CMR or CMP results. Leachate rate assumptions were the cause of most of the variability for the potential public and aquatic toxicity for the leaded baseline cables, and the percent of plastics going to thermoplastic recycling contributing highly to the uncertainty in the landfill space use impact category. Otherwise, most of the uncertainty in the CMR and CMP full life-cycle analyses was due to the variation of extrusion energy.

In the NM-B analysis, the full life cycle was not included due to lack of data. The same limitations to the upstream and manufacturing stages apply to the NM-B as described above for the CMR and CMP analyses. Lacking the full life-cycle analysis for this 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.

Due to the limitations in the LCI data, no category was given a “high” relative quality rating (see Tables 4-1, 4-3, and 4-5). 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 cancer impact category results were mostly based on materials that lack data on carcinogenicity rather than being based on known carcinogens (see methodology in Chapter 3, Section 3.2.10.1). 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 hydrocarbons during brominated phthalate production. In addition, 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. Finally, the occupational toxicity categories are dependent on the boundaries of the various datasets, and chemical intermediates that might be synthesized at a plant and consumed in subsequent reactions were unavailable from secondary data sets, limiting the robustness of this impact category.

## 5.4 Recommendations for Further Research

Below are recommendations for further research that serve to address some of the limitations and uncertainties of the Wire and Cable Project LCA described above. The research prescribed by these recommendations would build on the work of this report by focusing on areas where a lack of data or the need for tools that are more targeted than LCA restricted the present analysis.

The limitations of the WCP LCI (see Chapter 2) highlight the need for refinement of wire and cable inventory data, with a focus on those processes that drive impacts. Some examples of material and energy flows or processes that would benefit from inventory data refinement, due to magnitude of impact and uncertainty, are:

- Extrusion energy
- Resin production, including FEP, MFA, HD PE, and PVC data
- Plasticizer production
- Brominated phthalate production

Many of the comparisons in this report were constrained by limitations in or a complete absence of data describing particular life-cycle stages. Expanding the cradle-to-gate life-cycle models discussed in this report to include all life-cycle stages would allow for more comprehensive and valuable comparisons, as would refining assumptions in life-cycle stage where data were limited (e.g., EOL). The following list identifies areas where expansion of model boundaries or data refinement would improve LCA comparisons substantially:

- For zero-halogen CMR and NM-B lead and lead-free alternatives, adding extrusion data would allow for a more complete LCA (or manufacturers could supplement the information here with their own data to make a more complete assessment).
- Further refinement of EOL assumptions (e.g., percent of plastics to recycling after chopping).
- Landfill lining failure rates
- Rate of lead leaching out of cable jacketing
- Capture of lead air emissions by incinerator baghouses
- Detailing specific VOCs emitted during resin production
- Incorporate a scenario addressing uncontrolled burning (e.g., increase assumption of the percent of cable burned); also develop data that would better model releases in fires from each of the cable types (currently the fire data was based on PVC cables).
- Gather information on international trade in recycled cable and its constituent materials

This report presents screening-level results that explore the environmental burden of wire and cable products. However, to accurately estimate a products’ true burden in context-specific impact categories such as human and ecological toxicity, it is necessary to conduct more targeted, rigorous analyses of the product system. These analyses include investigations of chemical fate and transport, human and ecological exposure assessment, refinement of toxicological information, and risk assessment (e.g., fate and transport of lead out of a landfill, refinement of the lead hazard value, and potential for exposure).

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# Appendix A:  Data Forms (Manufacturing and EOL)

# DESIGN FOR THE ENVIRONMENT
# TOXICS USE REDUCTION INSTITUTE
# WIRE & CABLE PROJECT
## Life-Cycle Inventory (LCI) Data

### Introduction

In March 2004, the Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics (OPPT) and the Toxics Use Reduction Institute (TURI) at the University of Massachusetts Lowell formed a partnership to help the Wire and Cable industry assess the life-cycle environmental impacts of standard and alternative wire and cable formulations. The DfE Program conducts comparative analyses of alternative products or processes to provide businesses with data to make environmentally informed choices about product or Program has no regulatory or enforcement agenda and was established to act as a partner with industry to promote pollution prevention. TURI helps industries, institutions, and communities implement toxics use reduction as a means of achieving both a cleaner environment and a healthy economy. This environmental life-cycle assessment will address human and environmental impacts (e.g., energy, natural resource use, global warming, chronic toxicity) of various wire and cable formulations. Abt Associates Inc. is conducting the life-cycle inventory (LCI), which is the data collection phase of a life-cycle assessment, with technical assistance from the industry partners.

### Boundaries

A *life-cycle* assessment considers impacts from materials acquisition, material manufacturing, product manufacturing, use, and final disposition of a product. The LCI data are intended to be used to evaluate relative environmental impacts over the entire life cycle of a product. In this project, the product is a cable. Therefore, data associated with the materials and processes used directly in the manufacturing, use, and disposition of the product are relevant to the LCI and requested in the following tables. You will not need to include materials or energy *not directly* used in the production of the cable (e.g., general building heating and air conditioning).

### Product focus

This project will evaluate standard and alternative formulations for three product types:

1. Category 6, riser-rated communication wire (CMR)
2. Category 6, plenum-rated communication wire (CMP)
3. Non-metallic sheathed cable as used in building wire (NM-B)

Most recent (or projected) production data are desired.

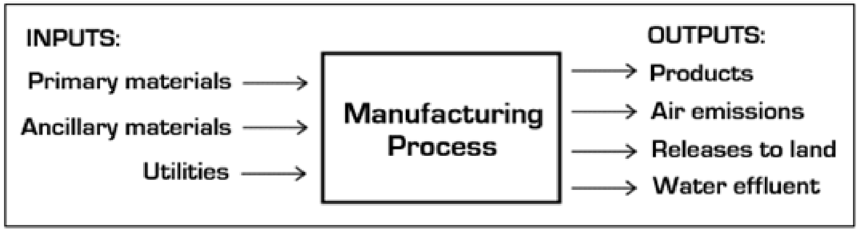

**Fig. 1. Manufacturing process inventory conceptual template**

### Inventory data

We are asking for data on one or multiple "product(s) of interest," or the components of the product(s), that you manufacture, which may be one as defined above under Product Focus. The inputs and outputs data (Fig. 1) that you provide will be aggregated in the LCI to quantify the overall inputs and outputs of a wire and cable formulation over its life cycle. A separate set of forms should be completed for each cable of interest.

**Data sources**

Much of the requested information can be drawn from existing sources, including, but not limited to the following:

1. Purchase and production records
2. Bills and invoices
3. Material Safety Data Sheets (MSDS)
4. Toxic Release Inventory (TRI) forms
5. Audit and analysis results (e.g., wastewater discharge analyses)
6. Local, state, and federal reporting forms (e.g., hazardous waste manifests)
7. Local, state, and federal permits
8. Monthly utility billing records

**How the data will be used**

Abt Associates will collect inventory data and tally the inputs and outputs for the different wire and cable formulations. Information gathered in these forms will be used to develop environmental profiles based on inputs and outputs for the manufacturin

**Results of project**

The results are intended to provide industry with an analysis of the life-cycle environmental impacts of standard and alternative wire and cable formulations. Results will help identify areas for product and process improvement as related to risk and env

*For any questions, please contact* ***Maria Leet Socolof at 301.347.5344*** *, <maria_socolof@abtassoc.com> or* ***David Cooper at 865.591.8966*** *, <david_cooper@abtassoc.com> at Abt Associates Inc., 4800 Montgomery Lane, Suite #600, Bethesda, MD 20814. Fax: 301.652.753*

*For more project details, see < http://www.epa.gov/dfe > and/or the Draft Final Goal Definition and Scoping Document.*

# INSTRUCTIONS

1. Please be sure to read the introductory text on each page before filling out the tables.
2. The data you supply in the tables should represent inputs and outputs associated only with the **"product of interest" (i.e., a wire and cable product or component as defined in the introduction under Product Focus, and what you specify in Table 2a, #1)**. If quantities provided are not specific to the "product of interest," please explain how they differ in the comments section at the bottom of the appropriate table. The ultimate goal is to quantify the amount of inputs and outputs per unit (e.g., ft) of cable manufactured.
3. Where supporting information is available as independent documents, reports, or calculations, please provide them as attachments with reference to the associated table(s).
4. If you have more than one product of interest to this project, please duplicate the forms and fill out one set of forms for each product.
5. If there is not adequate room on a page to supply your data (including comments), please copy the appropriate page and attach it to this packet.
6. The ensuing pages refer to the following indices to detail specifics about the data. Additional information is provided below as required.
   <u>Data Quality Indicators Index</u>: These indicators will be used to assess the level of data quality provided in the tables. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to a value that required one or more calculation(s) to obtain. The third category, **Estimated**, refers to a value that required a knowledgable employee's professional judgement to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.
   <u>Hazardous and Nonhazardous Waste Management Methods Index</u>: These methods are applicable to both hazardous and nonhazardous wastes (Tables 7a and 7b). Please give the appropriate abbreviation in the Management Method column on p. 7 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 7.

For Tables 3 - 6:

| **Data Quality Indicators Index** | |
|---|---|
| **M** | - Measured |
| **C** | - Calculated |
| **E** | - Estimated |
| **A** | - Assumed |

For Tables 6a and 6b:

| **Wastewater Treatment/Disposal Methods Index** | |
|---|---|
| **A** | - Direct discharge to surface water |
| **B** | - Discharge to offsite wastewater treatment facility |
| **C** | - Underground injection |
| **D** | - Surface impoundment (e.g., settling pond) |
| **E** | - Direct discharge to land |
| **F** | - Other (please specify in comments section) |

For Tables 7a and 7b (also provided on page 10):

| **Waste Management Methods Index** | |
|---|---|
| **RU** | - Reused |
| **R** | - Recycled |
| **L** | - Landfilled |
| **S** | - Solidified/stabilized |
| **Iv** | - Incinerated - volume reduction |
| **Ie** | - Incinerated - energy conversion |
| **D** | - Deep well injected |
| **O** | - Other (please specify in comments section) |

**IF YOU HAVE QUESTIONS, PLEASE CONTACT EITHER:**

Maria L. Socolof: Phone: 301.347.5344
Email: maria_socolof@abtassoc.com

OR

David Cooper: Phone: 865.591.8966
Email: david_cooper@abtassoc.com

# 1. FACILITY & CONTACT INFORMATION

**Table 1.**

## Facility Information

1. Company name: ______________________

2. Facility name: ______________________

3. Facility address (location): ______________________

______________________

______________________

______________________

## Contact Information

4a. Prepared by: ______________________ Date: __________

4b. Title: ______________________

4c. Phone number: ______________________ Ext.: __________

4d. Fax number: ______________________

4e. Email address: ______________________

5. Major products manufactured onsite and their % of your total production (by weight or volume--and please specify): ______________________

______________________

______________________

## 2. PRODUCT OF INTEREST INFORMATION

NOTE: The *product of interest* is the product that you manufacture that is of interest to this project (e.g., cable, compounded pellets, heat stabilizer) for which the following forms should be completed

**Table 2a.**

1. **Wire and cable product** (please check the cable type that you manufacture, compound, or supply a component for).

☐ CMR (Cat 6) ☐ CMP (Cat 6) ☐ NM-B

2. Which **product alternatives** do you manufacture or supply to? (See Tables 2b, 2c, and 2d for descriptions of these alternatives.)

| CMR | CMP | NM-B | |
|---|---|---|---|
| ☐ Lead-stabilized cable (baseline) | ☐ Lead-stabilized cable (baseline) | ☐ Lead-stablized cable (baseline) | ☐ Other (specify): ______ |
| ☐ Lead-free cable | ☐ Lead-free cable | ☐ Alternate lead-stabilized cable (alt plasticizer) | |
| ☐ Other (specify): ______ | ☐ Other (specify): *e.g., deca-BDE-free* | ☐ Lead-free cable | |
| ______ | ______ | ☐ Halogen-free cable | |

Note, for each alternative, please complete a separate set of forms (Tables 2-7) and specify at the top of each table which alternative the data represent.

3. Resin and additive **suppliers**: Please check the type of component and list the specific material you manufacture (see Tables 2b, 2c, and 2d for examples of the materials we are interested in receiving data for).

☐ Resin ______ ☐ Flame retardant ______ ☐ Plasticizer ______ ☐ Processing Aid ______

☐ Filler ______ ☐ Heat stabilizer ______ ☐ Other ______ ☐ N/A

4. Resin and additive **suppliers**: Please check the component for which you supply materials or products.

☐ Conductor insulation ☐ Cable jacketing

☐ Conductor jacketing ☐ Other (specify): ______

5. Please specify the product of interest for which the remainder of the forms will be completed (e.g., compounded pellets of PVC with additives used for CMP cable jacketing; lead-stabilized, baseline alternative):

______

6. Please provide a brief description of the main operations/subprocesses (e.g., compounding, extrusion) required to manufacture the product of interest: ______

______

______

7. Annual production (past, current, or projected) of product of interest (e.g., units of linear cable, kg of dibasic lead phthlate): ______

8. Year (or period of time) for which data are supplied (past, current, or projected): ______

9. Facility's percent global market share for product of interest (optional): ______

10. What % of the product of interest is recycled from your manufacturing process? ______ If recycled, (please check): ☐ **ON-SITE** ☐ **OFF-SITE**

a. If recycled on-site, how? ______

b. If recycled off-site, where? (please provide facility name and location if possible): ______

______

11. Do you have any information about post-consumer recycling of the product of interest? (We will collect more detailed information in Phase II of the study.): ☐ **YES** ☐ **NO**

**THE FOLLOWING DATA ARE APPLICABLE TO THE ITEM SPECIFIED IN TABLE 2a, #5**

## 3. PRIMARY & ANCILLARY INPUTS

1. Primary & Ancillary Materials: Primary materials are defined as those materials that become part of the final product. Ancillary materials are those material inputs that assist production, yet do not become part of the final product (e.g., cleaning materials). Please include the trade name and the generic name of each material where applicable.
2. CAS # or MSDS: Please include either the CAS (Chemical Abstract Service) number of each material (fill in the blank with the number) or state "MSDS" and append a copy to this document.
3. Annual quantity/units & Density/units: Please specify the annual amount of material consumed in the year of interest (as specified in Table 2a). Please use the units of mass-per-year (e.g., kg/yr, lb/yr). If you specify units of volume in lieu of mass, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
4. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
5. Recycled content: Please specify the recycled content of each material identified. For example, 60/40/0 would represent a material that has 60% virgin material, 40% pre-consumer recycled and 0% post-consumer recycled content. Enter N/A (not applicable) for all components that are assemblies.

| **Table 3a.** **Primary Materials**[1] | **CAS # or MSDS**[2] | **Annual Quantity**[3] | **Units** | **Density**[3] | **Units** | **DQI**[4] | **Recycled Content**[5] | **Country of origin of material (if known)** |
|---|---|---|---|---|---|---|---|---|
| *EXAMPLE: GRTX resin (polypropylene resin)* | *MSDS* | *450,000* | *kg/yr* | ----- | --- | *M* | *60/40/0* | USA |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |
| 6. | | | | | | | | |
| 7. | | | | | | | | |

Primary material comments:

| **Table 3b.** **Ancillary Materials**[1] | **CAS # or MSDS**[2] | **Annual Quantity**[3] | **Units** | **Density**[3] | **Units** | **DQI**[4] | **Recycled Content**[5] | **Country of origin of material (if known)** |
|---|---|---|---|---|---|---|---|---|
| *EXAMPLE: Petroleum naphtha (cleaning solvent)* | *8032-32-4* | *920* | *liters/yr* | *0.96* | *kg/liter* | *C* | *100/0/0* | USA |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |
| 6. | | | | | | | | |
| 7. | | | | | | | | |

Ancillary material comments:

## 4. UTILITY INPUTS

1. Annual quantity/units: Please specify the amount of the utility consumed in year of interest (as sepcified in Table 2a). If possible, please exclude nonprocess-related consump If this is not possible, please include a comment that nonprocess-related consumption is included. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
3. Individual Utility Notes:

**Electricity:**
The quantity of electricity should reflect only that used toward manufacturing the product of interest (identified on p. 2). One approach would be to start with your facility's to electrical energy consumption, remove nonprocess-related consumption, then estimate what portion of the remaining consumption is related to the specific operations of intere Please include consumption in all systems that use electricity for process-related purposes. Some examples include compressed air, chilled water, water deionization, and HV consumption where clean or controlled environments are utilized.

**Natural gas and LNG:**
Please exclude all use for space heating or other nonprocess-related uses. If you choose to use units other than MCF (thousand cubic feet), please utilize only units of energy content or volume (e.g., mmBTU, therm, CCF).

**Fuel oils:**
Please use units of either volume or energy content (e.g., liters, mmBTU, MJ). Additionally, if the fuel oil is not delivered by underground pipeline, please include the associa transportation information.

**All waters (e.g., DI, city):**
Please include all waters received onsite. Please indicate consumption in units of mass or volume.

| **Table 4.** | **Utilities[3]** | **Annual Quantity[1]** | **Units** | **DQI[2]** |
|---|---|---|---|---|
| 1. | Electricity | | e.g., MJ | |
| 2. | Natural gas | | e.g., MCF | |
| 3. | Liquified natural gas (LNG) | | e.g., MCF | |
| 4. | Fuel oil - type #2 (includes distillate and diesel) | | e.g., liters | |
| 5. | Fuel oil - type #4 | | e.g., liters | |
| 6. | Fuel oil - type #6 (includes residual) | | e.g., liters | |
| 7. | Other petroleum-based fuel | | e.g., liters | |
| 8. | Water | | e.g., liters | |
| 9. | | | | |
| 10. | | | | |
| 11. | | | | |
| 12. | | | | |
| 13. | | | | |

Utility comments:

## 5. AIR EMISSIONS

1. Air emissions: The emissions listed in the table below are some of the more common ones found in air release inventories; if you have information on other specific emissions, please provide them in the space provided. If you have any reporting forms or other air emission records for applicable year, please attach copies to this questionnaire. Also, if you have information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite to treat air emissions should be included in the utilities values on p. 7.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 2a). If the emissions data are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.

| **Table 5.**<br>**Air Emissions[1]** | **CAS number** | **Annual Quantity[2]** | **Units** | **DQI[3]** |
|---|---|---|---|---|
| Total particulates | ----- | | | |
| Particulates < 10 microns (PM-10) | ----- | | | |
| Sulfur oxides (SOx) | ----- | | | |
| Nitrogen oxides (NOx) | ----- | | | |
| Carbon monoxide | 630-08-0 | | | |
| Carbon dioxide | 124-38-9 | | | |
| Methane | 74-82-8 | | | |
| Benzene | 71-43-2 | | | |
| Toluene | 108-88-3 | | | |
| Xylenes | 1330-20-7 | | | |
| Naphthalene | 91-20-3 | | | |
| Total nonmethane VOCs | ----- | | | |
| Other speciated hydrocarbon emissions: | ▨ | ▨ | ▨ | ▨ |
| 1. | | | | |
| 2. | | | | |
| 3. | | | | |
| 4. | | | | |
| 5. | | | | |
| 6. | | | | |
| 7. | | | | |
| 8. | | | | |
| 9. | | | | |
| 10. | | | | |
| 11. | | | | |

| Table 5 (continued).<br>**Air Emissions[1]** | **CAS number** | **Annual Quantity[2]** | **Units** | **DQI[3]** |
|---|---|---|---|---|
| Ammonia | 7664-41-7 | | | |
| Arsenic | 7440-38-2 | | | |
| Chromium | 7440-47-3 | | | |
| Copper | 7440-50-8 | | | |
| Lead | 7439-92-1 | | | |
| Manganese | 7439-96-5 | | | |
| Mercury | 7439-98-7 | | | |
| Nickel | 7440-02-0 | | | |
| Other emissions: | ▨ | ▨ | ▨ | ▨ |
| 1. | | | | |
| 2. | | | | |
| 3. | | | | |
| 4. | | | | |
| 5. | | | | |
| 6. | | | | |
| 7. | | | | |
| 8. | | | | |
| 9. | | | | |
| 10. | | | | |
| 11. | | | | |

Air emission comments:

## 6. WASTEWATER RELEASES & CONSTITUENTS

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 2a). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. iii for method abbreviations.
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
4. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this questionnaire. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values on p. 7.
5. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).

| **Table 6a.** **Wastewater Stream** | **Annual Quantity[1]** | **Units** | **Treatment/Disposal Method[2]** | **DQI for Annual Quantity[3]** | **DQI for Constituents below[3]** |
|---|---|---|---|---|---|
| | | | | | |

| **Table 6b.** **Wastewater Constituents[4]** | **CAS number** | **Concentration[5]** | **Units** |
|---|---|---|---|
| Dissolved solids | ----- | | |
| Suspended solids | ----- | | |
| Carbonaceous Oxygen Demand (COD) | ----- | | |
| Biological Oxygen Demand (BOD) | ----- | | |
| Oil & grease | ----- | | |
| Hydrochloric acid | 7647-01-0 | | |
| Sulfuric acid | 7664-93-9 | | |
| Other acids (please specify): | | | |
| 1. | | | |
| 2. | | | |
| Phosphorus | | | |
| Phosphates | | | |
| Sulfates | | | |
| Fluorides | | | |
| Cyanide | | | |
| Chloride | | | |
| Chromium | | | |
| Aluminum | | | |
| Nickel | | | |

| Table 6b (continued). **Wastewater Constituents[4]** | **CAS number** | **Concentration[5]** | **Units** |
|---|---|---|---|
| Mercury | 7439-98-7 | | |
| Lead | 7439-92-1 | | |
| Nitrogen | | | |
| Zinc | | | |
| Tin | | | |
| Ferrous sulfate | | | |
| Ammonia | 7664-41-7 | | |
| Nitrates | | | |
| Pesticides | | | |
| Other speciated constituents: | | | |
| 1. | | | |
| 2. | | | |
| 3. | | | |
| 4. | | | |
| 5. | | | |
| 6. | | | |

Wastewater comments:

## 7. HAZARDOUS & NONHAZARDOUS WASTES

1. Hazardous wastes and EPA hazardous waste numbers: Please list your waste streams that are considered hazardous by the U.S. EPA. Include the hazardous waste codes for any hazardous waste you include. Nonhazardous wastes can include by-products and co-products that are reused, reintroduced, or recycled back into the product.
2. Annual quantity/units & Density/units: Please specify the amount of waste generated in the year of interest (as specified in Table 2a). Use units of mass-per-year (e.g., kg/yr, lb/yr). Please also provide the density for each waste. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. iii for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Management method: See key to right of tables for Management Methods Index. If none are applicable, please indicate other and use the comments section to expound.

| **Table 7a.** **Hazardous Wastes**[1] | **EPA Haz. Waste #**[1] | **Annual Quantity**[2] | **Units** | **Density**[2] | **Units** | **DQI**[3] | **Mgmt. method**[4] | **On or offsite?** |
|---|---|---|---|---|---|---|---|---|
| *EXAMPLE: Spent solvent (toluene)* | *F005* | *20,000* | *kg/yr* | *0.9* | *kg/liter* | *M* | *Ie* | *off* |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |
| 6. | | | | | | | | |
| 7. | | | | | | | | |
| 8. | | | | | | | | |

Hazardous waste comments:

| **Table 7b.** **Nonhazardous Wastes**[1] | **Annual Quantity**[2] | **Units** | **Density**[2] | **Units** | **DQI**[3] | **Mgmt. method**[4] | **On or offsite?** |
|---|---|---|---|---|---|---|---|
| *EXAMPLE: Waste metal chips* | *22,000* | *kg/yr* | *1,000* | *kg/m3* | *C* | *R* | *off* |
| 1. | | | | | | | |
| 2. | | | | | | | |
| 3. | | | | | | | |
| 4. | | | | | | | |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |

Nonhazardous waste comments:

| **Management Methods Index** | |
|---|---|
| **RU** | Reused |
| **R** | Recycled |
| **L** | Landfilled |
| **S** | Solidified/stabilized |
| **Iv** | Incinerated-volume reduction |
| **Ie** | Incinerated-energy conversion |
| **D** | Deep well injected |
| **O** | Other (specify in comments) |

# INSTRUCTIONS

1. **We are looking to identify inputs and outputs associated with the recycling of cables at your facility.**

2. Please be sure to read all the notes on each page when filling out the questionnaire.

3. Where supporting information is available as independent documents, reports, or calculations, please provide them as attachments with reference to the associated table(s) in this questionnaire.

4. The following indices refer to information requested in the ensuing pages:

For Tables 2 - 5:

| **Data Quality Indicators Index** | |
|---|---|
| **M** | - Measured |
| **C** | - Calculated |
| **E** | - Estimated |
| **A** | - Assumed |

Data Quality Indicators Index: These indicators will be used to assess the level of data quality provided in the tables. Please report a DQI for the numerical value requested in each table on the following pages. The first category, **Measured**, pertains to a value that is a directly measured quantity. The second category, **Calculated**, refers to a value that required one or more calculation(s) to obtain. The third category, **Estimated**, refers to a value that required a knowledgeable employee's professional judgment to estimate. Lastly, the fourth category, **Assumed**, should be used only when a number had to be speculatively estimated.

For Tables 4a and 4b:

| **Wastewater Treatment/Disposal Methods Index** | |
|---|---|
| **A** | - Direct discharge to surface water |
| **B** | - Discharge to offsite wastewater treatment facility |
| **C** | - Underground injection |
| **D** | - Surface impoundment (e.g., settling pond) |
| **E** | - Direct discharge to land |
| **F** | - Other (please specify in comments section) |

For Table 5:

| **Waste Management Methods Index** | |
|---|---|
| **RU** | - Reused |
| **R** | - Recycled |
| **L** | - Landfilled |
| **S** | - Solidified/stabilized |
| **Iv** | - Incinerated - volume reduction |
| **Ie** | - Incinerated - energy conversion |
| **D** | - Deep well injected |
| **O** | - Other (please specify in comments section) |

Hazardous and Nonhazardous Waste Management Methods Index: These methods are applicable to both hazardous and nonhazardous wastes (Table 5). Please give the appropriate abbreviation in the Management Method column on p. 5 where requested. Depending on whether the management method is on or offsite, please indicate by specifying "on" or "off" in the appropriate column on p. 5.

***Your cooperation and assistance are greatly appreciated.***

*For any questions, please contact* ***Maria Leet Socolof at 301.347.5344*** *, <maria_socolof@abtassoc.com> or* ***David Cooper at 865.824.3362*** *, <david_cooper@abtassoc.com> at Abt Associates Inc., 4800 Montgomery Lane, Suite #600, Bethesda, MD 20814. Fax: 301.652.7530.*

## 1. FACILITY & PROCESS INFORMATION

**Table 1a.** **Facility Information**

1. Company/Facility name: ____________________
2. Facility address (location): ____________________

____________________

____________________

____________________

**Contact Information**

3a. Prepared by: ____________________ Date: __________
3b. Title: ____________________
3c. Phone number: ____________________ Ext.: __________
3d. Fax number: ____________________
3e. Email address: ____________________

**Table 1b. Process Information**

1. Briefly describe the main operations you use to recycle cable scrap ____________________

____________________

____________________

2a How much cable scrap does your facility recycle annually? __________ (mass/y)

2b Can you estimate the % of total worldwide or U.S. scrap cables that you recycle: __________ (% of worldwide scrap) __________ (% of U.S. scrap)

2c How much scrap cable do you expect to recycle
5 years? __________ (mass/y or % of all worldwide cables) __________ (mass/yr or % of U.S. scrap)
10 years? __________ (mass/y or % of all worldwide cables) __________ (mass/yr or % of U.S. scrap)
25 years? __________ (mass/y or % of all worldwide cables) __________ (mass/yr or % of U.S. scrap)
40 years? __________ (mass/y or % of all worldwide cables) __________ (mass/yr or % of U.S. scrap)

3. What % of the cable scrap you recycle is telecom cable? __________ %

4. What % of the cable scrap you recycle is building cable? __________ %

5. What % of your cable recycling operations are from:
post industrial waste (e.g., out-of-spec cables): __________ %
post consumer waste (e.g., end-of-life cables): __________ %

6. Do you generate air emissions from recycling cables? __________ If so, complete Table 3.

7. Does your cable recycling involve any wet processes that generate wastewater effluents? __________ If so, complete Tables 4a and 4b.

8. What do you do with the recovered plastic fraction? ____________________

9. What do you do with the recovered conductor? ____________________

10. What is the year (or period of time) of the data you are supplying (in the following tables)? __________

11. Facility's percent global market share for recycling cables (optional): __________

## 2. MATERIAL AND UTILITY INPUTS

**Please provide the inputs associated with cable recycling**

| **Table 2a.** <br> **Input Streams & Materials**[1] | **Primary or ancillary**[2] | **CAS # or MSDS**[3] | **Annual Quantity**[4] | **Units** | **Density**[4] <br> *(needed only if volume given)* | **Units** | **DQI**[5] |
|---|---|---|---|---|---|---|---|
| *EXAMPLE: Cable scrap* | *P* | *NA* | *450,000* | *kg/yr* | ----- | --- | *M* |
| 1. | | | | | | | |
| 2. | | | | | | | |
| 3. | | | | | | | |
| 4. | | | | | | | |
| 5. | | | | | | | |

Material input comments:

| **Table 2b.** <br> **Utility Inputs**[1] | **Annual Quantity**[4] | **Units** | **DQI**[5] |
|---|---|---|---|
| *EXAMPLE: Fuel oil #6 (includes residual)* | *100* | *MJ* | *C* |
| 1. Electricity | | | |
| 2. Fuel (specify type): | | | |
| 3. Water | | | |
| 4. other fuels: | | | |
| 5. | | | |
| 6. | | | |
| 7. | | | |

Utility input comments:

NOTES:

1. Input Streams & Materials and Utility Inputs: Enter material inputs to the cable recycling operations (e.g., cable scrap) in Table 2a and utility inputs (e.g., electricity, fuel, water) in Table 2b.
2. Primary or Ancillary: Primary materials are defined as those materials that become part of the final product output. Ancillary materials are those material inputs that assist operations (e.g., lubricants).
3. CAS # or MSDS: For chemical compounds, please include either the CAS (Chemical Abstract Service) number of the material, or enter "MSDS" and append a copy of the MSDS.
4. Annual quantity/units & Density/units: Please specify the annual amount of material consumed (preferably in mass for Table 2a and either mass or energy for Table 2b).
   If you specify units of volume, please provide the density. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
5. Data quality indicators: See the Data Quality Indicators Index on p. i for abbreviations. Please supply the DQI for the *annual quantity* value given.

## 3. AIR EMISSIONS

**If you generate air emissions from your processes associated with cable recycling, please complete the following table.**

| **Table 3.**<br>**Air Emissions[1]** | **CAS number** | **Annual Quantity[2]** | **Units** | **DQI[3]** |
|---|---|---|---|---|
| Total particulates | ----- | | | |
| Particulates < 10 microns (PM-10) | ----- | | | |
| Sulfur oxides (SOx) | ----- | | | |
| Nitrogen oxides (NOx) | ----- | | | |
| Carbon monoxide | 630-08-0 | | | |
| Carbon dioxide | 124-38-9 | | | |
| Methane | 74-82-8 | | | |
| Benzene | 71-43-2 | | | |
| Toluene | 108-88-3 | | | |
| Xylenes | 1330-20-7 | | | |
| Naphthalene | 91-20-3 | | | |
| Total nonmethane VOCs | ----- | | | |
| Other speciated hydrocarbon emissions: | ▨ | ▨ | ▨ | ▨ |
| 1. | | | | |
| 2. | | | | |
| 3. | | | | |
| 4. | | | | |
| 5. | | | | |

| Table 3 (continued).<br>**Air Emissions[1]** | **CAS number** | **Annual Quantity[2]** | **Units** | **DQI[3]** |
|---|---|---|---|---|
| Ammonia | 7664-41-7 | | | |
| Arsenic | 7440-38-2 | | | |
| Chromium | 7440-47-3 | | | |
| Copper | 7440-50-8 | | | |
| Lead | 7439-92-1 | | | |
| Manganese | 7439-96-5 | | | |
| Mercury | 7439-98-7 | | | |
| Nickel | 7440-02-0 | | | |
| Other emissions: | ▨ | ▨ | ▨ | ▨ |
| 1. | | | | |
| 2. | | | | |
| 3. | | | | |
| 4. | | | | |
| 5. | | | | |

Air emission comments:

NOTES:

1. Air emissions: The emissions listed in the table above are some of the more common ones found in air release inventories; if you have information on other specific emissions, pl provide them in the space provided. If you have any reporting forms or other air emission records for the applicable year, please attach copies to this questionnaire. Also, if you h information on stack as well as fugitive emissions, please copy this page and place each set of emissions on a different page. The energy consumed in any equipment used onsite t air emissions should be included in the utilities values in Table 2b.
2. Annual quantity/units: Please specify the amount of air emissions generated and released to the environment in the year of interest (as specified in Table 1b). If the emissions dat are for a different year, please specify the year in the comments section below. Please use units of mass-per-year (e.g., kg/yr, lb/yr). If *annual* quantities are not available, provic units (e.g., kg/1000 kg of product).
3. Data quality indicators: See the Data Quality Indicators Index on p. i for abbreviations. Please supply the DQI for the *annual quantity* value given.

## 4. WASTEWATER RELEASES & CONSTITUENTS

**If you generate wastewater releases and constituents from your processes associated with cable recycling, please complete these tables.**

| **Table 4a.** **Wastewater Stream** | **Annual Quantity[1]** | **Units** | **Treatment/Disposal Method[2]** | **DQI for Annual Quantity[3]** | **DQI for Constituents below[3]** |
|---|---|---|---|---|---|
| | | | | | |

| **Table 4b.** **Wastewater Constituents[4]** | **CAS number** | **Concentration[5]** | **Units** |
|---|---|---|---|
| Dissolved solids | ----- | | |
| Suspended solids | ----- | | |
| Carbonaceous Oxygen Demand (COD) | ----- | | |
| Biological Oxygen Demand (BOD) | ----- | | |
| Oil & grease | ----- | | |
| Hydrochloric acid | 7647-01-0 | | |
| Sulfuric acid | 7664-93-9 | | |
| Other acids (please specify): | ▨ | ▨ | ▨ |
| 1. | | | |
| 2. | | | |
| Phosphorus | | | |
| Phosphates | | | |
| Sulfates | | | |
| Fluorides | | | |
| Cyanide | | | |
| Chloride | | | |
| Chromium | | | |
| Aluminum | | | |
| Nickel | | | |
| Table 4b (continued). **Wastewater Constituents[4]** | **CAS number** | **Concentration[5]** | **Units** |
| Mercury | 7439-98-7 | | |
| Lead | 7439-92-1 | | |
| Nitrogen | | | |
| Zinc | | | |
| Tin | | | |
| Ferrous sulfate | | | |
| Ammonia | 7664-41-7 | | |
| Nitrates | | | |
| Pesticides | | | |
| Other speciated constituents: | ▨ | ▨ | ▨ |
| 1. | | | |
| 2. | | | |
| 3. | | | |
| 4. | | | |
| 5. | | | |
| 6. | | | |

Wastewater comments:

NOTES:

1. Annual quantity/units: Please specify the amount of wastewater(s) generated in the year of interest (as specified in Table 1b). Please use units of mass-per-year (e.g., kg/yr, lb/yr). If multiple streams exist, please copy this page and fill it out for each stream. If *annual* quantities are not available, provide applicable units (e.g., kg/1000 kg of product).
2. Wastewater treatment/disposal method: See the Wastewater Treatment/Disposal Methods Index on p. i for method abbreviations.
3. Data quality indicators: See the Data Quality Indicators Index on p. i for abbreviations. Please include one DQI for the annual wastewater stream quantity value supplied, and one DQI for the wastewater constituents information supplied. If more than one DQI is applicable to the wastewater constituents data, please clarify this in the comment section.
4. Wastewater constituents: Please let us know what type of values you are supplying (e.g., daily maximums, monthly averages, annual averages). Additionally, if you have any reporting forms of other wastewater constituent records for the year of interest, please attach them to this questionnaire. The energy consumed in any equipment used onsite to treat wastewater releases should be included in the utilities values in Table 2b.
5. Concentration/units: Please specify the concentration of wastewater constituents generated in the year of interest. Please use units of mass-per-volume (e.g., mg/liter, lb/gal).

## 5. OUTPUTS -- PRODUCTS AND SOLID WASTE

**Please list the product and solid waste streams generated by your processes associated with cable recycling.**

| **Table 5.** Output Streams[1] | **Annual Production[2]** | **Units** | **DQI[3]** | **Density[4]** (needed only if landfilled) | **Units** | **Management Method[5]** | **On or Offsite?** | **Hazardous Waste?[6]** |
|---|---|---|---|---|---|---|---|---|
| *EXAMPLE 1: Copper conductor* | *100* | *kg/y* | *C* | ---- | ---- | *Sm** | *off* | *N* |
| *EXAMPLE 2: Lubricant* | *1,000* | *kg/yr* | *M* | *0.9* | *kg/liter* | *L* | *off* | *N* |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |
| 6. | | | | | | | | |
| 7. | | | | | | | | |
| 8. | | | | | | | | |
| 9. | | | | | | | | |
| 10. | | | | | | | | |

Waste comments:

NOTES:

1. Output Streams: This includes "product outputs that are sent for further processing or recycling as well as solid wastes (nonhazardous or EPA hazardous waste) that are treated or disposed of.
2. Annual Production & units: Please specify the amount of the output stream generated in the year of interest. Use units of mass-per-year (e.g., kg/yr, lb/yr).
3. Data Quality Indicator: See the Data Quality Indicators Index on p. i for abbreviations. Please supply the DQI for the *annual quantity* value given.
4. Density: Please provide the approximate bulk density for any waste that is landfilled (this will be used to calculate volume of landspace used).
5. Management Method: Please supply the follow-up processing method or the treatment/disposal method for each output stream . See the Waste Management Methods Index on abbreviations. If none are applicable, please indicate "other" and explain in the comments section.
6. Hazardous Waste?: If the output is a solid waste stream, is it an EPA Subtitle C hazardous waste? Indicate Yes or No.

# Appendix B: Fire Scenario: Estimation of Frequency of Structure Fires in Buildings Containing CMR / CMP Cables and NM-B Cables

The EOL distribution of pathways for wire and cable characterizes a portion of wire and cable as prematurely reaching the end of its life due to building fires. The annual quantity of wire and cable reaching it end-of-life state in this way may be calculated given data on the total amount of wire and cable installed in buildings, the annual frequency of fires in buildings containing cable, and the average damage caused by those fires.

Only data regarding the existing amount of wire and cable were readily available. This appendix describes a calculation made to estimate the annual frequency of structure fire containing CMR, CMP, and NM-B cables (calculated to be 1.1 percent of buildings containing CMR / CMP cables and 0.5 percent of cables containing NM-B cables). The third factor, the average cable loss per building fire is discussed in Section 2.4.5.1 of this report.

## Methodology

The annual frequency of fires in buildings containing CMR / CMP / NM-B cables is estimated using the following formulas:

- Annual frequency of fires in buildings with CMR = # of fires each year in buildings containing CMR / # of buildings containing CMR
- Annual frequency of fires in buildings with CMP = # of fires each year in buildings containing CMP / # of buildings containing CMP
- Annual frequency of fires in buildings with NM-B = # of fires each year in buildings containing NM-B / # of buildings containing NM-B

## Universe of Buildings

The universes of buildings used in the denominators of these equations were compiled from various sources of data and are listed in Tables B-1 through B-4 below. CMR and CMP cables were assumed to be found in only certain commercial buildings. Table B-5 displays a summary of the total universe of buildings and the number of buildings estimated to have CMR, CMP, and NM-B cables.

**Table B-1 Universe of Residential Buildings**

| Type of Housing Unit | Estimated Number of Housing Units[1] | Assumed Number of Housing Units per Building | Calculated Number of Buildings |
|---|---|---|---|
| Single, detached | 76,112,065 | 1 | 76,112,065 |
| Single, attached | 7,063,608 | 1 | 7,063,608 |
| 2 | 5,029,858 | 2 | 2,514,929 |
| 3 or 4 | 5,723,743 | 3.5 | 1,635,355 |
| 5 to 9 | 6,179,145 | 7 | 882,735 |
| 10 to 19 | 5,594,120 | 15 | 372,941 |
| 20 to 49 | 4,252,727 | 30 | 141,758 |
| 50 or more | 5,734,117 | 100 | 57,341 |
| Mobile Home | 8,737,428 | 1 | 8,737,428 |
| Boat, RV, van, etc. | 95,075 | 1 | 95,075 |
| **Total** | **124,521,886** | | **97,613,235** |

[1] Data taken from 2005 American Community Survey, http://factfinder.census.gov/servlet/DTTable?_bm=y&-geo_id=01000US&-ds_name=ACS_2005_EST_G00_&-SubjectID=14573966&-redoLog=true&-mt_name=ACS_2005_EST_G2000_B25024&-format=&-CONTEXT=dt

**Table B-2 Universe of Commercial Buildings[1]**

| Principal Building Use | Number of Buildings | Number of Buildings with CMR / CMP |
|---|---|---|
| Education | 386,000 | 386,000 |
| Food Sales | 226,000 | 226,000 |
| Food Service | 297,000 | 297,000 |
| Health Care – Inpatient | 8000 | 8000 |
| Health Care – Outpatient | 121000 | 121000 |
| Lodging | 142,000 | 142,000 |
| Mercantile – Retail (Other than Mall) | 443000 | 443000 |
| Mercantile – Enclosed and Strip Malls | 213000 | 213000 |
| Office | 824,000 | 824,000 |
| Public Assembly | 277,000 | |
| Public Order and Safety | 71,000 | 71,000 |
| Religious Worship | 370,000 | |
| Service | 622,000 | 622,000 |
| Warehouse and Storage | 597,000 | |
| Other | 79,000 | 79,000 |
| Vacant | 182,000 | 182,000 |
| **Total** | **4,859,000** | **3,615,000** |

[1] Data taken from 2003 Commercial Buildings Energy Consumption Survey (CBECS), http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/2003set1/2003pdf/a1.pdf.

### Table B-3 Universe of Industrial Buildings[1]

| | Number of Establishments | Assumed Number of Buildings per Establishment | Calculated Number of Buildings |
|---|---|---|---|
| US Manufacturing Establishments | 350,728 | 1 | 350,728 |
| **Total** | 350,728 | | 350,728 |

[1] Data are from "Table 1: Statistics for all Manufacturing Establishments: 2005 and Earlier Years", from "Statistics for Industry Groups and Industries: 2005"; Annual Survey of Manufactures, and are for the year 2002. http://www.census.gov/prod/2006pubs/am0531gs1.pdf.

### Table B-4 Universe of Agricultural Buildings[1]

| | Number of Establishments | Assumed Number of Buildings per Establishment | Calculated Number of Buildings |
|---|---|---|---|
| Total Farms | 2,128,982 | 1 | 2,128,982 |
| **Total** | 2,128,982 | | 2,128,982 |

[1] Data are from Agriculture Census of the United States, 2002, NASS, Table 50 - Selected Characteristics of Farms by North American Industry Classification System: 2002. http://www.nass.usda.gov/census/census02/volume1/us/st99_1_050_050.pdf

### Table B-5 Universe of Buildings with CMR, CMP, and NM-B

| Building Type | Number of Buildings in Universe | CMR | CMP | NM-B |
|---|---|---|---|---|
| Residential | 97,613,235 | 0 | 0 | 97,613,235 |
| Commercial | 4,859,000 | 3,615,000 | 3,615,000 | 4,859,000 |
| Industrial | 350,728 | 0 | 0 | 350,728 |
| Agricultural | 2,128,982 | 0 | 0 | 2,128,982 |
| **Total** | **104,951,945** | **3,615,000** | **3,615,000** | **104,951,945** |

### Universe of Structure Fires

Structure fires

**Table B-6 Universe of Structure Fires and Number involving Buildings with CMR, CMP, and NM-B**

| Building Type | % of Structure Fires | | | Number of Structure Fires | | |
|---|---|---|---|---|---|---|
| | Residential[1] | Non-Residential[2] | Total[1] | Total | CMR / CMP | NM-B |
| Residential - 1-/2-Family | 72% | | 53.9% | 275,575 | | 275,575 |
| Residential - Multifamily | 25% | | 18.6% | 94,920 | | 94,920 |
| Residential - Other | 4% | | 2.9% | 14,799 | | 14,799 |
| Non-Residential - Storage | | 30.9% | 7.6% | 38,843 | | 38,843 |
| Non-Residential - Business | | 19.8% | 4.9% | 24,890 | 24,890 | 24,890 |
| Non-Residential - Assembly | | 14.1% | 3.5% | 17,725 | | 17,725 |
| Non-Residential - Manufacturing | | 9.9% | 2.4% | 12,445 | | 12,445 |
| Non-Residential - Special Property | | 9.0% | 2.2% | 11,314 | | 11,314 |
| Non-Residential - Health Care, Detention | | 6.6% | 1.6% | 8,297 | 8,297 | 8,297 |
| Non-Residential - Educational | | 6.6% | 1.6% | 8,297 | 8,297 | 8,297 |
| Non-Residential - Industrial | | 2.9% | 0.7% | 3,645 | | 3,645 |
| **Total** | **100%** | **99.8%** | **100.0 %** | **511,000[3]** | **41,483** | **511,000** |

[1] Data are from U.S. Fire Administration/National Fire Data Center, "All Structure Fires in 2000," Figure 2. http://ww.usfa.dhs.gov/downloads/pdf/tfrs/v3i8.pdf.

[2] Data are from U.S. Fire Administration/National Fire Data Center, "Non-Residential Structure Fires in 2000," Figure 2. http://ww.usfa.dhs.gov/downloads/pdf/tfrs/v3i10.pdf.

[3] Data are from U.S. Fire Administration, "Structure Fires," 2005 value. http://www.usfa.dhs.gov/statistics/national/all_structures.shtm.

**Table B-7 Calculation of Annual Frequency of Fires in Buildings Containing CMR, CMP, and NM-B Cables**

| Cable Type | Number of Buildings Containing Cable | Number of Structure Fires in Buildings Containing Cable | Annual Frequency of Fires |
|---|---|---|---|
| **CMR** | 3,615,000 | 41,483 | 1.1% |
| **CMP** | 3,615,000 | 41,483 | 1.1% |
| **NM-B** | 104,951,945 | 511,000 | 0.5% |

*Note, the WCP assumes 10% of the cables in a fire are burned (see Section 2.4.5.1 of main report).*

# Appendix C: Waste Densities

**Table C-1. Waste Densities for Landfill Space Use Impact Category**

| Flow | Density (D) (kg/m$^3$) | Reference | Note |
|---|---|---|---|
| **Consumer Waste** | | | |
| Industrial waste for municipal disposal | 800 | (7) | N/A |
| Inert chemical waste | 445 | (4) | N/A |
| Liquid waste | 1000 | N/A | Assumed the same density as water |
| Mineral waste | 2560 | (7) | Average of miscellaneous materials densities |
| Municipal waste | 445 | (4) | N/A |
| Packaging waste (metal) | 267 | (1) | Combined values for steel and aluminum packaging waste, weighted by the percentage each contributed to the packaging waste total. |
| Packaging waste (plastic) | 192 | (1) | Used value for total plastics packaging |
| Paper (unspecified) | 472 | (1) | Used landfill density of paper and paperboard packaging |
| PVC Waste | 601 | (2) | Average of PVC chips and resin |
| Unspecified industrial waste | 800 | (7) | Used value for Industrial waste for municipal disposal |
| Waste (unspecified) | 445 | (4) | N/A |
| **Hazardous Waste** | | | |
| Hazardous waste (unspec.) | 445 | (4) | N/A |
| Hazardous waste incineration products (25% water) | 584 | (4) | Assumed the value was equal to 75% of that for hazardous waste density, plus 25% of that for water |
| Inert chemical waste | 445 | (4) | N/A |
| Liquid hazardous waste | 1000 | N/A | Assumed the same density as water |
| Regulated chemicals | 445 | (4) | Used value for inert chemical waste |
| Slag | 3000 | (9) | N/A |
| Slags and ash | 1900 | (7) and (9) | Used average of values for slag and ash |
| Sludge | 1000 | (7) | N/A |
| **Radioactive Waste** | | | |
| CaF2 (low radioactivity) | 3180 | (3) | N/A |
| Highly radioactive waste | 449 | (4) | N/A |
| Highly-active fission product solution | 1000 | N/A | Assumed the same density as water |

**Table C-1. Waste Densities for Landfill Space Use Impact Category**

| Flow | Density (D) (kg/m$^3$) | Reference | Note |
|---|---|---|---|
| Jacket and body material | 449 | (4) | N/A |
| Low to mid level radioactive waste | 449 | (4) | Used value of medium and low radioactive wastes |
| Medium and low radioactive liquid waste | 1000 | N/A | Used density of water |
| Medium and low radioactive wastes | 449 | (4) | N/A |
| Plutonium as residual product | 19800 | (5) | Assumed elemental density |
| Radioactive tailings | 449 | (4) | Used "mining waste" value |
| Uranium depleted | 19300 | (6) | N/A |
| Uranium spent as residue | 19000 | (5) | Assumed elemental density |
| Volatile fission products (inert gases;iodine;C14) | 11300 | (5) | Used the density of iodine gas |
| Waste radioactive | 449 | (4) | Used "mining waste" value |
| **Stockpile Goods** | | | |
| Ash | 800 | (7) | N/A |
| Demolition waste | 1900 | (7) and (9) | Used average of values for slag and ash |
| Overburden | 449 | (4) | Used "mining waste" value |
| Tailings | 449 | (4) | Used "mining waste" value |
| Treatment residue (mineral) | 449 | (4) | Used "mining waste" value |
| **Hazardous waste for disposal** | | | |
| Hazardous waste to landfill | 445 | (4) | Used value for Hazardous waste (unspec.) |
| Hazardous waste (misc.) | 445 | (4) | Used value for Hazardous waste (unspec.) |
| Toxic chemicals (unspecified) | 445 | (4) | Used value for inert chemical waste |
| **Waste for disposal** | | | |
| IWP Sludge to landfill | 1000 | (7) | Used value for Sludge |
| Misc trash to landfill | 800 | (7) | Used value for Industrial waste for municipal disposal |
| Nylon waste to landfill | 465 | (2) | Average of values for nylon fibers, flakes, pellets and powder |
| Other waste to landfill | 800 | (7) | Used value for Industrial waste for municipal disposal |
| Polyvinyl chloride (PVC) waste to landfill (PVC) | 601 | (2) | Average of PVC chips and resin |
| Scrap plastic to landfill | 220 | (1) | Used landfill density of plastics |
| Scrap polymer pellets and packaging to landfill (FEP) | 849 | (8) | Found FEP waste density through reference to the ratio of nylon waste |

**Table C-1. Waste Densities for Landfill Space Use Impact Category**

| Flow | Density (D) ($kg/m^3$) | Reference | Note |
|---|---|---|---|
| | | | density to nylon density, noted above, compared to FEP density. |
| WWTP sludge | 1000 | (7) | Used value for Sludge |

Sources:

(1) U.S. Environmental Protection Agency (EPA), 1999. "Characterization of Municipal Solid Waste in the United States: 1998 Update." Office of Solid Waste, Municipal Waste Division, Report No. EPA530-R-98-007. Prepared by Franklin Associates. July 1999. Tables B-9 and B-10.

(2) Machine and Process Design, Inc. Material Bulk Density Reference Chart. http://www.mpd-inc.com/material.htm. (accessed Feb 2008).

(3) Chemfinder.com. Calcium Fluoride [7789-75-5]. http://chemfinder.cambridgesoft.com. (accessed Feb 2008).

(4) U.S. Environmental Protection Agency (EPA), 1998. “Characterization of Municipal Solid Waste in the United States: 1997 Update.” Office of Solid Waste, Municipal Waste Division, Report No. EPA530-R-98-007. Prepared by Franklin Associates. May 1998.

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# Appendix D: Equivalency Factors

Tables D-1 through D-5 present equivalency factors for impact categories used in the impact assessment. These are comprehensive lists that exceed the number of chemicals found in the Wire and Cable Partnership life-cycle inventory.

Table D-1. Global warming potentials

Table D-2. Stratospheric ozone depletion equivalency factors

Table D-3. Photochemical Oxidant Creation Potentials (Photochemical smog)

Table D-4. Acidification potentials

Table D-5. Eutrophication potentials

## Table D-1. Global Warming Potentials

| Flow | Global warming potential ($CO_2$ equivalents) |
|---|---|
| 1,1,1-Trichloroethane [Halogenated organic emissions to air] | 140 |
| Carbon dioxide [Renewable resources] | 1 |
| Carbon dioxide [Inorganic emissions to air] | 1 |
| Carbon dioxide (biotic) [Air] | 1 |
| Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air] | 1800 |
| Chlorodifluoromethane (R22) [Halogenated organic emissions to air] | 1700 |
| Chloromethane (methyl chloride) [Halogenated organic emissions to air] | 16 |
| Dichloromethane (methylene chloride) [Halogenated organic emissions to air] | 10 |
| Dichloromonofluoromethane [Halogenated organic emissions to air] | 210 |
| Halon (1211) [Halogenated organic emissions to air] | 1300 |
| Halon (1301) [Halogenated organic emissions to air] | 6900 |
| Methane [Organic emissions to air (group VOC)] | 23 |
| Methane (biotic) [Air] | 23 |
| Methyl bromide [Halogenated organic emissions to air] | 5 |
| Nitrous oxide (laughing gas) [Inorganic emissions to air] | 296 |
| Perfluorobutane [Halogenated organic emissions to air] | 8600 |
| Perfluorocyclobutane [Halogenated organic emissions to air] | 8700 |
| Perfluorohexane [Organic intermediate products] | 9000 |
| Perfluorohexane [Halogenated organic emissions to air] | 9000 |
| Perfluoropentane [Halogenated organic emissions to air] | 8900 |
| Perfluoropropane [Halogenated organic emissions to air] | 8600 |
| R 11 (trichlorofluoromethane) [Halogenated organic emissions to air] | 4600 |
| R 113 (trichlorofluoroethane) [Halogenated organic emissions to air] | 6000 |
| R 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to air] | 9800 |
| R 115 (chloropentafluoroethane) [Halogenated organic emissions to air] | 7200 |
| R 116 (hexafluoroethane) [Halogenated organic emissions to air] | 11905 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to fresh water] | 10604 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to sea water] | 10604 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to air] | 10604 |
| R 123 (dichlorotrifluoroethane) [Halogenated organic emissions to air] | 120 |
| R 124 (chlorotetrafluoroethane) [Halogenated organic emissions to air] | 620 |
| R 125 (pentafluoroethane) [Halogenated organic emissions to air] | 3400 |
| R 13 (chlorotrifluoromethane) [Halogenated organic emissions to air] | 14006 |
| R 134 [Halogenated organic emissions to air] | 1100 |

| Flow | Global warming potential ($CO_2$ equivalents) |
|---|---|
| R 134a (tetrafluoroethane) [Halogenated organic emissions to air] | 1300 |
| R 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air] | 700 |
| R 142b (chlorodifluoroethane) [Halogenated organic emissions to air] | 2400 |
| R 143 (trifluoroethane) [Halogenated organic emissions to air] | 330 |
| R 143a (trifluoroethane) [Halogenated organic emissions to air] | 4300 |
| R 152a (difluoroethane) [Halogenated organic emissions to air] | 120 |
| R 22 (chlorodifluoromethane) [Halogenated organic emissions to air] | 1700 |
| R 225ca (dichloropentafluoropropane) [Halogenated organic emissions to air] | 180 |
| R 225cb (dichloropentafluoropentane) [Halogenated organic emissions to air] | 620 |
| R 227ea (septifluoropropane) [Halogenated organic emissions to air] | 3500 |
| R 23 (trifluoromethane) [Halogenated organic emissions to air] | 12005 |
| R 236fa (hexafluoropropane) [Halogenated organic emissions to air] | 9400 |
| R 245ca (pentafluoropropane) [Halogenated organic emissions to air] | 640 |
| R 32 (trifluoroethane) [Halogenated organic emissions to air] | 550 |
| R 41 [Halogenated organic emissions to air] | 97 |
| R 43-10 (decafluoropentane) [Halogenated organic emissions to air] | 1500 |
| Sulphur hexafluoride [Inorganic emissions to air] | 22200 |
| Tetrafluoromethane [Halogenated organic emissions to air] | 5700 |
| Trichloromethane (chloroform) [Halogenated organic emissions to air] | 30 |
| VOC [Organic emissions to sea water] | 16.1 |
| VOC [Organic emissions to fresh water] | 16.1 |
| VOC (unspecified) [Organic emissions to air (group VOC)] | 16.1 |

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## Table D-2. Stratospheric Ozone Depletion Equivalency Factors

| Flow | Ozone depletion potential (CFC-11 equivalents) |
|---|---|
| 1,1,1-Trichloroethane [Halogenated organic emissions to air] | 0.11 |
| Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air] | 1.10 |
| Chloromethane (methyl chloride) [Halogenated organic emissions to air] | 0.02 |
| Halon (1211) [Halogenated organic emissions to air] | 3 |
| Halon (1301) [Halogenated organic emissions to air] | 10 |
| Halon (2404) [Halogenated organic emissions to air] | 6 |
| HBFC-1201 (Halon-1201) [Halogenated organic emissions to air] | 1.40 |
| HBFC-1202 (Halon-1202) [Halogenated organic emissions to air] | 1.25 |
| HBFC-2311 (Halon-2311) [Halogenated organic emissions to air] | 0.14 |
| HBFC-2401 (Halon-2401) [Halogenated organic emissions to air] | 0.25 |
| HBFC-2402 (Halon-2402) [Halogenated organic emissions to air] | 7 |
| Methyl bromide [Halogenated organic emissions to air] | 0.60 |
| R 11 (trichlorofluoromethane) [Halogenated organic emissions to air] | 1 |
| R 113 (trichlorofluoroethane) [Halogenated organic emissions to air] | 0.90 |
| R 114 (dichlorotetrafluoroethane) [Halogenated organic emissions to air] | 0.85 |
| R 115 (chloropentafluoroethane) [Halogenated organic emissions to air] | 0.40 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to fresh water] | 0.82 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to sea water] | 0.82 |
| R 12 (dichlorodifluoromethane) [Halogenated organic emissions to air] | 0.82 |
| R 123 (dichlorotrifluoroethane) [Halogenated organic emissions to air] | 0.01 |
| R 124 (chlorotetrafluoroethane) [Halogenated organic emissions to air] | 0.03 |
| R 141b (dichloro-1-fluoroethane) [Halogenated organic emissions to air] | 0.09 |
| R 142b (chlorodifluoroethane) [Halogenated organic emissions to air] | 0.04 |
| R 22 (chlorodifluoromethane) [Halogenated organic emissions to air] | 0.03 |
| R 225ca (dichloropentafluoropropane) [Halogenated organic emissions to air] | 0.02 |
| R 225cb (dichloropentafluoropentane) [Halogenated organic emissions to air] | 0.02 |

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- Solomon, S. and Albritton, D.L. (1992) Time-Dependent Ozone Depletion Potentials for Short and Long-Term Forecasts. *Nature*, **357,** 33-37.

## Table D-3. Photochemical Oxidant Creation Potentials (Photochemical Smog)

| Flow | Photochemical oxidant potential (ethene equivalents) |
|---|---|
| 1,1,1-Trichloroethane [Halogenated organic emissions to air] | 0.01 |
| 1,2-Dichloroethylene [Halogenated organic emissions to air] | 0.42 |
| 1-Butoxypropanol [Group NMVOC to air] | 0.46 |
| 1-Butylene (Vinylacetylene) [Group NMVOC to air] | 1.08 |
| 1-Methoxy-2-propanol [Group NMVOC to air] | 0.36 |
| 1-Propanol [Group NMVOC to air] | 0.56 |
| 1-Propylbenzene [Group NMVOC to air] | 0.64 |
| 2,2-Dimethylbutane [Group NMVOC to air] | 0.24 |
| 2-Butoxy-ethanol [Group NMVOC to air] | 0.48 |
| 2-Ethoxy-ethanol [Group NMVOC to air] | 0.39 |
| 2-Methoxy-ethanol [Group NMVOC to air] | 0.31 |
| 2-Methylbutan-1-ol [Group NMVOC to air] | 0.41 |
| 2-Methylbutan-2-ol [Group NMVOC to air] | 0.14 |
| 2-Methylhexane [Group NMVOC to air] | 0.41 |
| 2-Methylnonane [Group NMVOC to air] | 0.40 |
| 3,5-Diethyltoluene [Group NMVOC to air] | 1.30 |
| 3-Methylbutan-1-ol [Group NMVOC to air] | 0.41 |
| 3-Methylbutan-2-ol [Group NMVOC to air] | 0.37 |
| 3-Methylhexane [Group NMVOC to air] | 0.36 |
| Acetic acid [Group NMVOC to air] | 0.10 |
| Acetone (dimethylcetone) [Group NMVOC to air] | 0.18 |
| Alcohols (unspec.) [Group NMVOC to air] | 0.20 |
| Alkane (unspecified) [Group NMVOC to air] | 0.40 |
| Benzaldehyde [Group NMVOC to air] | -0.09 |
| Benzene [Group NMVOC to air] | 0.19 |
| Butane [Group NMVOC to air] | 0.35 |
| Butane (n-butane) [Group NMVOC to air] | 0.41 |
| Butanol (n-Butanol) [Organic intermediate products] | 0.40 |
| Butanol (tertiary butanol) [Organic intermediate products] | 0.11 |
| Butanone (methyl ethyl ketone) [Group NMVOC to air] | 0.37 |
| Butylene glycol (butane diol) [Group NMVOC to air] | 0.20 |
| Butyraldehyde [Group NMVOC to air] | 0.80 |
| Carbon monoxide [Inorganic emissions to air] | 0.04 |

| Flow | Photochemical oxidant potential (ethene equivalents) |
|---|---|
| Carbon monoxide (biotic) [Air] | 0.03 |
| Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air] | 0.02 |
| Chlorobenzene [Halogenated organic emissions to air] | 0.02 |
| Chloromethane (methyl chloride) [Halogenated organic emissions to air] | 0.01 |
| cis-Dichloroethene [Halogenated organic emissions to air] | 0.45 |
| Crude oil [Crude oil (resource)] | 0.40 |
| Cyclohexanone [Group NMVOC to air] | 0.30 |
| Decane [Group NMVOC to air] | 0.38 |
| Diacetone alcohol [Group NMVOC to air] | 0.31 |
| Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [Halogenated organic emissions to air] | 0.02 |
| Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [Halogenated organic emissions to fresh water] | 0.02 |
| Dichloroethane (ethylene dichloride) [Halogenated organic emissions to air] | 0.02 |
| Dichloroethane (isomers) [Halogenated organic emissions to air] | 0.02 |
| Dichloromethane (methylene chloride) [Halogenated organic emissions to air] | 0.07 |
| Diisopropylether [Group NMVOC to air] | 0.40 |
| Dimethoxy methane [Group NMVOC to air] | 0.16 |
| Dimethyl carbonate [Group NMVOC to air] | 0.03 |
| Dimethyl ether [Group NMVOC to air] | 0.19 |
| Dodecane [Group NMVOC to air] | 0.36 |
| Ethane [Group NMVOC to air] | 0.12 |
| Ethanol [Group NMVOC to air] | 0.40 |
| Ethene (ethylene) [Group NMVOC to air] | 0.09 |
| Ethylene acetate (ethyl acetate) [Group NMVOC to air] | 0.21 |
| Ethylene glycol [Group NMVOC to air] | 0.37 |
| Ethylene oxide [Group NMVOC to air] | 0.38 |
| Ethyl-trans-butyl ether [Group NMVOC to air] | 0.24 |
| Formic acid (methane acid) [Group NMVOC to air] | 0.03 |
| Furfuryl alcohol [Group NMVOC to air] | 0.20 |
| Gasoline (regular) [Crude oil products] | 0.40 |
| iso-Butyl acetate [Group NMVOC to air] | 0.40 |
| iso-Butyraldehyde [Group NMVOC to air] | 0.51 |
| iso-Pentane [Group NMVOC to air] | 0.41 |
| meta-Ethyltoluene [Group NMVOC to air] | 1.02 |

| Flow | Photochemical oxidant potential (ethene equivalents) |
|---|---|
| Methane [Organic emissions to air (group VOC)] | 0.01 |
| Methane (biotic) [Air] | 0.01 |
| Methanol [Group NMVOC to air] | 0.14 |
| Methyl acetate [Group NMVOC to air] | 0.06 |
| Methyl ethyl ketone (MEK, 78-93-3) [Emissions to air] | 0.37 |
| Methyl formate [Group NMVOC to air] | 0.03 |
| Methyl isopropylketone [Group NMVOC to air] | 0.36 |
| Methyl tert-butylether [Group NMVOC to air] | 0.18 |
| Methyl tert-butylketone [Group NMVOC to air] | 0.32 |
| Methylpentanone [Group NMVOC to air] | 0.49 |
| n-Butyl acetate [Group NMVOC to air] | 0.27 |
| Neopentane [Group NMVOC to air] | 0.17 |
| Nitrogen dioxide [Inorganic emissions to air] | 0.03 |
| Nitrogen oxides [Inorganic emissions to air] | 0.03 |
| Pentanaldehyde [Group NMVOC to air] | 0.77 |
| Pentane (n-pentane) [Group NMVOC to air] | 0.40 |
| Polychlorinated biphenyls (PCB unspecified) [Halogenated organic emissions to air] | 0.02 |
| Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air] | 0.02 |
| Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD) [Halogenated organic emissions to air] | 0.02 |
| Propane [Group NMVOC to air] | 0.18 |
| Propanol (iso-propanol; isopropanol) [Group NMVOC to air] | 0.19 |
| Propionaldehyde [Group NMVOC to air] | 0.80 |
| Propionic acid (propane acid) [Group NMVOC to air] | 0.15 |
| Propyl acetate [Group NMVOC to air] | 0.22 |
| sec-Butyl acetate [Group NMVOC to air] | 0.28 |
| Styrene [Group NMVOC to air] | 0.14 |
| Sulphur dioxide [Inorganic emissions to air] | 0.05 |
| tertiary-Butyl acetate [Group NMVOC to air] | 0.05 |
| Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air] | 0.03 |
| Tetrafluoromethane [Halogenated organic emissions to air] | 0.02 |
| trans-2-Butene [Group NMVOC to air] | 1.13 |
| trans-2-Pentene [Group NMVOC to air] | 1.12 |

| Flow | Photochemical oxidant potential (ethene equivalents) |
|---|---|
| trans-Dichloroethene [Halogenated organic emissions to air] | 0.39 |
| Trichloroethene (isomers) [Halogenated organic emissions to air] | 0.33 |
| Trichloromethane (chloroform) [Halogenated organic emissions to air] | 0.02 |
| Trimethylbenzene [Group NMVOC to air] | 1.38 |
| Vinyl acetate (108-05-4) [Emissions to air] | 0.22 |
| Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air] | 0.02 |
| VOC (unspecified) [Organic emissions to air (group VOC)] | 0.34 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) [Group NMVOC to air] | 1.01 |

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## Table D-4. Acidification Potentials

| Flow | Acidification potential ($SO_2$ equivalents) |
|---|---|
| Ammonia [Inorganic emissions to air] | 1.88 |
| Ammonium [Inorganic emissions to air] | 3.76 |
| Ammonium nitrate [Inorganic emissions to air] | 0.85 |
| Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions to air] | 0.83 |
| Chloromethane (methyl chloride) [Halogenated organic emissions to air] | 0.63 |
| Dichloromethane (methylene chloride) [Halogenated organic emissions to air] | 0.74 |
| Hydrochloric acid (100%) [Inorganic emissions to air] | 0.88 |
| Hydrogen bromine (hydrobromic acid) [Inorganic emissions to air] | 0.40 |
| Hydrogen chloride [Inorganic emissions to agricultural soil] | 0.88 |
| Hydrogen chloride [Inorganic emissions to air] | 0.88 |
| Hydrogen chloride [Inorganic emissions to fresh water] | 0.88 |
| Hydrogen chloride [Inorganic emissions to sea water] | 0.88 |
| Hydrogen chloride [Inorganic emissions to industrial soil] | 0.88 |
| Hydrogen cyanide (prussic acid) [Inorganic emissions to air] | 1.60 |
| Hydrogen fluoride [Inorganic emissions to air] | 1.60 |
| Hydrogen fluoride (hydrofluoric acid) [Inorganic emissions to sea water] | 1.60 |
| Hydrogen fluoride (hydrofluoric acid) [Inorganic emissions to agricultural soil] | 1.60 |
| Hydrogen fluoride (hydrofluoric acid) [Inorganic emissions to industrial soil] | 1.60 |
| Hydrogen sulphide [Inorganic emissions to agricultural soil] | 1.88 |
| Hydrogen sulphide [Inorganic emissions to air] | 1.88 |
| Hydrogen sulphide [Inorganic emissions to industrial soil] | 1.88 |
| Hydrogen sulphide [Inorganic emissions to sea water] | 1.88 |
| Hydrogen sulphide [Inorganic emissions to fresh water] | 1.88 |
| Nitric acid [Inorganic emissions to air] | 0.51 |
| Nitric acid [Inorganic emissions to sea water] | 0.51 |
| Nitric acid [Inorganic emissions to fresh water] | 0.51 |
| Nitric acid [Inorganic emissions to industrial soil] | 0.51 |
| Nitric acid [Inorganic emissions to agricultural soil] | 0.51 |
| Nitrogen dioxide [Inorganic emissions to air] | 0.70 |
| Nitrogen monoxide [Inorganic emissions to air] | 1.07 |
| Nitrogen oxides [Inorganic emissions to air] | 0.70 |
| Phosphoric acid [Inorganic emissions to agricultural soil] | 0.98 |
| Phosphoric acid [Inorganic emissions to sea water] | 0.98 |
| Phosphoric acid [Inorganic emissions to air] | 0.98 |

| Flow | Acidification potential ($SO_2$ equivalents) |
|---|---|
| Phosphoric acid [Inorganic emissions to fresh water] | 0.98 |
| Phosphoric acid [Inorganic emissions to industrial soil] | 0.98 |
| Sulphur dioxide [Inorganic emissions to air] | 1 |
| Sulphur trioxid [Inorganic emissions to air] | 0.80 |
| Sulphuric acid [Inorganic emissions to air] | 0.65 |
| Sulphuric acid [Inorganic emissions to agricultural soil] | 0.65 |
| Sulphuric acid [Inorganic emissions to fresh water] | 0.65 |
| Sulphuric acid [Inorganic emissions to industrial soil] | 0.65 |
| Sulphuric acid [Inorganic emissions to sea water] | 0.65 |
| Sulphuric acid aerosol [Inorganic emissions to air] | 0.65 |
| Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air] | 0.19 |
| Trichloroethene (isomers) [Halogenated organic emissions to air] | 0.72 |
| Trichloromethane (chloroform) [Halogenated organic emissions to air] | 0.80 |
| Vinyl chloride (VCM; chloroethene) [Halogenated organic emissions to air] | 0.63 |

**Sources:**

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### Table D-5. Eutrophication Potentials[a]

| Flow | Eutrophication potential (phosphate equivalents) |
|---|---|
| Acetic acid [Hydrocarbons to fresh water] | 0.02 |
| Acetic acid [Hydrocarbons to sea water] | 0.02 |
| Ammonia [Waste to POTW] | 0.35 |
| Ammonium / ammonia [Inorganic emissions to sea water] | 0.33 |
| Ammonium / ammonia [Inorganic emissions to fresh water] | 0.33 |
| Biological oxygen demand (BOD) [Analytical measures to sea water] | 0.02 |
| Biological oxygen demand (BOD) [Analytical measures to fresh water] | 0.02 |
| Biological oxygen demand (BOD) [Waste to POTW] | 0.02 |
| Calcium nitrate (Ca(NO3)2) [Inorganic emissions to fresh water] | 0.08 |
| Calcium nitrate (Ca(NO3)2) [Inorganic emissions to sea water] | 0.08 |
| Chemical oxygen demand (COD) [Analytical measures to sea water] | 0.02 |
| Chemical oxygen demand (COD) [Analytical measures to fresh water] | 0.02 |
| Ethanol [Hydrocarbons to sea water] | 0.04 |
| Ethanol [Hydrocarbons to fresh water] | 0.04 |
| Heptane [Hydrocarbons to sea water] | 0.08 |
| Heptane [Hydrocarbons to fresh water] | 0.08 |
| Hexane (isomers) [Hydrocarbons to sea water] | 0.08 |
| Hexane (isomers) [Hydrocarbons to fresh water] | 0.08 |
| Hydrocarbons (unspecified) [Hydrocarbons to fresh water] | 0.08 |
| Hydrocarbons (unspecified) [Hydrocarbons to sea water] | 0.08 |
| Methanol [Hydrocarbons to fresh water] | 0.03 |
| Methanol [Hydrocarbons to sea water] | 0.03 |
| Nitrate [Inorganic emissions to sea water] | 0.10 |
| Nitrate [Inorganic emissions to fresh water] | 0.10 |
| Nitric acid [Inorganic emissions to sea water] | 0.10 |
| Nitric acid [Inorganic emissions to fresh water] | 0.10 |
| Nitrite [Inorganic emissions to fresh water] | 0.10 |
| Nitrite [Inorganic emissions to sea water] | 0.10 |
| Nitrogen [Inorganic emissions to fresh water] | 0.42 |
| Nitrogen [Inorganic emissions to sea water] | 0.42 |
| Nitrogen monoxide [Inorganic emissions to air] | 0.13 |
| Nitrogen organic bounded [Inorganic emissions to sea water] | 0.42 |
| Nitrogen organic bounded [Inorganic emissions to fresh water] | 0.42 |
| Octane [Hydrocarbons to sea water] | 0.08 |

| Flow | Eutrophication potential (phosphate equivalents) |
|---|---|
| Octane [Hydrocarbons to fresh water] | 0.08 |
| Oil (unspecified) [Hydrocarbons to fresh water] | 0.08 |
| Oil (unspecified) [Hydrocarbons to sea water] | 0.08 |
| Organic compounds (dissolved) [Organic emissions to fresh water] | 0.02 |
| Organic compounds (dissolved) [Organic emissions to sea water] | 0.03 |
| Organic compounds (unspecified) [Organic emissions to sea water] | 0.03 |
| Organic compounds (unspecified) [Organic emissions to fresh water] | 0.02 |
| Phosphate [Waste to POTW] | 1 |
| Phosphate [Inorganic emissions to sea water] | 1 |
| Phosphate [Inorganic emissions to fresh water] | 1 |
| Phosphoric acid [Inorganic emissions to sea water] | 0.97 |
| Phosphoric acid [Inorganic emissions to fresh water] | 0.97 |
| Phosphoruos-pent-oxide [Inorganic emissions to sea water] | 1.34 |
| Phosphoruos-pent-oxide [Inorganic emissions to fresh water] | 1.34 |
| Phosphorus [Inorganic emissions to sea water] | 3.06 |
| Phosphorus [Inorganic emissions to fresh water] | 3.06 |
| Sodium nitrate (NaNO3) [Inorganic emissions to sea water] | 0.07 |
| Sodium nitrate (NaNO3) [Inorganic emissions to fresh water] | 0.07 |
| Total dissolved organic bounded carbon [Analytical measures to fresh water] | 0.06 |
| Total dissolved organic bounded carbon [Analytical measures to sea water] | 0.06 |
| Total organic bounded carbon [Analytical measures to sea water] | 0.06 |
| Total organic bounded carbon [Analytical measures to fresh water] | 0.06 |
| Xylene (isomers; dimethyl benzene) [Hydrocarbons to fresh water] | 0.07 |
| Xylene (isomers; dimethyl benzene) [Hydrocarbons to sea water] | 0.07 |
| Xylene (meta-Xylene; 1,3-Dimethylbenzene) [Hydrocarbons to sea water] | 0.07 |
| Xylene (meta-Xylene; 1,3-Dimethylbenzene) [Hydrocarbons to fresh water] | 0.07 |
| Xylene (ortho-Xylene; 1,2-Dimethylbenzene) [Hydrocarbons to fresh water] | 0.07 |
| Xylene (ortho-Xylene; 1,2-Dimethylbenzene) [Hydrocarbons to sea water] | 0.07 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) [Hydrocarbons to sea water] | 0.07 |
| Xylene (para-Xylene; 1,4-Dimethylbenzene) [Hydrocarbons to fresh water] | 0.07 |

[a] Only includes water emissions.

**Sources:**

(a) *Handbook on life cycle assessment - Operational Guide to the ISO Standards*, Guinée, J.B., Ed.; Kluwer, Dordrecht, 2002, and Heijungs, R., J. Guinée, g. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. Van Duin en H.P. de Goede. Environmental life cycle assessment of products. Guide and background (ISBN 90-5191-064-9). Leiden (the Netherlands), Centre of Environmental Science of Leiden Univerisity, 1992.

# Appendix E: Supporting Toxicity Data for the Wire and Cable Partnership

## Appendix E-1: Toxicity Data Collection

**Background:**

In the Wire and Cable Partnership (WCP), human and ecological toxicity impacts of chemicals found in the life-cycle inventory of selected cable resins are calculated by using a chemical ranking method. This method was originally developed for a life-cycle assessment (LCA) done with support from the EPA Office of Research and Development (ORD) and Saturn Corporation. It was updated for the EPA's Design for the Environment (DfE) Program Computer Display Project (CDP) in consultation with ORD. The final CDP method was reviewed by ORD as well as EPA's Office of Pollution Prevention and Toxics Risk Assessment Division (RAD) prior to publication (Socolof *et al*., 2001). The methodology was subsequently used for the DfE Lead Free Solder Project (LFSP) (Geibig and Socolof, 2005), when other minor updates were made which included (1) separating chronic heath impacts into cancer impacts and chronic non-cancer impacts (for both public and occupational impacts) and (2) removing the presentation of the terrestrial ecotoxicity impact category.

Separating the chronic human impacts into two separate categories was done because the hazard values (HVs) calculated for each of these two impact categories are calculated based on geometric means for different endpoints. For cancer impacts, the HV is based on the geometric mean of cancer slope factors. The geometric mean for cancer slope factors are largely influenced by the slope factors for dioxins, which are very high. Thus the associated hazard values of most cancer impacts have numerically small HVs (since the HV is calculated by dividing the chemical specific slope factor by the geometric mean). Compared to the non-cancer HVs, the cancer HVs are generally much smaller numbers. Therefore, combining the two impact scores into one impact category causes the non-cancer impacts to overshadow the cancer impacts. Therefore, to observe any real resolution in the cancer impact category, the cancer and non-cancer impact categories were separated for the LFSP, as will also be done for the WCP.

The other change from the CDP was to remove the terrestrial toxicity impact category as being presented independently because the chronic non-cancer impacts presented alone are calculated the same way as the terrestrial ecotoxicity impacts. Thus, the terrestrial ecotoxicity impacts are represented by the non-cancer impacts and thus were not presented separately in the LFSP. The WCP LCA will use the methodology as it was used in the LFSP.

In the LCA, there is no intent to conduct a full risk assessment or even a screening level risk assessment, given that there are no real spatial or temporal boundaries to this global, industry-wide LCA. In order to provide some weighting of the inventory data to represent potential toxicity, basic toxicity data (e.g., a NOAEL for chronic, non-carcinogenic effects) are used. The intent is to modify the inventory data by the inherent toxicity of the material to provide a relative toxicity measure.

Toxicity data are being collected for potentially toxic chemicals in the WCP inventory. To save project resources, toxicity data that have been collected for previous DfE projects will be used in the WCP. Toxicity data used prior to this project were collected by Syracuse Research Corporation (SRC) (under contract with EPA) and EPA's RAD for the CDP, and by the Toxicity and Hazard Assessment Group in the Life Sciences Division at the Oak Ridge National Laboratory (ORNL) for the LFSP. ORNL conducted their search in April, 2003 and the data were subsequently reviewed and/or supplemented by EPA's RAD. The description below presents the method to be used to collect the WCP toxicity data.

**Data Collection Approach:**

Once inventory data are collected for the project, the inventory flows are checked to determine if they are potentially toxic. The lists of potentially toxic and non-toxic chemicals will be reviewed by EPA. Those excluded from the toxicity list are assumed to be non-toxic. The chemicals then deemed potentially toxic are assembled for toxicity data collection. The data are first checked for correct chemical name and Chemical Abstracts Service (CAS) registry number and the associated inventory disposition (e.g., release to water) is identified to help determine classification into different toxicity impact categories. Classification helps determine what toxicity data need to be collected. For example, if an inventory flow is released to water, it will require aquatic toxicity data.

For chemicals identified in the inventory of the life cycle of the wire and cable alternatives, for which toxicity data were collected for previous projects, data from the previous projects will be used. For new chemicals identified in this LCA, chronic human toxicity endpoints and both acute and chronic aquatic toxicity endpoints are being searched. The following specific endpoints will be used for calculating human toxicity scores:

- inhalation or oral NOAEL (or inhalation or oral LOAEL),
- cancer slope factors, and
- cancer weight of evidence (WOE).

For ecological toxicity, the following endpoints are used for calculating aquatic toxicity:

- fish $LC_{50}$ and
- fish NOEL.

EPA's RAD provided guidance for collecting toxicity data for DfE Cleaner Technology Substitutes Assessments. This served as the basis for data collection for this LCA; however, it was modified as applicable to an LCA. As stated in the RAD guidance, when searching for the toxicity endpoints, the first sources to be reviewed will be:

- EPA's Integrated Risk Information System (IRIS) (http://www.epa.gov/iris/)—reference dose, reference concentration, cancer slope factor, unit risk, and weight-of-evidence classification.
- ATSDR (Agency for Toxic Substances and Disease Registry)—a federal public health agency of the U.S. Department of Health and Human Services, provides trusted health information to prevent harmful exposures and diseases related to toxic substances.

- EPA’s High Production Volume (HPV) Challenge robust summaries and supporting documents contain information on physical properties, environmental fate and transport, toxicity, and ecotoxicity data submitted by Industry to the HPV Challenge Program, and
- Organization for Economic Cooperation and Development’s (OECD’s) Screening Information Data Set (SIDS) robust summaries and supporting documents.

If endpoints from these sources are found, and do not conflict with other sources from this list, those data are chosen. If more than one value is found for an endpoint, decisions of what data to use will be presented to EPA by Abt Associates with any final decisions made by EPA.

If endpoints are not found from the above sources, the following databases would be searched:

- STN (CAS-Online)—provides information on chemical identity and chemical use. TOXLINE “special” database plus BIOSIS was searched in conjunction with MEDLINE.
- TSCATS (Toxic Substances Control Act Test Submissions)–the EPA database that holds data submitted to the Agency under TSCA sections 4 and 8). Although data in TSCATS may be unpublished and, therefore, not subjected to peer review by the editors of a journal, the data may provide useful information on particular chemicals and can be considered for preparation of robust summaries if the TSCATS data meet Agency standards for data quality/data adequacy.
- IUCLID (International Uniform ChemicaL Information Database) – maintained under the responsibility of the European Chemicals Bureau (ECB) within the Institute for Health and Consumer Protection (IHCP) of the Joint Research Centre (JRC) of the European Commission, and is distributed free of charge; includes, for example, chemical substances composition, physical/chemical properties, toxicological properties, and eco-toxicological properties.

Other databases have also served as sources (e.g., Health Effects Assessment Summary Tables [HEAST], Hazardous Substances Data Bank [HSDB], Registry of Toxic Effects of Chemical Substances [RTECS]). In general, priority is given to peer-reviewed databases such as IRIS, HEAST, HDSB, then other databases (e.g., RTECS), then other studies or literature, and finally estimation methods (e.g., structure-activity relationships [SARs] or quantitative structure-activity relationships [QSARs]).

In cases where there is more than one data point, we will select a data point based on the applicability of the study to the endpoint of interest and the robustness of the study (as best could be determined from the available data). If the original sources are not reviewed, information from secondary sources (e.g., EPA’s ECOTOXicology Data Base System, version 4 [U.S. EPA, 2007]) on the test type and duration will be considered. The following hierarchy of fish studies, based on Swanson *et al.* 1997, will be employed to choose $LC_{50}$ ecotoxicity data in order of preference:

(1) fathead minnow 96-h flow-through test

(2) 96-h flow-through test for another freshwater fish, excluding trout

(3) fathead minnow 96-h static test

(4) 96-h static test for another freshwater fish, excluding trout

If the only adequate data are for trout, they will also be used. In cases where multiple data points (with equivalent quality, test type, and species type) are available, an average of those data will be taken as the data point of interest. This is preferred over taking the most toxic response as these data are used in relative ranking of chemicals and not to serve as protective exposure limits.

Other aquatic species (e.g., daphnia, algae) were not used in the original methodology used to develop the LCIA toxicity method used in this study (i.e., CHEMS-1, Swanson *et al.*, 1997); however, this does not preclude future versions of this methodology from using other species besides fish, which would represent lower trophic levels (e.g., daphnia or algae).

**Toxicity Data:**

The toxicity data required for the LCIA, and to be collected are as follows:

- Cancer (mammalian toxicity)
    - oral SF
    - inhalation SF
    - WOE
- Noncancer (mammalian toxicity)
    - oral NOAEL (or LOAEL)
    - inhalation NOAEL (or LOAEL)
- Aquatic ecotoxicity
    - $LC_{50}$
    - NOEL or NOEC

In the cases where chronic ecotoxicity (i.e., NOEL or NOEC) data are not available, the log $K_{ow}$ and the $LC_{50}$ can be used to predict the NOEL (described in Geibig and Socolof, 2005, Volume 1, Section 3.1.2.13). The log $K_{ow}$ values will be determined using a LOGKOW/KOWWIN Program (http://www.syrres.com/esc/est_kowdemo.htm), provided the appropriate Simplified Molecular Input line Entry System (SMILES) notation is determined. When other data related to the toxicity of a chemical are readily available, such data will also be reported as "other" toxicity values. For the WCP, new data were searched for approximately 30 chemicals for which we did not already have existing data.

## REFERENCES

Geibig, J.R. and M.L. Socolof. 2005. *Solder in Electronics: A Life-Cycle Assessment.* U.S. Environmental Protection Agency Design for the Environment Program, EPA 744-R-05-001. Washington DC. August. Available at: http://www.epa.gov/dfe/pubs/solder/lca/index.htm.

Socolof, M.L. J.G. Overly, L.E. Kincaid, J.R. Geibig. 2001. Desktop Computer Displays: A Life-Cycle Assessment, Volumes 1 and 2. U.S. Environmental Protection Agency, EPA 744-R-01-004a,b, 2001. Available at: http://www.epa.gov/oppt/dfe/pubs/comp-dic/lca/.

Swanson, M.B., G.A. Davis, L.E. Kincaid, T.W. Schultz, J.E. Bartmess, *et al*. 1997. “A Screening Method for Ranking and Scoring Chemicals by Potential Human Health and Environmental Impacts,” *Environmental Toxicology and Chemistry*, Vol. 16, No. 2, pp. 372-383, SETAC Press.

U.S. EPA. 2007. ECOTOXicology Data base System, version 4. http://cfpub.epa.gov/ecotox/quick_query.htm. Latest update: March 12, 2007.

## GLOSSARY OF TOXICITY COMPARISON TERMS

LD50 (Lethal Dose 50)

A calculated dose of a substance which is expected to cause the death of 50 percent of a defined experimental animal population.

LC50 (Lethal Concentration 50)

A calculated concentration of a substance in air or water, which is expected to cause the death of 50 percent of a defined experimental animal population.

LOAEL (Lowest observable adverse effect level)

Lowest concentration or amount of a substance, found by experiment or observation, which causes an adverse alteration of morphology, functional capacity, growth, development, or life span of a target organism distinguishable from normal (control) organisms of the same species and strain under defined conditions of exposure.

NOAEL (No observable adverse effect level)

No-observed-adverse-effect level. Greatest concentration or amount of a substance, found by experiment or observation, which causes no detectable adverse alteration of morphology, functional capacity, growth, development, or life span of the target organism under defined conditions.

WOE (Weight of evidence)

Classification of relevance and quality of studies used to make a determination of carcinogenicity.

# Appendix E-2: Toxicity Data Used in Hazard Value Calculations

The toxicity data presented in the following tables are for the master list of chemicals used to calculate endpoint-specific geometric means, which are then used to develop hazard values (HVs) for the chemicals in the WCP inventory. The HVs are a relative ranking of potentially toxic materials used in the occupational, public, and ecotoxicity impact categories. Details of the methodology are described in Chapter 3. Note that the chemicals listed for oral and inhalation NOAELs only include those with NOAEL values in the literature. Chemicals for which we used LOAELs to estimate NOAELs were not included in the calculation of the NOAEL geometric means. Further, the chemicals in the WCP inventory are a subset of the chemicals used to generate the geometric means presented in the following tables:

Table E-1. Slope Factors
Table E-2. Oral NOAELs
Table E-3. Inhalation NOAELs
Table E-4. Fish LC50s
Table E-5. Fish NOELs

## Table E-1. Slope Factors[a]

| Chemical | CAS # | Oral Slope Factor (mg/kg-day)-1 | Inhalation Slope Factor (mg/kg-day)-1 |
|---|---|---|---|
| Acephate | 30560-19-1 | 8.70E-03 | |
| Acetaldehyde | 75-07-0 | | 7.70E-03 |
| Acrylamide | 79-06-1 | 4.50E+00 | 4.50E+00 |
| Acrylonitrile | 107-13-1 | 5.40E-01 | 2.40E-01 |
| Alachlor | 15972-60-8 | 8E-02 | |
| Aldrin | 309-00-2 | 1.70E+01 | 1.70E+01 |
| Aniline | 62-53-3 | 5.70E-03 | |
| Aramite | 140-57-8 | 2.50E-02 | 2.50E-02 |
| Aroclor 1016 | 12674-11-2 | 4E-01 | 4E-01 |
| Aroclor 1016 | 12674-11-2 | 2E+00 | 2E+00 |
| Aroclor 1221 | 11104-28-2 | 4E-01 | 4E-01 |
| Aroclor 1221 | 11104-28-2 | 2E+00 | 2E+00 |
| Aroclor 1232 | 11141-16-5 | 4E-01 | 4E-01 |
| Aroclor 1232 | 11141-16-5 | 2E+00 | 2E+00 |
| Aroclor 1242 | 53469-21-9 | 4E-01 | 4E-01 |
| Aroclor 1242 | 53469-21-9 | 2E+00 | 2E+00 |
| Aroclor 1248 | 12672-29-6 | 4E-01 | 4E-01 |
| Aroclor 1248 | 12672-29-6 | 2E+00 | 2E+00 |
| Aroclor 1254 | 11097-69-1 | 4E-01 | 4E-01 |
| Aroclor 1254 | 11097-69-1 | | 2E+00 |
| Aroclor 1260 | 11096-82-5 | 4E-01 | 4E-01 |
| Aroclor 1260 | 11096-82-5 | 2E+00 | 2E+00 |
| Arsenic, Inorganic | 7440-38-2 | 1.50E+00 | 5E+01 |
| Atrazine | 1912-24-9 | 2.22E-01 | |
| Azobenzene | 103-33-3 | 1.10E-01 | 1.10E-01 |
| Benz[a]anthracene | 56-55-3 | 7.30E-01 | 3.10E-01 |
| Benzene | 71-43-2 | 5.50E-02 | 2.90E-02 |
| Benzidine | 92-87-5 | 2.30E+02 | 2.30E+02 |
| Benzo[a]pyrene | 50-32-8 | 7.30E+00 | 3.10E+00 |
| Benzo[b]fluoranthene | 205-99-2 | 7.30E-01 | 3.10E-01 |
| Benzo[k]fluoranthene | 207-08-9 | 7.30E-02 | 3.10E-02 |
| Benzotrichloride | 98-07-7 | 1.30E+01 | |
| Benzyl Chloride | 100-44-7 | 1.70E-01 | |
| Beryllium and compounds | 7440-41-7 | 4.30E+00 | 8.40E+00 |
| Bis(2-chloro-1-methylethyl)ether (Technical) | 108-60-1 | 7E-02 | 3.50E-02 |
| Bis(2-chloroethyl)ether | 111-44-4 | 1.10E+00 | 1.10E+00 |
| Bis(2-ethylhexyl)phthalate | 117-81-7 | 1.40E-02 | |
| Bis(chloromethyl)ether | 542-88-1 | 2.20E+02 | 2.20E+02 |
| Bromodichloromethane | 75-27-4 | 6.20E-02 | |
| Bromoform | 75-25-2 | 7.90E-03 | 3.90E-03 |
| Butadiene, 1,3- | 106-99-0 | | 1.80E+00 |
| Cadmium (Diet) | 7440-43-9 | | 6.10E+00 |

| Chemical | CAS # | Oral Slope Factor (mg/kg-day)-1 | Inhalation Slope Factor (mg/kg-day)-1 |
|---|---|---|---|
| Cadmium (Water) | 7440-43-9 | | 6.10E+00 |
| Captafol | 2425-06-1 | 8.60E-03 | |
| Captan | 133-06-2 | 3.50E-03 | |
| Carbazole | 86-74-8 | 2E-02 | |
| Carbon Tetrachloride | 56-23-5 | 1.30E-01 | 5.30E-02 |
| Chloranil | 118-75-2 | 4.03E-01 | |
| Chlordane | 057-74-9 | 3.50E-01 | 1.30E+00 |
| Chloro-2-methylaniline HCl, 4- | 3165-93-3 | 4.60E-01 | |
| Chloro-2-methylaniline, 4- | 95-69-2 | 5.80E-01 | |
| Chlorobenzilate | 510-15-6 | 2.70E-01 | 2.70E-01 |
| Chlorodibromoethane | 73506-94-2 | 8.40E-02 | |
| Chloroform | 67-66-3 | 6.10E-03 | 8.10E-02 |
| Chloromethane | 74-87-3 | 1.30E-02 | 6.30E-03 |
| Chloronitrobenzene, o- | 88-73-3 | 2.50E-02 | |
| Chloronitrobenzene, p- | 121-73-3 | 1.80E-02 | |
| Chlorothalonil | 1897-45-6 | 1.10E-02 | |
| Chromium VI (chromic acid mists) | 18540-29-9 | | 4.10E+01 |
| Chromium VI (particulates) | 18540-29-9 | | 4.10E+01 |
| Chrysene | 218-01-9 | 7.30E-03 | 3.10E-03 |
| Coke Oven Emissions | 8007-45-2 | | 2.20E+00 |
| Crotonaldehyde, trans- | 123-73-9 | 1.90E+00 | |
| Cyanazine | 21725-46-2 | 8.40E-01 | |
| Cyclohexane, 1,2,3,4,5-pentabromo-6-chloro- | 87-84-3 | 2.30E-02 | |
| DDD | 72-54-8 | 2.40E-01 | |
| DDE | 72-55-9 | 3.40E-01 | |
| DDT | 50-29-3 | 3.40E-01 | 3.40E-01 |
| Di(2-ethylhexyl)adipate | 103-23-1 | 1.20E-03 | |
| Diallate | 2303-16-4 | 6.10E-02 | |
| Dibenz[a,h]anthracene | 53-70-3 | 7.30E+00 | 3.10E+00 |
| Dibromo-3-chloropropane, 1,2- | 96-12-8 | 1.40E+00 | 2.40E-03 |
| Dibromochloromethane | 124-48-1 | 8.40E-02 | |
| Dibromoethane, 1,2- | 106-93-4 | 8.50E+01 | 7.60E-01 |
| Dichloro-2-butene, 1,4- | 764-41-0 | | 9.30E+00 |
| Dichlorobenzene, 1,4- | 106-46-7 | 2.40E-02 | |
| Dichlorobenzidine, 3,3'- | 91-94-1 | 4.50E-01 | |
| Dichloroethane, 1,2- | 107-06-2 | 9.10E-02 | 9.10E-02 |
| Dichloroethylene, 1,1- | 75-35-4 | 6E-01 | 1.20E+00 |
| Dichloropropane, 1,2- | 78-87-5 | 6.80E-02 | |
| Dichloropropene, 1,3- | 542-75-6 | 1E-01 | 1.40E-02 |
| Dichlorvos | 62-73-7 | 2.90E-01 | |
| Dieldrin | 60-57-1 | 1.60E+01 | 1.60E+01 |
| Diethylstilbesterol | 56-53-1 | 4.70E+03 | 4.90E+02 |
| Dimethoxybenzidine, 3,3'- | 119-90-4 | 1.40E-02 | |
| Dimethylaniline HCl, 2,4- | 21436-96-4 | 5.80E-01 | |

| Chemical | CAS # | Oral Slope Factor (mg/kg-day)-1 | Inhalation Slope Factor (mg/kg-day)-1 |
|---|---|---|---|
| Dimethylaniline, 2,4- | 095-68-1 | 7.50E-01 | |
| Dimethylbenzidine, 3,3'- | 119-93-7 | 9.20E+00 | |
| Dimethylhydrazine, 1,1- | 57-14-7 | 3E+00 | 1.72E+01 |
| Dinitrotoluene Mixture, 2,4/2,6- | 25321-14-6 | 6.80E-01 | |
| Dinitrotoluene, 2,4- | 121-14-2 | 6.80E-01 | |
| Dinitrotoluene, 2,6- | 606-20-2 | 6.80E-01 | |
| Dioxane, 1,4- | 123-91-1 | 1.10E-02 | |
| Diphenylhydrazine, 1,2- | 122-66-7 | 8E-01 | 8E-01 |
| Direct Black 38 | 1937-37-7 | 8.60E+00 | |
| Direct Blue 6 | 2602-46-2 | 8.10E+00 | |
| Direct Brown 95 | 16071-86-6 | 9.30E+00 | |
| Epichlorohydrin | 106-89-8 | 9.90E-03 | 4.20E-03 |
| Ethyl Acrylate | 140-88-5 | 4.80E-02 | |
| Ethylbenzene | 100-41-4 | | 3.85E-03 |
| Ethylene Oxide | 75-21-8 | 1.02E+00 | 3.50E-01 |
| Ethylene Thiourea | 96-45-7 | 1.10E-01 | |
| Folpet | 133-07-3 | 3.50E-03 | |
| Fomesafen | 72178-02-0 | 1.90E-01 | |
| Formaldehyde | 50-00-0 | | 4.50E-02 |
| Furazolidone | 67-45-8 | 3.80E+00 | |
| Furium | 531-82-8 | 5E+01 | |
| Furmecyclox | 60568-05-0 | 3E-02 | |
| Heptachlor | 76-44-8 | 4.50E+00 | 4.50E+00 |
| Heptachlor Epoxide | 1024-57-3 | 9.10E+00 | 9.10E+00 |
| Hexachlorobenzene | 118-74-1 | 1.60E+00 | 1.60E+00 |
| Hexachlorobutadiene | 87-68-3 | 7.80E-02 | 7.80E-02 |
| Hexachlorocyclohexane, Alpha- | 319-84-6 | 6.30E+00 | 6.30E+00 |
| Hexachlorocyclohexane, Beta- | 319-85-7 | 1.80E+00 | 1.80E+00 |
| Hexachlorocyclohexane, Gamma- | 58-89-9 | 1.30E+00 | |
| Hexachlorocyclohexane, Technical | 608-73-1 | 1.80E+00 | 1.80E+00 |
| Hexachlorodibenzo-p-dioxin, Mixture | 19408-74-3 | 6.20E+03 | 4.55E+03 |
| Hexachloroethane | 67-72-1 | 1.40E-02 | 1.40E-02 |
| Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) | 121-82-4 | 1.10E-01 | |
| HpCDD, 2,3,7,8- | 37871-00-4 | 1.50E+03 | 1.50E+03 |
| HpCDF, 2,3,7,8- | 38998-75-3 | 1.50E+03 | 1.50E+03 |
| HxCDD, 2,3,7,8- | 34465-46-8 | 1.50E+04 | 1.50E+04 |
| HxCDF, 2,3,7,8- | 55684-94-1 | 1.50E+04 | 1.50E+04 |
| Hydrazine | 302-01-2 | 3E+00 | 1.70E+01 |
| Hydrazine Sulfate | 10034-93-2 | 3E+00 | 1.70E+01 |
| Indeno[1,2,3-cd]pyrene | 193-39-5 | 7.30E-01 | 3.10E-01 |
| Isophorone | 78-59-1 | 9.50E-04 | |
| Methoxy-5-nitroaniline, 2- | 99-59-2 | 4.60E-02 | |
| Methyl Hydrazine | 60-34-4 | 3E+00 | 1.72E+01 |
| Methyl-5-Nitroaniline, 2- | 99-55-8 | 3.30E-02 | |

| Chemical | CAS # | Oral Slope Factor (mg/kg-day)-1 | Inhalation Slope Factor (mg/kg-day)-1 |
|---|---|---|---|
| Methylaniline Hydrochloride, 2- | 636-21-5 | 1.80E-01 | |
| Methylene Chloride | 75-09-2 | 7.50E-03 | 1.65E-03 |
| Methylene-bis(2-chloroaniline), 4,4'- | 101-14-4 | 1.30E-01 | 1.30E-01 |
| Methylene-bis(N,N-dimethyl) Aniline, 4,4'- | 101-61-1 | 4.60E-02 | |
| Methylenebisbenzenamine, 4,4'- | 101-77-9 | 2.50E-01 | |
| Mirex | 2385-85-5 | 1.80E+00 | |
| Nickel Refinery Dust | NA | | 8.40E-01 |
| Nickel Subsulfide | 12035-72-2 | | 1.70E+00 |
| Nitrofurazone | 59-87-0 | 1.50E+00 | |
| Nitropropane, 2- | 79-46-9 | 9.50E+00 | 9.40E+00 |
| Nitrosodiethanolamine, N- | 1116-54-7 | 2.80E+00 | |
| Nitrosodiethylamine, N- | 55-18-5 | 1.50E+02 | 1.50E+02 |
| Nitrosodimethylamine, N- | 62-75-9 | 5.10E+01 | 5.10E+01 |
| Nitroso-di-N-butylamine, N- | 924-16-3 | 5.40E+00 | 5.40E+00 |
| Nitroso-di-N-propylamine, N- | 621-64-7 | 7E+00 | |
| Nitrosodiphenylamine, N- | 86-30-6 | 4.90E-03 | |
| Nitrosomethylethylamine, N- | 10595-95-6 | 2.20E+01 | |
| Nitroso-N-ethylurea, N- | 759-73-9 | 1.40E+02 | |
| Nitrosopyrrolidine, N- | 930-55-2 | 2.10E+00 | 2.10E+00 |
| OCDD | 3268-87-9 | 1.50E+02 | 1.50E+02 |
| OCDF | 39001-02-0 | 1.50E+02 | 1.50E+02 |
| PeCDD, 2,3,7,8- | 36088-22-9 | 7.50E+04 | 7.50E+04 |
| PeCDF, 1,2,3,7,8- | 57117-41-6 | 7.50E+04 | 7.50E+04 |
| PeCDF, 2,3,4,7,8- | 57117-31-4 | 7.50E+03 | 7.50E+03 |
| Pentachloronitrobenzene | 82-68-8 | 2.60E-01 | |
| Pentachlorophenol | 87-86-5 | 1.20E-01 | |
| Phenylenediamine, o- | 95-54-5 | 4.70E-02 | |
| Phenylphenol, 2- | 90-43-7 | 1.94E-03 | |
| Polybrominated Biphenyls | 59536-65-1 | 8.90E+00 | |
| Polychlorinated Biphenyls (high risk) | 1336-36-3 | 2E+00 | 2E+00 |
| Polychlorinated Biphenyls (low risk) | 1336-36-3 | 4E-01 | 4E-01 |
| Polychlorinated Biphenyls (lowest risk) | 1336-36-3 | 7E-02 | |
| Prochloraz | 67747-09-5 | 1.50E-01 | |
| Propylene Oxide | 75-56-9 | 2.40E-01 | 1.30E-02 |
| Quinoline | 91-22-5 | 1.20E+01 | |
| Simazine | 122-34-9 | 1.20E-01 | |
| Sodium Diethyldithiocarbamate | 148-18-5 | 2.70E-01 | |
| Stirofos (Tetrachlorovinphos) | 961-11-5 | 2.40E-02 | |
| TCDD, 2,3,7,8- | 1746-01-6 | 1.50E+05 | 1.50E+05 |
| TCDF, 2,3,7,8- | 51207-31-9 | 1.50E+04 | 1.50E+04 |
| Tetrachloroethane, 1,1,1,2- | 630-20-6 | 2.60E-02 | 2.60E-02 |
| Tetrachloroethane, 1,1,2,2- | 79-34-5 | 2E-01 | 2E-01 |
| Tetrachloroethylene | 127-18-4 | 5.20E-02 | 2E-03 |
| Tetrachlorotoluene, p- alpha, alpha, alpha- | 5216-25-1 | 2E+01 | |

| Chemical | CAS # | Oral Slope Factor (mg/kg-day)-1 | Inhalation Slope Factor (mg/kg-day)-1 |
|---|---|---|---|
| Toluene-2,4-diamine | 95-80-7 | 3.20E+00 | |
| Toluidine, o- (Methylaniline, 2-) | 95-53-4 | 2.40E-01 | |
| Toluidine, p- | 106-49-0 | 1.90E-01 | |
| Toxaphene | 8001-35-2 | 1.10E+00 | 1.10E+00 |
| Trichloroaniline HCl, 2,4,6- | 33663-50-2 | 2.90E-02 | |
| Trichloroaniline, 2,4,6- | 634-93-5 | 3.40E-02 | |
| Trichloroethane, 1,1,2- | 79-00-5 | 5.70E-02 | 5.70E-02 |
| Trichloroethylene | 79-01-6 | 1.10E-02 | 6E-03 |
| Trichlorophenol, 2,4,6- | 88-06-2 | 1.10E-02 | 1E-02 |
| Trichloropropane, 1,2,3- | 96-18-4 | 7E+00 | |
| Trifluralin | 1582-09-8 | 7.70E-03 | |
| Trimethyl Phosphate | 512-56-1 | 3.70E-02 | |
| Trinitrotoluene, 2,4,6- | 118-96-7 | 3E-02 | |
| Vinyl Bromide | 593-60-2 | | 1.10E-01 |
| Vinyl Chloride | 75-01-4 | 1.40E+00 | 3.08E-02 |

[a] The hazard value for each chemical was derived by dividing the toxicity values shown here by the applicable geometric mean presented in Appendix E-3

## Table E-2. Oral NOAELs[a]

| Chemical | CAS # | Oral NOAEL | unit |
|---|---|---|---|
| 1,1,1-Trichloroethane | 71-55-6 | 250 | mg/kg-day |
| 1,1,2-Trichloroethane | 79-00-5 | 3.9 | mg/kg-day |
| 1,2,4-Benzenetricarboxylic Acid, Tris(2-Ethylhexyl) Ester | 3319-31-1 | 100 | mg/kg-day |
| 1,2,4-Trichlorobenzene | 120-82-1 | 7.8 | mg/kg-day |
| 1,2-Benzenedicarboxylic Acid, 3,4,5,6-Tetrabromo-, Bis(2-Ethylhexyl) Ester (9ci) | 26040-51-7 | 223.4 | mg/kg-day |
| 1,2-Dichlorobenzene | 95-50-1 | 18.8 | mg/kg-day |
| 1,2-Dichloroethane | 107-06-2 | 18 | mg/kg-day |
| 1,2-Dichloropropane | 78-87-5 | 250 | mg/kg-day |
| 1,2-Dichlorotetrafluoroethane | 76-14-2 | 273 | mg/kg-day |
| 1,3-Dichloropropene | 542-75-6 | 0.125 | mg/kg-day |
| 1.4-Dichlorobenzene | 106-46-7 | 10 | mg/kg-day |
| 2-(2-butoxyethoxy)-ethanol acetate | 124-17-4 | 1000 | mg/kg-day |
| 2,3,7,8-TCDD | 1746-01-6 | 9E-08 | mg/kg-day |
| 2,4-D | 94-75-7 | 15 | mg/kg-day |
| 2,4-Dinitrotoluene | 121-14-2 | 0.2 | mg/kg-day |
| 2-ethoxyethanol | 110-80-5 | 250 | mg/kg-day |
| 2-methoxyethanol | 109-86-4 | 50 | mg/kg-day |
| 4,4'-Isopropylidenediphenol | 80-05-7 | 500 | mg/kg-day |
| 4,4'-Methylenedianiline | 101-77-9 | 3.2 | mg/kg-day |
| 4-Nitrophenol | 100-02-7 | 70 | mg/kg-day |
| Acenaphthene | 83-32-9 | 175 | mg/kg-day |
| Acetaldehyde | 75-07-0 | 125 | mg/kg-day |
| Acetic acid | 64-19-7 | 195 | mg/kg-day |
| Acetone | 67-64-1 | 100 | mg/kg-day |
| Acetonitrile | 75-05-8 | 50 | mg/kg-day |
| Acetophenone | 98-86-2 | 423 | mg/kg-day |
| Acrylamide | 79-06-1 | 0.1 | mg/kg-day |
| Acrylic acid | 79-10-7 | 83 | mg/kg-day |
| Acrylonitrile | 107-13-1 | 1 | mg/kg-day |
| Alachlor | 15972-60-8 | 1 | mg/kg-day |
| Aluminum (elemental) | 7429-90-5 | 60 | mg/kg-day |
| Aluminum hydroxide | 21645-51-2 | 23 | mg/kg-day |
| Ammonia | 7664-41-7 | 34 | mg/kg-day |
| Ammonium bifluoride | 1341-49-7 | 0.05 | mg/kg-day |
| Anthracene | 120-12-7 | 1000 | mg/kg-day |
| Antioxida | 2082-79-3 | 30 | mg/kg-day |
| Arsenic | 7440-38-2 | 008 | mg/kg-day |
| Atrazine | 1912-24-9 | 3.5 | mg/kg-day |
| Barium | 7440-39-3 | 0.21 | mg/kg-day |
| Barium carbonate | 513-77-9 | 0.21 | mg/kg-day |
| Barium cmpds | 20-02-0 | 0.21 | mg/kg-day |

| Chemical | CAS # | Oral NOAEL | unit |
|---|---|---|---|
| Barium sulfate | 7727-43-7 | 0.21 | mg/kg-day |
| Benzaldehyde | 100-52-7 | 143 | mg/kg-day |
| Benzene | 71-43-2 | 1 | mg/kg-day |
| Biphenyl | 92-52-4 | 50 | mg/kg-day |
| Bis (2-ethylhexyl) adipate | 103-23-1 | 610 | mg/kg-day |
| Bismuth | 7440-69-9 | 3243 | mg/kg-day |
| Boric acid | 11113-50-1 | 67 | mg/kg-day |
| Boron | 7440-42-8 | 8.8 | mg/kg-day |
| Bromoform | 75-25-2 | 17.9 | mg/kg-day |
| Bromomethane | 74-83-9 | 0.4 | mg/kg-day |
| Butyl acrylate | 141-32-2 | 84 | mg/kg-day |
| Butyl benzyl phthalate | 85-68-7 | 151 | mg/kg-day |
| Butylate | 2008-41-5 | 5 | mg/kg-day |
| Butyraldehyde | 123-72-8 | 75 | mg/kg-day |
| Cadmium cmpds | 20-04-2 | 05 | mg/kg-day |
| Captan | 133-06-2 | 12.5 | mg/kg-day |
| Carbaryl | 63-25-2 | 9.6 | mg/kg-day |
| Carbon tetrachloride | 56-23-5 | 1 | mg/kg-day |
| Chlorine | 7782-50-5 | 14 | mg/kg-day |
| Chlorobenzene | 108-90-7 | 12.5 | mg/kg-day |
| Chlorophenols [o] | 20-05-3 | 50 | mg/kg-day |
| Chloropyrifos | 2921-88-2 | 0.03 | mg/kg-day |
| Chlorothalonil | 1897-45-6 | 1.5 | mg/kg-day |
| Chromium (III) | 16065-83-1 | 1468 | mg/kg-day |
| Chromium (VI) | 18540-29-9 | 2.5 | mg/kg-day |
| Chromium trioxide | 1333-82-0 | 1468 | mg/kg-day |
| Coolant | not available | 71 | mg/kg-day |
| Copper | 7440-50-8 | 0.53 | mg/kg-day |
| Crude oil | 8002-05-9 | 893 | mg/kg-day |
| Cumene | 98-82-8 | 154 | mg/kg-day |
| Cyanazine | 21725-46-2 | 0.625 | mg/kg-day |
| Cyanide (-1) | 57-12-5 | 10.8 | mg/kg-day |
| Decabromodiphenyl oxide | 1163-19-5 | 1 | mg/kg-day |
| Di (2-ethylhexyl) phthalate | 117-81-7 | 50 | mg/kg-day |
| Di propylene glycol butyl ether | 29911-28-2 | 450 | mg/kg-day |
| Dibutyl phthalate | 84-74-2 | 125 | mg/kg-day |
| Dichlorodifluoromethane | 75-71-8 | 15 | mg/kg-day |
| Dichloromethane | 75-09-2 | 155 | mg/kg-day |
| Diethanolamine | 111-42-2 | 75 | mg/kg-day |
| Diethyl ether | 60-29-7 | 500 | mg/kg-day |
| Diethyl phthalate | 84-66-2 | 150 | mg/kg-day |
| Diethylene glycol | 111-46-6 | 1250 | mg/kg-day |
| Diisoundecyl phthalate | 85507-79-5 | 790 | mg/kg-day |
| Dimethyl phthalate | 131-11-3 | 1000 | mg/kg-day |
| Dioctyl sebacate | 122-62-3 | 200 | mg/kg-day |

| Chemical | CAS # | Oral NOAEL | unit |
|---|---|---|---|
| Erucamide | 112-84-5 | 7500 | mg/kg-day |
| Ethanol amine | 141-43-5 | 320 | mg/kg-day |
| Ethyl dipropylthiocarbamate | 759-94-4 | 2.5 | mg/kg-day |
| Ethylbenzene | 100-41-4 | 136 | mg/kg-day |
| Ethylene glycol | 107-21-1 | 71 | mg/kg-day |
| Ethylene oxide | 75-21-8 | 30 | mg/kg-day |
| Fluoranthene | 206-44-0 | 125 | mg/kg-day |
| Fluorene | 86-73-7 | 125 | mg/kg-day |
| Fluorine | 7782-41-4 | 0.06 | mg/kg-day |
| Fluorspar (Fluorite) (Calcium fluoride) | 7789-75-5 | 47.5 | mg/kg-day |
| Formaldehyde | 50-00-0 | 15 | mg/kg-day |
| Freon 113 | 76-13-1 | 273 | mg/kg-day |
| Glycol ethers | 111-76-2 | 203 | mg/kg-day |
| Glyphosate | 1071-83-6 | 800 | mg/kg-day |
| Heptane | 142-82-5 | 1000 | mg/kg-day |
| Hexachloro-1,3-butadiene | 87-68-3 | 0.2 | mg/kg-day |
| Hexachlorobenzene | 118-74-1 | 0.5 | mg/kg-day |
| Hexachloroethane | 67-72-1 | 1 | mg/kg-day |
| Hydrogen cyanide | 74-90-8 | 10.8 | mg/kg-day |
| Hydrogen sulfide | 7783-06-4 | 3.1 | mg/kg-day |
| Hydroquinone | 123-31-9 | 5 | mg/kg-day |
| Hydrotalcite/zeolite | 12304-65-3;<br>1318-02-1 | 5000 | mg/kg-day |
| Antioxidant | 32687-78-8 | 25 | mg/kg-day |
| Isophorone | 78-59-1 | 150 | mg/kg-day |
| Isopropyl alcohol | 67-63-0 | 230 | mg/kg-day |
| m, p-xylene | 1330-20-7 | 179 | mg/kg-day |
| Maleic anhydride | 108-31-6 | 10 | mg/kg-day |
| Maneb | 12427-38-2 | 25 | mg/kg-day |
| Manganese | 7439-96-5 | 0.14 | mg/kg-day |
| Manganese oxide | 1313-13-9 | 05 | mg/kg-day |
| Methanol | 67-56-1 | 500 | mg/kg-day |
| Methyl ethyl ketone | 78-93-3 | 125 | mg/kg-day |
| Methyl isobutyl ketone | 108-10-1 | 50 | mg/kg-day |
| Methyl methacrylate | 80-62-6 | 7.5 | mg/kg-day |
| Methyl parathion | 298-00-0 | 2.5 | mg/kg-day |
| Methyl tert-butyl ether | 1634-04-4 | 100 | mg/kg-day |
| Metolachlor | 51218-45-2 | 300 | mg/kg-day |
| m-xylene | 108-38-3 | 250 | mg/kg-day |
| N,N-dimethylaniline | 121-69-7 | 32 | mg/kg-day |
| Naphthalene | 91-20-3 | 71 | mg/kg-day |
| N-butyl alcohol | 71-36-3 | 125 | mg/kg-day |
| Nickel | 7440-02-0 | 5 | mg/kg-day |
| Nickel chloride | 7718-54-9 | 5 | mg/kg-day |
| Nickel cmpds | 20-14-4 | 100 | mg/kg-day |

| Chemical | CAS # | Oral NOAEL | unit |
|---|---|---|---|
| Nitrate | | 1.6 | mg/kg-day |
| Nitrates/nitrites | 14797-55-8 | 1.6 | mg/kg-day |
| Nitrites | 14797-65-0 | 1 | mg/kg-day |
| Nitrobenzene | 98-95-3 | 0.46 | mg/kg-day |
| Orthoboric acid | 10043-35-3 | 67 | mg/kg-day |
| o-xylene | 95-47-6 | 179 | mg/kg-day |
| P-cresol | 106-44-5 | 50 | mg/kg-day |
| Pentachlorophenol | 87-86-5 | 3 | mg/kg-day |
| Phenol | 108-95-2 | 60 | mg/kg-day |
| Phosphate ester | 57583-54-7 | 1000 | mg/kg-day |
| Phosphine | 7803-51-2 | 0.026 | mg/kg-day |
| Phosphorus (yellow or white) | 7723-14-0 | 0.015 | mg/kg-day |
| Polychlorinated biphenyls | 1336-36-3 | 07 | mg/kg-day |
| Polyethylene mono (nonylphenyl) ether glycol | 9016-45-9 | 1000 | mg/kg-day |
| Polyvinyl pyrrolidone (PVP) | 9003-39-8 | 550 | mg/kg-day |
| Propylene oxide | 75-56-9 | 200 | mg/kg-day |
| p-xylene | 106-42-3 | 1000 | mg/kg-day |
| Pyrene | 129-00-0 | 75 | mg/kg-day |
| Pyridine | 110-86-1 | 1 | mg/kg-day |
| Santicizer 2148 | 29761-21-5 | 235 | mg/kg-day |
| Selenium | 7782-49-2 | 0.015 | mg/kg-day |
| Sodium hypochlorite | 7681-52-9 | 2.1 | mg/kg-day |
| Stabilizer | 1843-05-6 | 41 | mg/kg-day |
| Strontium | 7440-24-6 | 190 | mg/kg-day |
| Strontium carbonate | 1633-05-2 | 190 | mg/kg-day |
| Styrene | 100-42-5 | 100 | mg/kg-day |
| Terbufos | 13071-79-9 | 025 | mg/kg-day |
| Terephthalic acid | 100-21-0 | 500 | mg/kg-day |
| Tert-butyl alcohol | 75-65-0 | 1599 | mg/kg-day |
| Tetrachloroethylene | 127-18-4 | 14 | mg/kg-day |
| Tetrahydrofuran | 109-99-9 | 782 | mg/kg-day |
| Toluene | 108-88-3 | 100 | mg/kg-day |
| Trichloroethylene | 79-01-6 | 24 | mg/kg-day |
| Trifluralin | 1582-09-8 | 0.75 | mg/kg-day |
| Uranium | 7440-61-6 | 0.2 | mg/kg-day |
| Vanadium | 7440-62-2 | 03 | mg/kg-day |
| Vinyl acetate | 108-05-4 | 100 | mg/kg-day |
| Xylene (mixed isomers) | 1330-20-7 | 179 | mg/kg-day |
| Zinc (elemental) | 7440-66-6 | 0.9 | mg/kg-day |
| Zirconium | 7440-67-7 | 3494 | mg/kg-day |

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[a] The hazard value for each chemical was derived by dividing the toxicity values shown here by the applicable geometric mean presented in Appendix E-3.

## Table E-3. Inhalation NOAEL Data[a]

| Chemical | CAS # | Inhalation NOAEL | unit |
|---|---|---|---|
| 1,1,1-Trichloroethane | 71-55-6 | 1214.9 | $mg/m^3$ |
| 1,2,4-Benzenetricarboxylic Acid, Tris(2-Ethylhexyl) Ester | 3319-31-1 | 260 | $mg/m^3$ |
| 1,2,4-Trichlorobenzene | 120-82-1 | 24.3 | $mg/m^3$ |
| 1,2-Dichloroethane | 107-06-2 | 221 | $mg/m^3$ |
| 1,2-Dichloropropane | 78-87-5 | 710 | $mg/m^3$ |
| 1,3-Butadiene | 106-99-0 | 2800 | $mg/m^3$ |
| 1,3-Dichloropropene | 542-75-6 | 49.6 | $mg/m^3$ |
| 1,4-Dichlorobenzene | 106-46-7 | 75 | $mg/m^3$ |
| 1,4-Dioxane | 123-91-1 | 360 | $mg/m^3$ |
| 1-Methoxy-2-propanol | 107-98-2 | 658 | $mg/m^3$ |
| 2-Ethoxyethanol | 110-80-5 | 7480 | $mg/m^3$ |
| 2-Methoxyethanol | 109-86-4 | 93.3 | $mg/m^3$ |
| 4,4'-Isopropylidenediphenol | 80-05-7 | 10 | $mg/m^3$ |
| 4-Nitrophenol | 100-02-7 | 30 | $mg/m^3$ |
| Acetaldehyde | 75-07-0 | 300 | $mg/m^3$ |
| Acetonitrile | 75-05-8 | 91.5 | $mg/m^3$ |
| Acrylic acid | 79-10-7 | 74 | $mg/m^3$ |
| Allyl chloride | 107-05-1 | 68.3 | $mg/m^3$ |
| Ammonia | 7664-41-7 | 40 | $mg/m^3$ |
| Ammonium nitrate (solution) | 6484-52-2 | 185 | $mg/m^3$ |
| Aniline | 62-53-3 | 19 | $mg/m^3$ |
| Antimony trioxide | 1309-64-4 | 0.51 | $mg/m^3$ |
| Benzene | 71-43-2 | 1.15 | $mg/m^3$ |
| Bromomethane | 74-83-9 | 4.3 | $mg/m^3$ |
| Butyl acrylate | 141-32-2 | 120 | $mg/m^3$ |
| Butyl benzyl phthalate | 85-68-7 | 144 | $mg/m^3$ |
| Butyraldehyde | 123-72-8 | 3200 | $mg/m^3$ |
| Carbon disulfide | 75-15-0 | 10 | $mg/m^3$ |
| Carbon monoxide | 630-08-0 | 114.5 | $mg/m^3$ |
| Carbon tetrachloride | 56-23-5 | 34.3 | $mg/m^3$ |
| Chlorobenzene | 108-90-7 | 377 | $mg/m^3$ |
| Coolant | not available | 10 | $mg/m^3$ |
| Cumene | 98-82-8 | 537 | $mg/m^3$ |
| Cumene hydroperoxide | 80-15-9 | 31 | $mg/m^3$ |
| Cyclohexane | 110-82-7 | 1500 | $mg/m^3$ |
| Di (2-ethylhexyl) phthalate | 117-81-7 | 50 | $mg/m^3$ |
| Dichlorobenzene (mixed isomers) | 25321-22-6 | 610.4 | $mg/m^3$ |
| Dichloromethane | 75-09-2 | 796 | $mg/m^3$ |
| Diethanolamine | 111-42-2 | 0.27 | $mg/m^3$ |
| Diisoundecyl phthalate | 85507-79-5 | 180 | $mg/m^3$ |
| Epichlorohydrin | 106-89-8 | 20.7 | $mg/m^3$ |
| Ethyl chloride | 75-00-3 | 3600 | $mg/m^3$ |

| Chemical | CAS # | Inhalation NOAEL | unit |
|---|---|---|---|
| Ethylbenzene | 100-41-4 | 2370 | mg/m$^3$ |
| Ethylene | 74-85-1 | 11600 | mg/m$^3$ |
| Ethylene glycol | 107-21-1 | 10 | mg/m$^3$ |
| Ethylene oxide | 75-21-8 | 18 | mg/m$^3$ |
| Formaldehyde | 50-00-0 | 0.6 | mg/m$^3$ |
| Glycol ethers | 111-76-2 | 121 | mg/m$^3$ |
| HCFC-22 | 75-45-6 | 5260 | mg/m$^3$ |
| Hexachloro-1,3-butadiene | 87-68-3 | 58.2 | mg/m$^3$ |
| Hexafluoropropylene (HFP) | 116-15-4 | 67 | mg/m$^3$ |
| HFC-125 | 354-33-6 | 245000 | mg/m$^3$ |
| Hydrochloric acid | 7647-01-0 | 15 | mg/m$^3$ |
| Hydrotalcite/zeolite | 12304-65-3;<br>1318-02-1 | 20 | mg/m$^3$ |
| Isopropyl alcohol | 67-63-0 | 268.3 | mg/m$^3$ |
| Ligroine | 8032-32-4 | 14560 | mg/m$^3$ |
| Maneb | 12427-38-2 | 10 | mg/m$^3$ |
| Mercury | 7439-97-6 | 06 | mg/m$^3$ |
| Methanol | 67-56-1 | 130 | mg/m$^3$ |
| Methyl chloride | 74-87-3 | 1138.4 | mg/m$^3$ |
| Methyl ethyl ketone | 78-93-3 | 8047 | mg/m$^3$ |
| Methyl isobutyl ketone | 108-10-1 | 224 | mg/m$^3$ |
| Methyl methacrylate | 80-62-6 | 111.7 | mg/m$^3$ |
| Metyl tert-butyl ether | 1634-04-4 | 2880 | mg/m$^3$ |
| N,N-Dimethylaniline | 121-69-7 | 06 | mg/m$^3$ |
| N-butyl alcohol | 71-36-3 | 0.1 | mg/m$^3$ |
| Nitrobenzene | 98-95-3 | 27.5 | mg/m$^3$ |
| p-cresol | 106-44-5 | 10 | mg/m$^3$ |
| Phosphine | 7803-51-2 | 0.25 | mg/m$^3$ |
| Phosphoric acid | 7664-38-2 | 50 | mg/m$^3$ |
| Propionaldehyde | 123-38-6 | 200 | mg/m$^3$ |
| Propylene | 115-07-1 | 9375 | mg/m$^3$ |
| Propylene glycol | 57-55-6 | 170 | mg/m$^3$ |
| Propylene oxide | 75-56-9 | 237 | mg/m$^3$ |
| p-xylene | 106-42-3 | 5812.6 | mg/m$^3$ |
| Sec-butyl alcohol | 78-92-2 | 8270 | mg/m$^3$ |
| Styrene | 100-42-5 | 565 | mg/m$^3$ |
| Sulfur dioxide | 7446-09-5 | 0.104 | mg/m$^3$ |
| Sulfuric acid | 7664-93-9 | 0.1 | mg/m$^3$ |
| Terephthalic acid | 100-21-0 | 3 | mg/m$^3$ |
| Tetrachloroethylene | 127-18-4 | 740.2 | mg/m$^3$ |
| Tetrahydrofuran | 109-99-9 | 0.2 | mg/m$^3$ |
| Titanium | 7440-32-6 | 0.8 | mg/m$^3$ |
| Titanium tetrachloride | 7550-45-0 | 09 | mg/m$^3$ |
| Toluene | 108-88-3 | 411.1 | mg/m$^3$ |
| Toluene-2,4-diisocyanate | 584-84-9 | 0.03 | mg/m$^3$ |

| Chemical | CAS # | Inhalation NOAEL | unit |
|---|---|---|---|
| Trichloroethylene | 79-01-6 | 586.6 | $mg/m^3$ |
| Vinyl acetate | 108-05-4 | 176 | $mg/m^3$ |
| Vinyl chloride | 75-01-4 | 69754.5 | $mg/m^3$ |
| Vinylidene chloride | 75-35-4 | 120 | $mg/m^3$ |

[a] The hazard value for each chemical was derived by dividing the toxicity values shown here by the applicable geometric mean presented in Appendix E-3.

## Table E-4. Fish LC50 Data[a]

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| 1,1,1-Trichloroethane | 71-55-6 | 48 | mg/L |
| 1,1,2-Trichloroethane | 79-00-5 | 82 | mg/L |
| 1,2,3,5-Tetrachlorobenzene | 634-90-2 | 4 | mg/L |
| 1,2,4-Trichlorobenzene | 120-82-1 | 3 | mg/L |
| 1,2,4-Trimethylbenzene | 95-63-6 | 8 | mg/L |
| 1,2-Dichlorobenzene | 95-50-1 | 1 | mg/L |
| 1,2-Dichloroethane | 107-06-2 | 136 | mg/L |
| 1,2-Dichloropropane | 78-87-5 | 127 | mg/L |
| 1,3-Butadiene | 106-99-0 | 4 | mg/L |
| 1,3-Dichloropropene | 542-75-6 | 0.24 | mg/L |
| 1,4-Dichlorobenzene | 106-46-7 | 34 | mg/L |
| 1,4-Dioxane | 123-91-1 | 9850 | mg/L |
| 1-Methylphenanthrene | 832-69-9 | 1 | mg/L |
| 2,2-Dimethylolpropionic acid | 4767-03-7 | 1000 | mg/L |
| 2,4,5-Trichlorotoluene | 6639-30-1 | 1 | mg/L |
| 2,4,6-Trichlorophenol | 88-06-2 | 3 | mg/L |
| 2,4-D | 94-75-7 | 71 | mg/L |
| 2,4-Dinitrophenol | 51-28-5 | 11 | mg/L |
| 2,4-Dinitrotoluene | 121-14-2 | 24 | mg/L |
| 2-Ethoxyethanol | 110-80-5 | 16305 | mg/L |
| 2-Methoxyethanol | 109-86-4 | 22655 | mg/L |
| 2-Nitropropane | 79-46-9 | 5 | mg/L |
| 3,4-Dinitrotoluene | 610-39-9 | 2 | mg/L |
| 4,4'-Isopropylidenediphenol | 80-05-7 | 5 | mg/L |
| 4,4'-Methylenedianiline | 101-77-9 | 45 | mg/L |
| 4-Nitrophenol | 100-02-7 | 41 | mg/L |
| Acetaldehyde | 75-07-0 | 34 | mg/L |
| Acetone | 67-64-1 | 7200 | mg/L |
| Acetonitrile | 75-05-8 | 1640 | mg/L |
| Acrylamide | 79-06-1 | 109 | mg/L |
| Acrylic acid | 79-10-7 | 186 | mg/L |
| Acrylonitrile | 107-13-1 | 10 | mg/L |
| Alachlor | 15972-60-8 | 5 | mg/L |
| Allyl chloride | 107-05-1 | 72 | mg/L |
| Aluminum | 7429-90-5 | 11 | mg/L |
| Aluminum (+3) |  | 3.6 | mg/L |
| Aluminum Hydroxide | 21645-51-2 | 32 | mg/L |
| Ammonia | 7664-41-7 | 2 | mg/L |
| Ammonium nitrate (solution) | 6484-52-2 | 800 | mg/L |
| Ammonium sulfate (solution) | 7783-20-2 | 4000 | mg/L |
| Aniline | 62-53-3 | 108 | mg/L |
| Anthracene | 120-12-7 | 0.01 | mg/L |
| Antimony | 7440-36-0 | 14.4 | mg/L |

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| Antimony cmpds | 20-00-8 | 833 | mg/L |
| Antioxidant | 32687-78-8 | 100 | mg/L |
| Arsenic | 7440-38-2 | 14.4 | mg/L |
| Arsenic cmpds | 20-01-9 | 32 | mg/L |
| Atrazine | 1912-24-9 | 16 | mg/L |
| Barium | 7440-39-3 | 580 | mg/L |
| Barium cmpds | 20-02-0 | 200 | mg/L |
| Bentonite | 1302-78-9 | 1000 | mg/L |
| Benzaldehyde | 100-52-7 | 27 | mg/L |
| Benzene | 71-43-2 | 19 | mg/L |
| Benzo(k)fluoranthene | 207-08-9 | 1000 | mg/L |
| Benzoyl chloride | 98-88-4 | 35 | mg/L |
| Beryllium | 7440-90-5 | 2 | mg/L |
| Beta diketone |  | 140 | mg/L |
| Beta terpineol | 138-87-4 | 5.4 | mg/L |
| Biphenyl | 92-52-4 | 2 | mg/L |
| Bis(2-ethylhexyl) adipate | 103-23-1 | 0.35 | mg/L |
| Bismuth | 7440-69-9 | 5 | mg/L |
| Boron | 7440-42-8 | 113 | mg/L |
| Boron (B III) |  | 113 | mg/L |
| Bromomethane | 74-83-9 | 11 | mg/L |
| Butyl benzyl phthalate | 85-68-7 | 43 | mg/L |
| Butylate | 2008-41-5 | 7 | mg/L |
| Butyraldehyde | 123-72-8 | 32 | mg/L |
| Cadmium | 7440-43-9 | 01 | mg/L |
| Cadmium cmpds | 20-04-2 | 0.1 | mg/L |
| Caffeine | 58-08-2 | 151 | mg/L |
| Captan | 133-06-2 | 0.2 | mg/L |
| Carbaryl | 63-25-2 | 8 | mg/L |
| Carbon disulfide | 79-15-0 | 694 | mg/L |
| Carbon tetrachloride | 56-23-5 | 41 | mg/L |
| Carbonyl sulfide | 463-58-1 | 2685 | mg/L |
| Catechol | 120-80-9 | 9 | mg/L |
| Chlorine | 7782-50-5 | 0.34 | mg/L |
| Chlorine dioxide | 10049-04-4 | 0.17 | mg/L |
| Chlorobenzene | 108-90-7 | 17 | mg/L |
| Chloroform | 67-66-3 | 71 | mg/L |
| Chlorophenols [o] | 20-05-3 | 19 | mg/L |
| Chloroprene | 126-99-8 | 2 | mg/L |
| Chlorothalonil | 1897-45-6 | 0.05 | mg/L |
| Chlorpyrifos | 2921-88-2 | 2.4 | mg/L |
| Chromium | 7440-47-3 | 52 | mg/L |
| Chromium (VI) | 18540-29-9 | 22.6 | mg/L |
| Chromium cmpds | 20-06-4 | 33 | mg/L |

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| Chromium III | 16065-83-1 | 3.3 | mg/L |
| Cobalt cmpds | 20-07-5 | 0.38 | mg/L |
| Coolant | | 227634 | mg/L |
| Copper | 7440-50-8 | 0.014 | mg/L |
| Copper (+1 & +2) | | 0.014 | mg/L |
| Copper cmpds | 20-08-6 | 0.33 | mg/L |
| Cresol (mixed isomers) | 1319-77-3 | 13 | mg/L |
| Crude Oil | 8002-05-9 | 7.1 | mg/L |
| Cumene | 98-82-8 | 6 | mg/L |
| Cumene hydroperoxide | 80-15-9 | 62 | mg/L |
| Cyanazine | 21725-46-2 | 18 | mg/L |
| Cyanide (-1) | 57-12-5 | 56 | mg/L |
| Cyclohexane | 110-82-7 | 5 | mg/L |
| Cyclohexanone | 108-94-1 | 630 | mg/L |
| Cyclohexylamine | 108-91-8 | 222 | mg/L |
| Decabromodiphenyl oxide | 1163-19-5 | 0.06 | mg/L |
| Di (2-ethylhexyl)phthalate | 117-81-7 | 1 | mg/L |
| Di propylene glycol butyl ether | 29911-28-2 | 930 | mg/L |
| Diaminotoluene (mixed isomers) | 25376-45-8 | 37 | mg/L |
| Dibutyl phthalate | 84-74-2 | 1 | mg/L |
| Dichlorobenzene (mixed isomers) | 25321-22-6 | 1 | mg/L |
| Dichloromethane | 75-09-2 | 330 | mg/L |
| Diethanolamine | 111-42-2 | 4710 | mg/L |
| Diethyl phthalate | 84-66-2 | 32 | mg/L |
| Dimethyl phthalate | 131-11-3 | 121 | mg/L |
| Di-n-octyl phthalate | 117-84-0 | 1 | mg/L |
| Edetic acid (EDTA) | 60-00-4 | 473 | mg/L |
| Epichlorohydrin | 106-89-8 | 35 | mg/L |
| Ethoduomeen | 53127-17-6 | 0.5 | mg/L |
| Ethyl chloride | 75-00-3 | 16 | mg/L |
| Ethyl dipropylthiocarbamate | 759-94-4 | 27 | mg/L |
| Ethylbenzene | 100-41-4 | 11 | mg/L |
| Ethylene | 74-85-1 | 14 | mg/L |
| Ethylene glycol | 107-21-1 | 227634 | mg/L |
| Ethylene oxide | 75-21-8 | 84 | mg/L |
| Fluorine | 7782-49-2 | 100 | mg/L |
| Fluoroboric acid | 16872-11-0 | 1000 | mg/L |
| Fluorosilicic acid | 16961-83-4 | 100 | mg/L |
| Fluorspar | 7789-75-5 | 100 | mg/L |
| Formaldeyde | 50-00-0 | 24 | mg/L |
| Freon 113 | 76-13-1 | 290 | mg/L |
| Glycol ethers | 111-76-2 | 1490 | mg/L |
| Glyphosate | 1071-83-6 | 600 | mg/L |
| Heavy fuel oil | 64741-62-4 | 316 | mg/L |

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| Hexachloro-1,3-butadiene | 87-68-3 | 0.09 | mg/L |
| Hexachlorobenzene | 118-74-1 | 22 | mg/L |
| Hexachlorocyclopentadiene | 77-47-4 | 07 | mg/L |
| Hexachloroethane | 67-72-1 | 1 | mg/L |
| Hexafluoropropylene | 116-15-4 | 245 | mg/L |
| Hexane | 110-54-3 | 2.5 | mg/L |
| Hydrazine | 302-01-2 | 4.83 | mg/L |
| Hydrochloric acid | 7647-01-0 | 19 | mg/L |
| Hydrofluoric acid | 7664-39-3 | 265 | mg/L |
| Hydrogen cyanide | 74-90-8 | 1385 | mg/L |
| Hydroquinone | 123-31-9 | 141 | mg/L |
| Hydrotalcite/zeolite | 12304-65-3 | 2900 | mg/L |
| Iron pyrite | 1309-36-0 | 1000 | mg/L |
| Isobutyraldehyde | 78-84-2 | 41 | mg/L |
| Isopropyl alcohol | 67-63-0 | 8623 | mg/L |
| Lead | 7439-92-1 | 31.5 | mg/L |
| Lead cmpds | 20-11-1 | 5 | mg/L |
| Lead sulfate cake | 7446-14-2 | 60.8 | mg/L |
| Limestone flour | 471-34-1 | 100 | mg/L |
| Lithium salts |  | 2600 | mg/L |
| M,p-xylene |  | 13 | mg/L |
| Malathion | 121-75-5 | 0.1 | mg/L |
| Maleic anhydride | 108-31-6 | 2963 | mg/L |
| Maneb | 12427-38-2 | 2 | mg/L |
| Manganese cmpds | 20-12-2 | 150 | mg/L |
| Mercury | 7439-97-6 | 0.155 | mg/L |
| Mercury cmpds |  | 0.155 | mg/L |
| Metam sodium | 137-42-8 | 0.39 | mg/L |
| Methanol | 67-56-1 | 29400 | mg/L |
| Methl mercury | 115-09-3 | 0.09 | mg/L |
| Methyl chloride | 74-87-3 | 550 | mg/L |
| Methyl ethyl ketone | 78-93-3 | 3220 | mg/L |
| Methyl isobutyl ketone | 108-10-1 | 572 | mg/L |
| Methyl methacrylate | 80-62-6 | 259 | mg/L |
| Methyl parathion | 298-00-0 | 9 | mg/L |
| Methyl tert-butyl ether | 1634-04-4 | 786 | mg/L |
| Methylenebis (phenylisocyanate) | 101-68-8 | 1 | mg/L |
| Metolachlor | 51218-45-2 | 15 | mg/L |
| Metribuzin | 21087-64-9 | 80 | mg/L |
| Molybdenum | 7439-98-7 | 157 | mg/L |
| Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI) |  | 157 | 3.09 |
| Molybdenum trioxide | 1313-27-5 | 370 | mg/L |
| Monochlorohexafluoropropane (HCFC-226) | 431-87-8 | 23 | mg/L |
| m-xylene | 108-38-3 | 16 | mg/L |

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| N, N-Demethylaniline | 121-69-7 | 65 | mg/L |
| Naphthalene | 91-20-3 | 6 | mg/L |
| N-butyl alcohol | 71-36-3 | 1860 | mg/L |
| Nickel | 7440-02-0 | 2.48 | mg/L |
| Nickel cmpds | 20-14-4 | 27 | mg/L |
| Nitrate |  | 2213 | mg/L |
| Nitrates/nitrites | 14797-55-8 | 2213 | mg/L |
| Nitric acid | 7697-37-2 | 26 | mg/L |
| Nitrites | 14797-65-0 | 225 | mg/L |
| Nitrobenzene | 98-95-3 | 119 | mg/L |
| Nitrogen dioxide | 10102-44-0 | 196 | mg/L |
| N-nitrosodiphenylamine | 86-30-6 |  | mg/L |
| o-xylene | 95-47-6 | 16 | mg/L |
| p-cresol | 106-44-5 | 25 | mg/L |
| Perfluorooctanoic acid (PFOA) | 335-67-1 | 455 | mg/L |
| Phenol | 108-95-2 | 34 | mg/L |
| Phosphoric acid | 7664-38-2 | 70 | mg/L |
| Phosphorus (yellow or white) | 7723-14-0 | 0.02 | mg/L |
| Phthalic anhydride | 85-44-9 | 364 | mg/L |
| Picric acid | 88-89-1 | 170 | mg/L |
| Polychlorinated biphenyls | 1336-36-3 | 3 | mg/L |
| Potassium bicarbonate | 298-14-6 | 305 | mg/L |
| Propionaldehyde | 123-38-6 | 44 | mg/L |
| Propylene | 115-07-1 | 5 | mg/L |
| Propylene oxide | 75-56-9 | 306 | mg/L |
| p-xylene | 106-42-3 | 2 | mg/L |
| Pyridine | 110-86-1 | 100 | mg/L |
| Sec-butyl alcohol | 78-92-2 | 3670 | mg/L |
| Selenium | 7782-49-2 | 4.9 | mg/L |
| Silver | 7440-22-4 | 04 | mg/L |
| Silver cmpds |  | 12 | mg/L |
| Silvex | 93-72-1 | 13 | mg/L |
| Sodium Hypochlorite | 7681-52-9 | 0.53 | mg/L |
| Strontium | 7440-24-6 | 210 | mg/L |
| Styrene | 100-42-5 | 4 | mg/L |
| Sulfuric acid | 7664-93-9 | 31 | mg/L |
| Terbufos | 13071-79-9 | 0.01 | mg/L |
| Terephthalic acid | 100-21-0 | 29 | mg/L |
| Tert-butyl alcohol | 75-65-0 | 1954 | mg/L |
| Tetrachloroethylene | 127-18-4 | 17 | mg/L |
| Tin | 7440-31-5 | 626 | mg/L |
| Tin (Sn++, Sn4+) |  | 626 | mg/L |
| Titanium tetrachloride | 7550-45-0 | 25 | mg/L |
| Toluene | 108-88-3 | 34 | mg/L |

| Chemical | CAS # | Fish LC50 | unit |
|---|---|---|---|
| Toluene-2,4-diisocyanate | 584-84-9 | 53 | mg/L |
| Trans-1,2-dichloroethylene | 156-60-5 | 45 | mg/L |
| Tri propylene glycol butyl ether | 55934-93-5 | 900 | mg/L |
| Trichloroethylene | 79-01-6 | 44 | mg/L |
| Trichlorofluoromethane | 75-69-4 | 114 | mg/L |
| Triethylene glycol | 112-27-6 | 88100 | mg/L |
| Trifluralin | 1582-09-8 | 0.11 | mg/L |
| Vanadium | 7440-62-2 | 4 | mg/L |
| Vinyl acetate | 108-05-4 | 100 | mg/L |
| Vinyl chloride | 75-01-4 | 143 | mg/L |
| Vinylidene chloride | 75-35-4 | 108 | mg/L |
| Xylene (mixed isomers) | 1330-20-7 | 13 | mg/L |
| Zinc (+2) |  | 0.09 | mg/L |
| Zinc (elemental) | 7440-66-6 | 0.09 | mg/L |
| Zinc borate | 1332-07-6 | 409 | mg/L |
| Zinc cmpds | 20-19-9 | 17 | mg/L |
| Zinc sulfate | 7733-02-0 | 14 | mg/L |

[a] The hazard value for each chemical was derived by dividing the toxicity values shown here by the applicable geometric mean presented in Appendix E-3.

## Table E-5.  Fish NOEL Data[a]

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| 1,1,1-Trichloroethane | 71-55-6 | 48 | mg/L |
| 1,1,2-Trichloroethane | 79-00-5 | 82 | mg/L |
| 1,2,3,5-Tetrachlorobenzene | 634-90-2 | 4 | mg/L |
| 1,2,4-Trichlorobenzene | 120-82-1 | 3 | mg/L |
| 1,2,4-Trimethylbenzene | 95-63-6 | 8 | mg/L |
| 1,2-Dichlorobenzene | 95-50-1 | 1 | mg/L |
| 1,2-Dichloroethane | 107-06-2 | 136 | mg/L |
| 1,2-Dichloropropane | 78-87-5 | 127 | mg/L |
| 1,3-Butadiene | 106-99-0 | 4 | mg/L |
| 1,3-Dichloropropene | 542-75-6 | 0.24 | mg/L |
| 1,4-Dichlorobenzene | 106-46-7 | 34 | mg/L |
| 1,4-Dioxane | 123-91-1 | 9850 | mg/L |
| 1-Methylphenanthrene | 832-69-9 | 1 | mg/L |
| 2,2-Dimethylolpropionic acid | 4767-03-7 | 1000 | mg/L |
| 2,4,5-Trichlorotoluene | 6639-30-1 | 1 | mg/L |
| 2,4,6-Trichlorophenol | 88-06-2 | 3 | mg/L |
| 2,4-D | 94-75-7 | 71 | mg/L |
| 2,4-Dinitrophenol | 51-28-5 | 11 | mg/L |
| 2,4-Dinitrotoluene | 121-14-2 | 24 | mg/L |
| 2-Ethoxyethanol | 110-80-5 | 16305 | mg/L |
| 2-Methoxyethanol | 109-86-4 | 22655 | mg/L |
| 2-Nitropropane | 79-46-9 | 5 | mg/L |
| 3,4-Dinitrotoluene | 610-39-9 | 2 | mg/L |
| 4,4'-Isopropylidenediphenol | 80-05-7 | 5 | mg/L |
| 4,4'-Methylenedianiline | 101-77-9 | 45 | mg/L |
| 4-Nitrophenol | 100-02-7 | 41 | mg/L |
| Acetaldehyde | 75-07-0 | 34 | mg/L |
| Acetone | 67-64-1 | 7200 | mg/L |
| Acetonitrile | 75-05-8 | 1640 | mg/L |
| Acrylamide | 79-06-1 | 109 | mg/L |
| Acrylic acid | 79-10-7 | 186 | mg/L |
| Acrylonitrile | 107-13-1 | 10 | mg/L |
| Alachlor | 15972-60-8 | 5 | mg/L |
| Allyl chloride | 107-05-1 | 72 | mg/L |
| Aluminum | 7429-90-5 | 11 | mg/L |
| Aluminum (+3) |  | 3.6 | mg/L |
| Aluminum Hydroxide | 21645-51-2 | 32 | mg/L |
| Ammonia | 7664-41-7 | 2 | mg/L |
| Ammonium nitrate (solution) | 6484-52-2 | 800 | mg/L |
| Ammonium sulfate (solution) | 7783-20-2 | 4000 | mg/L |
| Aniline | 62-53-3 | 108 | mg/L |
| Anthracene | 120-12-7 | 0.01 | mg/L |
| Antimony | 7440-36-0 | 14.4 | mg/L |
| Antimony cmpds | 20-00-8 | 833 | mg/L |
| Arsenic | 7440-38-2 | 14.4 | mg/L |

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| Arsenic cmpds | 20-01-9 | 32 | mg/L |
| Atrazine | 1912-24-9 | 16 | mg/L |
| Barium | 7440-39-3 | 580 | mg/L |
| Barium cmpds | 20-02-0 | 200 | mg/L |
| Bentonite | 1302-78-9 | 1000 | mg/L |
| Benzaldehyde | 100-52-7 | 27 | mg/L |
| Benzene | 71-43-2 | 19 | mg/L |
| Benzo(k)fluoranthene | 207-08-9 | 1000 | mg/L |
| Benzoyl chloride | 98-88-4 | 35 | mg/L |
| Beryllium | 7440-90-5 | 2 | mg/L |
| Beta diketone |  | 140 | mg/L |
| Beta terpineol | 138-87-4 | 5.4 | mg/L |
| Biphenyl | 92-52-4 | 2 | mg/L |
| Bis(2-ethylhexyl) adipate | 103-23-1 | 0.35 | mg/L |
| Bismuth | 7440-69-9 | 5 | mg/L |
| Boron | 7440-42-8 | 113 | mg/L |
| Boron (B III) |  | 113 | mg/L |
| Bromomethane | 74-83-9 | 11 | mg/L |
| Butyl benzyl phthalate | 85-68-7 | 43 | mg/L |
| Butylate | 2008-41-5 | 7 | mg/L |
| Butyraldehyde | 123-72-8 | 32 | mg/L |
| Cadmium | 7440-43-9 | 01 | mg/L |
| Cadmium cmpds | 20-04-2 | 0.1 | mg/L |
| Caffeine | 58-08-2 | 151 | mg/L |
| Captan | 133-06-2 | 0.2 | mg/L |
| Carbaryl | 63-25-2 | 8 | mg/L |
| Carbon disulfide | 79-15-0 | 694 | mg/L |
| Carbon tetrachloride | 56-23-5 | 41 | mg/L |
| Carbonyl sulfide | 463-58-1 | 2685 | mg/L |
| Catechol | 120-80-9 | 9 | mg/L |
| Chlorine | 7782-50-5 | 0.34 | mg/L |
| Chlorine dioxide | 10049-04-4 | 0.17 | mg/L |
| Chlorobenzene | 108-90-7 | 17 | mg/L |
| Chloroform | 67-66-3 | 71 | mg/L |
| Chlorophenols [o] | 20-05-3 | 19 | mg/L |
| Chloroprene | 126-99-8 | 2 | mg/L |
| Chlorothalonil | 1897-45-6 | 0.05 | mg/L |
| Chlorpyrifos | 2921-88-2 | 2.4 | mg/L |
| Chromium | 7440-47-3 | 52 | mg/L |
| Chromium (VI) | 18540-29-9 | 22.6 | mg/L |
| Chromium cmpds | 20-06-4 | 33 | mg/L |
| Chromium III | 16065-83-1 | 3.3 | mg/L |
| Cobalt cmpds | 20-07-5 | 0.38 | mg/L |
| Coolant |  | 227634 | mg/L |
| Copper | 7440-50-8 | 0.014 | mg/L |
| Copper (+1 & +2) |  | 0.014 | mg/L |

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| Copper cmpds | 20-08-6 | 0.33 | mg/L |
| Cresol (mixed isomers) | 1319-77-3 | 13 | mg/L |
| Crude Oil | 8002-05-9 | 7.1 | mg/L |
| Cumene | 98-82-8 | 6 | mg/L |
| Cumene hydroperoxide | 80-15-9 | 62 | mg/L |
| Cyanazine | 21725-46-2 | 18 | mg/L |
| Cyanide (-1) | 57-12-5 | 56 | mg/L |
| Cyclohexane | 110-82-7 | 5 | mg/L |
| Cyclohexanone | 108-94-1 | 630 | mg/L |
| Cyclohexylamine | 108-91-8 | 222 | mg/L |
| Decabromodiphenyl oxide | 1163-19-5 | 0.06 | mg/L |
| Di (2-ethylhexyl)phthalate | 117-81-7 | 1 | mg/L |
| Di propylene glycol butyl ether | 29911-28-2 | 930 | mg/L |
| Diaminotoluene (mixed isomers) | 25376-45-8 | 37 | mg/L |
| Dibutyl phthalate | 84-74-2 | 1 | mg/L |
| Dichlorobenzene (mixed isomers) | 25321-22-6 | 1 | mg/L |
| Dichloromethane | 75-09-2 | 330 | mg/L |
| Diethanolamine | 111-42-2 | 4710 | mg/L |
| Diethyl phthalate | 84-66-2 | 32 | mg/L |
| Dimethyl phthalate | 131-11-3 | 121 | mg/L |
| Di-n-octyl phthalate | 117-84-0 | 1 | mg/L |
| Edetic acid (EDTA) | 60-00-4 | 473 | mg/L |
| Epichlorohydrin | 106-89-8 | 35 | mg/L |
| Ethoduomeen | 53127-17-6 | 0.5 | mg/L |
| Ethyl chloride | 75-00-3 | 16 | mg/L |
| Ethyl dipropylthiocarbamate | 759-94-4 | 27 | mg/L |
| Ethylbenzene | 100-41-4 | 11 | mg/L |
| Ethylene | 74-85-1 | 14 | mg/L |
| Ethylene glycol | 107-21-1 | 227634 | mg/L |
| Ethylene oxide | 75-21-8 | 84 | mg/L |
| Fluorine | 7782-49-2 | 100 | mg/L |
| Fluoroboric acid | 16872-11-0 | 1000 | mg/L |
| Fluorosilicic acid | 16961-83-4 | 100 | mg/L |
| Fluorspar | 7789-75-5 | 100 | mg/L |
| Formaldeyde | 50-00-0 | 24 | mg/L |
| Freon 113 | 76-13-1 | 290 | mg/L |
| Glycol ethers | 111-76-2 | 1490 | mg/L |
| Glyphosate | 1071-83-6 | 600 | mg/L |
| Heavy fuel oil | 64741-62-4 | 316 | mg/L |
| Hexachloro-1,3-butadiene | 87-68-3 | 0.09 | mg/L |
| Hexachlorobenzene | 118-74-1 | 22 | mg/L |
| Hexachlorocyclopentadiene | 77-47-4 | 07 | mg/L |
| Hexachloroethane | 67-72-1 | 1 | mg/L |
| Hexafluoropropylene | 116-15-4 | 245 | mg/L |
| Hexane | 110-54-3 | 2.5 | mg/L |
| Hydrazine | 302-01-2 | 4.83 | mg/L |

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| Hydrochloric acid | 7647-01-0 | 19 | mg/L |
| Hydrofluoric acid | 7664-39-3 | 265 | mg/L |
| Hydrogen cyanide | 74-90-8 | 1385 | mg/L |
| Hydroquinone | 123-31-9 | 141 | mg/L |
| Hydrotalcite/zeolite | 12304-65-3 | 2900 | mg/L |
| Irganox MD1024 | 32687-78-8 | 100 | mg/L |
| Iron pyrite | 1309-36-0 | 1000 | mg/L |
| Isobutyraldehyde | 78-84-2 | 41 | mg/L |
| Isopropyl alcohol | 67-63-0 | 8623 | mg/L |
| Lead | 7439-92-1 | 31.5 | mg/L |
| Lead cmpds | 20-11-1 | 5 | mg/L |
| Lead sulfate cake | 7446-14-2 | 60.8 | mg/L |
| Limestone flour | 471-34-1 | 100 | mg/L |
| Lithium salts |  | 2600 | mg/L |
| M,p-xylene |  | 13 | mg/L |
| Malathion | 121-75-5 | 0.1 | mg/L |
| Maleic anhydride | 108-31-6 | 2963 | mg/L |
| Maneb | 12427-38-2 | 2 | mg/L |
| Manganese cmpds | 20-12-2 | 150 | mg/L |
| Mercury | 7439-97-6 | 0.155 | mg/L |
| Mercury cmpds |  | 0.155 | mg/L |
| Metam sodium | 137-42-8 | 0.39 | mg/L |
| Methanol | 67-56-1 | 29400 | mg/L |
| Methl mercury | 115-09-3 | 0.09 | mg/L |
| Methyl chloride | 74-87-3 | 550 | mg/L |
| Methyl ethyl ketone | 78-93-3 | 3220 | mg/L |
| Methyl isobutyl ketone | 108-10-1 | 572 | mg/L |
| Methyl methacrylate | 80-62-6 | 259 | mg/L |
| Methyl parathion | 298-00-0 | 9 | mg/L |
| Methyl tert-butyl ether | 1634-04-4 | 786 | mg/L |
| Methylenebis (phenylisocyanate) | 101-68-8 | 1 | mg/L |
| Metolachlor | 51218-45-2 | 15 | mg/L |
| Metribuzin | 21087-64-9 | 80 | mg/L |
| Molybdenum | 7439-98-7 | 157 | mg/L |
| Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI) |  | 157 | mg/L |
| Molybdenum trioxide | 1313-27-5 | 370 | mg/L |
| Monochlorohexafluoropropane (HCFC-226) | 431-87-8 | 23 | mg/L |
| m-xylene | 108-38-3 | 16 | mg/L |
| N, N-Demethylaniline | 121-69-7 | 65 | mg/L |
| Naphthalene | 91-20-3 | 6 | mg/L |
| N-butyl alcohol | 71-36-3 | 1860 | mg/L |
| Nickel | 7440-02-0 | 2.48 | mg/L |
| Nickel cmpds | 20-14-4 | 27 | mg/L |
| Nitrate |  | 2213 | mg/L |
| Nitrates/nitrites | 14797-55-8 | 2213 | mg/L |
| Nitric acid | 7697-37-2 | 26 | mg/L |

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| Nitrites | 14797-65-0 | 225 | mg/L |
| Nitrobenzene | 98-95-3 | 119 | mg/L |
| Nitrogen dioxide | 10102-44-0 | 196 | mg/L |
| N-nitrosodiphenylamine | 86-30-6 |  | mg/L |
| o-xylene | 95-47-6 | 16 | mg/L |
| p-cresol | 106-44-5 | 25 | mg/L |
| Perfluorooctanoic acid (PFOA) | 335-67-1 | 455 | mg/L |
| Phenol | 108-95-2 | 34 | mg/L |
| Phosphoric acid | 7664-38-2 | 70 | mg/L |
| Phosphorus (yellow or white) | 7723-14-0 | 0.02 | mg/L |
| Phthalic anhydride | 85-44-9 | 364 | mg/L |
| Picric acid | 88-89-1 | 170 | mg/L |
| Polychlorinated biphenyls | 1336-36-3 | 3 | mg/L |
| Potassium bicarbonate | 298-14-6 | 305 | mg/L |
| Propionaldehyde | 123-38-6 | 44 | mg/L |
| Propylene | 115-07-1 | 5 | mg/L |
| Propylene oxide | 75-56-9 | 306 | mg/L |
| p-xylene | 106-42-3 | 2 | mg/L |
| Pyridine | 110-86-1 | 100 | mg/L |
| Sec-butyl alcohol | 78-92-2 | 3670 | mg/L |
| Selenium | 7782-49-2 | 4.9 | mg/L |
| Silver | 7440-22-4 | 04 | mg/L |
| Silver cmpds |  | 12 | mg/L |
| Silvex | 93-72-1 | 13 | mg/L |
| Sodium Hypochlorite | 7681-52-9 | 0.53 | mg/L |
| Strontium | 7440-24-6 | 210 | mg/L |
| Styrene | 100-42-5 | 4 | mg/L |
| Sulfuric acid | 7664-93-9 | 31 | mg/L |
| Terbufos | 13071-79-9 | 0.01 | mg/L |
| Terephthalic acid | 100-21-0 | 29 | mg/L |
| Tert-butyl alcohol | 75-65-0 | 1954 | mg/L |
| Tetrachloroethylene | 127-18-4 | 17 | mg/L |
| Tin | 7440-31-5 | 626 | mg/L |
| Tin (Sn++, Sn4+) |  | 626 | mg/L |
| Titanium tetrachloride | 7550-45-0 | 25 | mg/L |
| Toluene | 108-88-3 | 34 | mg/L |
| Toluene-2,4-diisocyanate | 584-84-9 | 53 | mg/L |
| Trans-1,2-dichloroethylene | 156-60-5 | 45 | mg/L |
| Tri propylene glycol butyl ether | 55934-93-5 | 900 | mg/L |
| Trichloroethylene | 79-01-6 | 44 | mg/L |
| Trichlorofluoromethane | 75-69-4 | 114 | mg/L |
| Triethylene glycol | 112-27-6 | 88100 | mg/L |
| Trifluralin | 1582-09-8 | 0.11 | mg/L |
| Vanadium | 7440-62-2 | 4 | mg/L |
| Vinyl acetate | 108-05-4 | 100 | mg/L |
| Vinyl chloride | 75-01-4 | 143 | mg/L |

| Chemical | CAS # | Fish NOEL | unit |
|---|---|---|---|
| Vinylidene chloride | 75-35-4 | 108 | mg/L |
| Xylene (mixed isomers) | 1330-20-7 | 13 | mg/L |
| Zinc (+2) | | 0.09 | mg/L |
| Zinc (elemental) | 7440-66-6 | 0.09 | mg/L |
| Zinc borate | 1332-07-6 | 409 | mg/L |
| Zinc cmpds | 20-19-9 | 17 | mg/L |
| Zinc sulfate | 7733-02-0 | 14 | mg/L |

[a] The hazard value for each chemical was derived by dividing the toxicity values shown here by the applicable geometric mean presented in Appendix E-3.

## Appendix E-3: Geometric Means Used in Hazard Value Calculations

**Table E-6. Geometric Means Used to Calculate Toxicity Hazard Values**

| Parameter | n | min | max | Geometric mean |
|---|---|---|---|---|
| Oral SF | 175 | 0.00095 | 150000 | **0.707** |
| Inhalation SF | 105 | 0.00165 | 150000 | **1.70** |
| Oral NOAEL | 171 | 9E-08 | 7500 | **16.8** |
| Inhalation NOAEL | 90 | 0.006 | 245000 | **69.8** |
| Fish LC50 | 235 | 0.001 | 227634 | **27.4** |
| Fish NOEL | 213 | 0.001 | 56909 | **4.07** |

[a] The chemical data used to generate the geometric means are listed in Appendix E-2.

# Appendix E-4: Example Toxicity Calculation

The following example illustrates how toxicity impacts are calculated. Please refer to Section 3.2.11 of the main body of this report for descriptions of the methodologies for calculating these impacts.

If two toxic chemicals (e.g., toluene and benzo(a)pyrene) are included in a waterborne release to surface water from Process A, impact scores would be calculated for the following impact categories (based on the classification shown in Table 3-1 of the main report):

- Chronic public health effects, cancer and non-cancer; and,
- Aquatic ecotoxicity.

Despite the output types being waterborne releases, the water eutrophication and water quality impact categories are not applicable here because the chemical properties criteria in Table 3-1 are not met. That is, these chemicals do not contain nitrogen or phosphorus and are not themselves wastewater streams.

Using chronic public health effects as an example, impact scores are then calculated for each chemical as follows:

*Cancer effects:*

$$IS_{CHP\text{-}CA:toluene} = HV_{CA:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}CA:benzo(a)pyrene} = HV_{CA:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

*Non-cancer effects:*

$$IS_{CHP\text{-}NC:toluene} = HV_{NC:toluene} \times Amt_{TCoutput:toluene}$$

$$IS_{CHP\text{-}NC:benzo(a)pyrene} = HV_{NC:benzo(a)pyrene} \times Amt_{TCoutput:benzo(a)pyrene}$$

Table E-7 presents toxicity data for the example chemicals. The hazard values and impact scores are calculated as follows:

**Table E-7. Toxicity Data Used in Example Calculations**

| Chemical | Cancer | | Chronic non-cancer effects | |
|---|---|---|---|---|
| | Weight of evidence | Slope factor (SF) $(mg/kg\text{-}day)^{-1}$ | Oral (mg/kg-day) | Inhalation $(mg/m^3)$ |
| Toluene | D, 3 | None | 100 (NOAEL) | 411.1 (NOAEL) |
| Benzo(a)pyrene | B2, 2A | 7.3 (oral)<br>3.1 (inhalation) | No data | No data |

*Cancer effects:*

The cancer HV for benzo(a)pyrene is calculated as follows:

$$oral: \qquad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$HV_{CAoral:benzo(a)pyrene}$ $= 7.3\ (mg/kg\text{-}day)^{-1}\ )\ 0.71\ (mg/kg\text{-}day)^{-1}$

$= 10.3$

$$inhalation: \qquad (HV_{CA_{inh}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

$HV_{CAinhalation:benzo(a)pyrene}$ $= 3.1\ (mg/kg\text{-}day)^{-1}\ )\ 1.7\ (mg/kg\text{-}day)^{-1}$

$= 1.82$

Thus, the cancer HV is 10.3, the greater of the two values. The cancer HV for toluene is zero since it has no slope factor and a WOE classification of D (EPA) and 3 (IARC).

Given a hypothetical waterborne release amount of 0.1 kg of benzo(a)pyrene per functional unit, the impact score for benzo(a)pyrene cancer effects is given by:

$IS_{CHP\text{-}CA,W:benzo(a)pyrene}$ $= 10.3 \times 0.1$

= 1.03 kg cancertox-equivalents of benzo(a)pyrene
per functional unit

Toluene=s impact score for cancer is zero since its HV is zero.

*Non-cancer effects:*

Since no data are available for non-cancer effects of benzo(a)pyrene, a default HV of one is assigned, representative of mean toxicity.

The non-cancer HV for toluene is calculated as follows:

$$oral: \qquad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

= 1/100 mg/kg-day ) 1/14.0 mg/kg-day

= 0.140

$$inhalation: \qquad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ \ NOAEL_i)}{1/(inhal\ \ NOAELSUBmean)}$$

= 1/411.1 mg/m$^3$ ) 1/68.7 mg/m$^3$

= 0.167

Thus, the non-cancer HV for toluene is 0.167, the greater of the two values.

Given the following hypothetical output amounts:

$Amt_{TC\text{-}O:TOLUENE}$ = 1.3 kg of toluene per functional unit

$Amt_{TC\text{-}O:BENZO(A)PYRENE}$ = 0.1 kg of benzo(a)pyrene per functional unit

The resulting non-cancer impact scores are as follows:

$IS_{CHP\text{-}NC,W:TOLUENE}$ = 0.167 x 1.3

= 0.22 kg non-cancer-equivalents of toluene per functional unit

$IS_{CHP\text{-}NC,W:BENZO(A)PYRENE}$ = 1 x 0.1

= 0.1 kg non-cancer-equivalents of benzo(a)pyrene per functional unit

If these were the only outputs from Process A relevant to chronic public health effects, the total non-cancer impact score for this impact category for Process A would be:

$IS_{CHP\text{-}NC:PROCESS\_A}$ = $IS_{CHP\text{-}NC\text{-}W:TOLUENE}$ + $IS_{CHP\text{-}NC\ \text{-}W:BENZO(A)PYRENE}$

= 0.22 + 0.1

= 0.23 nkg non-cancertox-equivalents per functional unit for Process A.

If the product system Y contained three processes altogether (Processes A, B, and C), and the non-cancer impact scores for Process B and C were 0.5 and 1.0, respectively, impact scores would be added together to yield a total impact score for the product system relevant to chronic public non-cancer health effects:

$$
\begin{aligned}
IS_{CHP\text{-}NC:PROFILE\_Y} &= IS_{CHP\text{-}NC:PROCESS\_A} + IS_{CHP\text{-}NC:PROCESS\_B} + IS_{CHP\text{-}NC:PROCESS\_C} \\
&= 0.23 + 0.5 + 1.0 \\
&= 1.73 \text{ kg non-cancertox-equivalents per functional unit for Profile Y.}
\end{aligned}
$$

An environmental profile would then be the sum of all the processes within that profile for each impact category.

# APPENDIX F:  Review Statement

The LCA was extensively reviewed by the Core Group.  Over 100 comments were addressed prior to the preparation of the final report.  Below are the comments received by the EPA LCA expert and how they were addressed.  The reviewer found the responses acceptable.

**Comments from EPA LCA expert, MaryAnn Curran, Office of Research and Development:**

| | COMMENT: | RESPONSE: |
|---|---|---|
| 1. | Overall the contractors did a very nice job with the study.  I did not delve into the data so I can't speak to their accuracy but I did take a look at the LCA methodology that was used. I really don't see much wrong in what they did. | |
| 2. | The goal of the study is clearly stated, they followed ISO methodology, clearly state all assumptions and data sources, and use a multi-media/multi-impact approach.  They have obviously done LCAs before. The only weakness I can see is the use of an "energy use" category. Typically, accounting for energy use doesn't allow for identification of impacts such as fossil fuel depletion (that is, not all energy is the same). But if for this industry and product type, the energy is being sourced basically from the same place (such as the national grid), then you can get a way with the energy use comparison.  The report touches on this a bit in the conclusion section. | For clarification, our "energy use" category is the quantity of energy (electrical or fuel energy) used throughout the life cycle, measured in megajoules per functional unit.  It includes electric energy from the national grid (which accounts for energy produced by various fuel types--coal, natural gas, nuclear, etc.), as well as energy used directly from fuels in industrial processes (e.g., natural gas or fuel oil #2).  Our energy use category does not account for fossil fuel depletion directly (as you say), and it is only intended to reflect energy use, knowing that some of that energy is from different sources; however we have an impact category for "non-renewable resource use impacts" where fossil fuel depletion is accounted for, along with any other non-renewables. |
| 3. | Also, the data are obviously not the best.  I am glad to see this mentioned in the section on recommended improvements.  In many places the data are pretty old. (There should be some indication of how age was handled - can it be assumed that the industry didn't change much in certain so that older data is acceptable?) and in other places only limited sources were used to average data.  These are very limiting to the robustness of the study, but I think the authors did a good job of identifying these weaknesses and did the best with what they could get.  I would just like to see this addressed a little better (more?) in the executive summary, without being too apologetic. | RESPONSE:  We have attached an excerpt from the Executive Summary with a suggested sentence to "beef up" the discussion on the data age issue.<br>Excerpt:  Last 2 paragraphs of section 3.2.1 of Executive Summary (suggested addition in ALL CAPS):  "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 database (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 WHICH 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- |

| | COMMENT: | RESPONSE: |
|---|---|---|
| | | 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." |
| 4. | I only found one typo: Check the last reference for Lovstof/mech_recylce.pdf (I assume this should be recycle) | Typo fixed. |