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).