Table 3-31. Top 99% of the CRT acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	47%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	16%
Manufacturing	LPG production	Sulfur oxides	Secondary	15%
Manufacturing	LPG production	Nitrogen oxides	Secondary	7.6%
Materials processing	Invar	Sulfur dioxide	Secondary	4.8%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.8%
Manufacturing	Japanese electric grid	Sulfur dioxide	Secondary	1.6%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.76%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	0.73%
Manufacturing	CRT glass/frit manufacturing	Nitrogen oxides	Primary	0.59%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	0.54%
Use	U.S. electric grid	Hydrofluoric acid	Model/secondary	0.41%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.40%
Materials processing	Polycarbonate production	Nitrogen dioxide	Secondary	0.26%
Manufacturing	U.S. electric grid	Nitrogen oxides	Model/secondary	0.25%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.23%
Manufacturing	LPG production	Nitrous oxide	Secondary	0.22%

*Column may not add to 99% due to rounding.

3.3.8.2 Major contributors to the LCD acidification impact results

Table 3-32 lists the materials responsible for the top 99% of the LCD acidification impact results and the LCI data type. Sulfur dioxide emissions from the U.S. electric grid during the use stage are the greatest contributor at 31%, followed by NO_x from natural gas production in the materials processing stage. The latter process produces natural gas used by one LCD monitor/module manufacturer as an ancillary material, indicating the LCD monitor/module manufacturing process group is ultimately responsible for this contribution to the impact score. However, as noted previously, only one LCD monitor/module manufacturer reported the ancillary use of LNG. Other LCD monitor/module manufacturers reported using LNG as a fuel, but not as an ancillary material. NO_x, ammonia, hydrofluoric acid, and hydrochloric acid emissions from LCD monitor/module manufacturing contribute another 22% of the LCD acidification impact score. LCD monitor/module manufacturing data were collected directly by the CDP from manufacturers in Asia.

NO_x emissions from the U.S. electric grid during the use stage, and SO_x and NO_x emissions from the Japanese electric grid during manufacturing are also among the top contributors to the LCD acidification results. LCI data for these process groups were developed by the CDP from secondary sources.

Table 3-32. Top 99% to the LCD acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	31%
Materials processing	Natural gas prod.	Nitrogen oxides	Secondary	15%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	13%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	10%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	9.8%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	4.0%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	3.2%
Manufacturing	LCD monitor/module mfg.	Hydrofluoric acid	Primary	2.8%
Manufacturing	LCD monitor/module mfg.	Hydrochloric acid	Primary	1.8%
Manufacturing	LPG production	Sulfur oxides	Secondary	1.3%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.2%
Manufacturing	LCD backlight	Nitrogen oxides	Primary	0.70%
Materials processing	Natural gas production	Ammonia	Secondary	0.69%
Materials processing	Natural gas production	Sulfur oxides	Secondary	0.65%
Manufacturing	LPG production	Nitrogen oxides	Secondary	0.65%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur oxides	Secondary	0.64%
Materials processing	PMMA sheet production	Sulfur oxides	Secondary	0.44%
Manufacturing	Natural gas production	Nitrogen oxides	Secondary	0.35%
Use	U.S. electric gird	Hydrofluoric acid	Model/secondary	0.27%

*Column may not add to 99% due to rounding.

3.3.8.3 Limitations and uncertainties

Acidification impact characterization is 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 mass unit of the pollutant being released compared to SO_2. This is a full equivalency approach to impact characterization where all substances are addressed in a unified, technical model, which lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.3.7).

For the CRT, and less so for the LCD, impact results are being driven primarily by SO_2 and NO_x emissions from U.S. power plants during use of the monitor by the consumer. As discussed in Section 3.3.5 and noted above, the U.S. and Japanese electric grid inventories were developed by the CDP from secondary sources. U.S. electric grid emissions of the criteria pollutants, including SO_2 and NO_x, are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, 1998), which were the best data available when the electric grid inventory data was developed and are expected to be reasonably accurate. However, the Japanese electric grid inventory was derived from the U.S. inventory based on the mix of fuels used in Japan. Because Japanese power plants may employ different pollution control devices, use fuels of different quality, or other factors, their emissions could actually be higher or lower than those reported in the inventory.

LCI data for many of the other primary contributors to the CRT acidification impact category are from existing LCI databases. The limitations and uncertainties associated with these data have been discussed extensively in other subsections of this chapter and pertain here. On the other hand, LCI data for many of the other primary contributors to the LCD acidification indicator results were collected directly by the CDP from manufacturers in Asia. These data are considered to be of better quality since they were collected to meet the goals, objectives and temporal and spatial boundaries of the CDP.

3.3.9 Air Particulates

Figure 3-12 presents the CRT and LCD LCIA results for the air particulates impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.8. Tables M-21 and M-22 in Appendix M list complete air particulates results for the CRT and LCD, respectively.

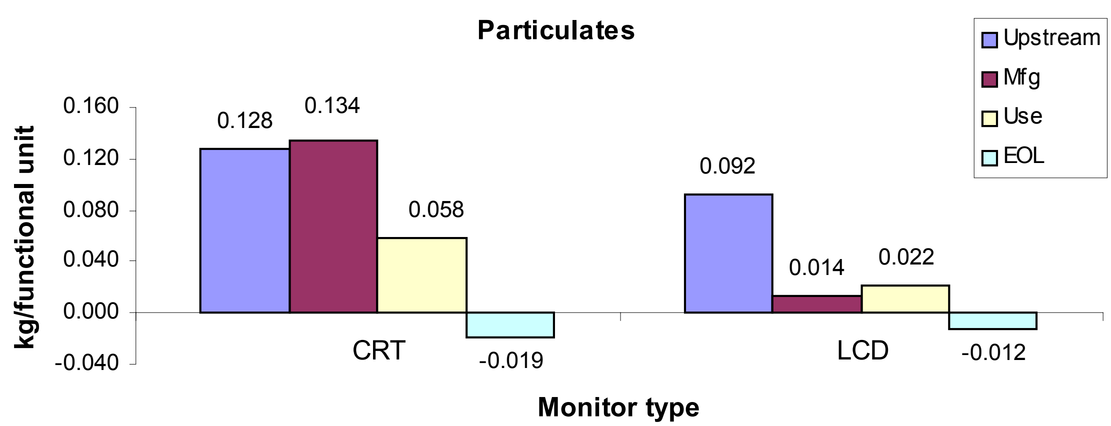

Figure 3-12. Particulates impacts by life-cycle stage

The life-cycle air particulates indicator is 0.30 kg of air particulates per monitor for the CRT and 0.115 kg of air particulates per monitor for the LCD. Recall from Section 3.1.2.8 that air particulates impact results are ideally based on release amounts of particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}) to the air. This is the size of particulate matter that is most damaging to the respiratory system. However, as will be shown later in this section, a significant portion of the particulate emissions data for both monitor types do not specify a particulate size. This makes it more difficult to draw conclusions about the relative life-cycle air particulate impacts of the CRT and LCD.

The manufacturing and upstream materials processing stages have almost equal contribution to CRT air particulate impacts, at 45% of the total for the manufacturing stage and 43% of the total for the upstream stages. LCD impacts, on the other hand, are dominated by particulate emissions during the upstream, materials processing stages, which contribute 80% of the total score. Both technologies receive a substantial reduction in life-cycle air particulate impacts at EOL due to an energy credit from incineration with energy recovery. The energy credit, which is from incineration with energy recovery, is applied to electric power production where it offsets some particulate emissions that would otherwise occur from electrical power production.

3.3.9.1 Major contributors to the CRT air particulates impact results

Table 3-33 lists the materials that contribute to the top 99% of the CRT air particulates impact score and their LCI data type. PM emissions from LPG production are the single largest contributor to the overall score, at 43% of the total. This LPG is primarily an energy source in CRT glass manufacturing, indicating the glass/frit process group is the ultimate source of these air particulate emissions. As noted previously, CRT glass energy inputs are the subject of a sensitivity analysis, discussed in Section 3.4.

Other major contributors to the CRT air particulates impact results are PM emissions from the steel production process group, PM_{10} emissions from the U.S. electric grid during the use stage, and PM emissions from aluminum production processes. Note that the inventories for steel and aluminum production combine data from the raw materials extraction, materials manufacture, and electricity generation processes. The PM emissions reported for the material production process group could be from any one of these individual processes, but particulate matter emissions are most often associated with combustion processes.

Table 3-33. Top 99% of the CRT air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	PM	Secondary	43%
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	35%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Materials processing	Aluminum production	PM	Secondary	3.0%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-33**,** the impact scores associated with the LPG, steel, and aluminum production process groups—82% of CRT air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups (that is, PM is used to represent PM_{10}), or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that CRT air particulate impacts are overstated.

3.3.9.2 Major contributors to the LCD air particulates impact results

Table 3-34 lists the materials that contribute to the top 99% of the LCD air particulates impact score and their LCI data type. PM emissions from steel production are the largest contributor to the overall score, followed by PM emissions from natural gas production. Natural gas from this process supplies the LNG used as an ancillary material by one LCD monitor/module manufacturer.

Other major contributors to the LCD air particulates impact results are PM_{10} emissions from the U.S. electric grid during the use stage and from the Japanese electric grid during manufacturing, and PM emissions from LPG production. LPG from the latter process supplies energy to the LCD glass manufacturing process.

Table 3-34. Top 99% of the LCD air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	45%
Materials processing	Natural gas production	PM	Secondary	25%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Manufacturing	Japanese electric grid	PM-10	Model/secondary	5.9%
Manufacturing	LPG production	PM	Secondary	5.4%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-34, the impact scores associated with the steel, natural gas, and LPG production process groups—roughly 75% of LCD air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. As with the CRT, air particulate impacts should be based on PM_{10} emissions, indicating LCD air particulate impacts may be overstated.

3.3.9.3 Limitations and uncertainties

The CDP LCIA methodology for air particulates is based on emissions of PM_{10} to air, which is the size of particulate matter that is most damaging to the respiratory system. However, as noted in Tables 3-33 and 3-34, the majority of the CRT and LCD impacts were calculated from emissions of "PM" rather than PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups, or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that both the CRT and LCD air particulate impacts are overstated.

The LCI data for all of the major contributors to both the CRT and LCD were either developed by the CDP from secondary sources (e.g., the U.S. and Japanese electric grids) or are from secondary LCI data sets (e.g., the fuel and upstream materials production processes). The limitations and uncertainties associated with these data have been discussed in other subsections of this chapter and pertain here. Note that U.S. electric grid emissions of the criteria pollutant PM_{10} are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, December, 1998, EPA/454/R-98-016), and are expected to be reasonably accurate.

Finally, the amount of LPG used to produce CRT glass, which is ultimately driving the CRT air particulates results, is also uncertain due to the large variability in CRT glass energy inputs received from glass manufacturers. See Section 3.4 for a sensitivity analysis of CRT glass energy inputs.

3.3.10 Water Eutrophication

Figure 3-13 presents the CRT and LCD LCIA results for the water eutrophication impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.9. Tables M-23 and M-24 in Appendix M are complete results for the CRT and LCD, respectively.

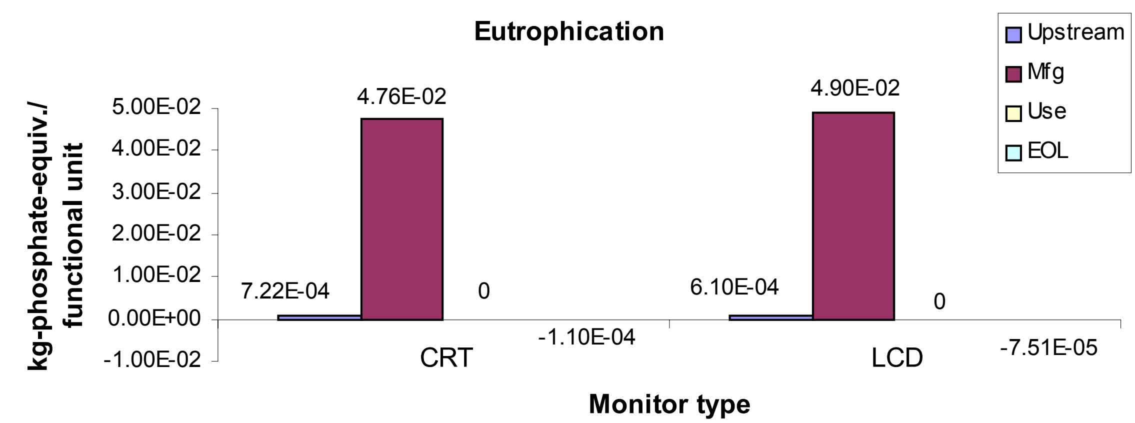

Figure 3-13. Eutrophication impacts by life-cycle stage

The life-cycle water eutrophication indicators are 0.048 kg of phosphate equivalents for the CRT and 0.050 kg of phosphate equivalents for the LCD. Results for both the CRT and LCD are completely dominated by emissions from the manufacturing stage, which accounts for 99% of the indicator for both technologies. Both technologies have negative scores at the end-of-life due to incineration with energy recovery. The energy recovery offsets some of the water emissions from the electricity generation inventory included in the incineration data set.

3.3.10.1 Major contributors to the CRT water eutrophication impact results

Table 3-35 lists the materials that contribute to the top 99% of the CRT water eutrophication results. Together, chemical oxygen demand (COD) and ammonia ions from the LPG production process group account for about 91% of the total score. Most of the LPG from this process is used as an energy source in CRT glass manufacturing (see Section 3.4 for the sensitivity analysis of CRT glass energy inputs). Emissions of nitrogen, COD and phosphorus from the CRT tube manufacturing process group contribute about seven percent of the CRT water eutrophication impacts. COD and other nitrogen emissions from steel production are the remaining top contributors to the CRT eutrophication score. LPG and steel production data are from secondary sources, while the CRT tube manufacturing outputs are primary data collected by the CDP.

Table 3-35. Top 99% of the CRT water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	COD	Secondary	72%
Manufacturing	LPG production	Ammonia ions	Secondary	19%
Manufacturing	CRT tube manufacturing	Nitrogen	Primary	6.3%
Materials processing	Steel production, cold-rolled, semi-finished	Other nitrogen	Secondary	0.37%
Materials processing	Steel production, cold-rolled, semi-finished	COD	Secondary	0.33%
Manufacturing	CRT tube manufacturing	COD	Primary	0.33%
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	0.32%

*Column may not add to 99% due to rounding.

3.3.10.2 Major contributors to the LCD water eutrophication impact results

Table 3-36 lists the materials that contribute to the top 99% of the LCD water eutrophication results. Like the CRT, the LCD water eutrophication indicator is driven by emissions from a single process group, in this case, LCD monitor/module manufacturing. Together, emissions of nitrogen and phosphorus from that process account for 94% of the total score. The LPG production process is the next largest contributor to the LCD water eutrophication score, where water releases of COD and ammonia ions account for more than 4% of the total.

Table 3-36. Top 99% to the LCD water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Nitrogen	Primary	67%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	27%
Manufacturing	LPG production	COD	Secondary	3.4%
Manufacturing	LPG production	Ammonia ions	Secondary	0.88%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.48%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.40%

*Column may not add to 99% due to rounding.

3.3.10.3 Limitations and uncertainties

Eutrophication (nutrient enrichment) impacts are calculated from the mass of a chemical released directly to surface water and the chemical's eutrophication potential (EP). 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 (see Section 3.1.2.9). As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. However, the methodology does take into account nitrogen and phosphorus, which are the two major limiting nutrients of importance to eutrophication.

CRT water eutrophication results are dominated by LCI data from secondary sources, and are therefore subject to the limitations and uncertainties associated with secondary data. Furthermore, these results are ultimately due to the large amount of LPG reported to be used as a fuel in LPG glass production. Because of the large degree of variability in glass energy data received from three CRT glass manufacturers, CRT glass energy inputs are also uncertain and the subject of a sensitivity analysis (see Section 3.4). LCD results, on the other hand, are driven almost entirely by primary LCI data from the manufacturing life-cycle stage, which were collected to meet the goals, objectives, and temporal and geographic boundaries of the CDP and are therefore considered to be of better quality.

3.3.11 Water Quality

3.3.11.1 Biological oxygen demand (BOD)

Figure 3-14 presents the CRT and LCD LCIA results for the BOD water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Complete results are listed in Tables M-25 (CRT) and M-26 (LCD) in Appendix M.

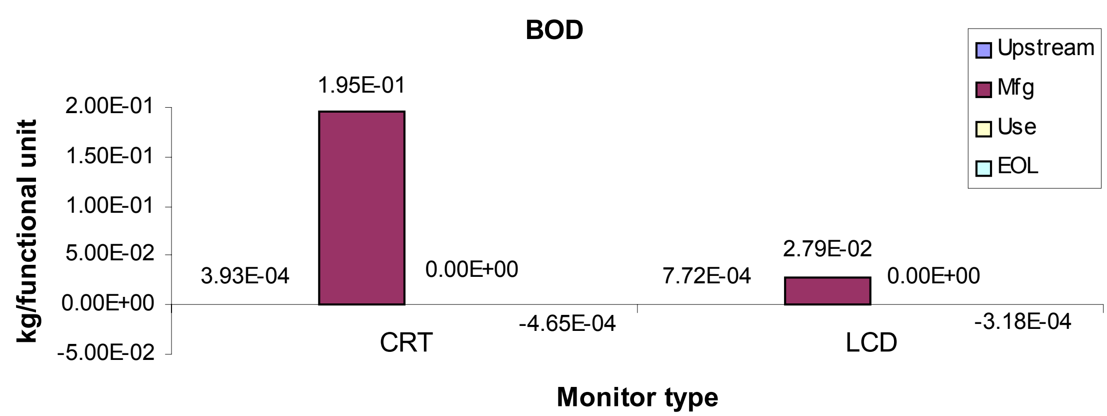

Figure 3-14. BOD impacts by life-cycle stage

During the life-cycle of a 17" CRT monitor, 0.195 kg of BOD are released to surface water. The life-cycle of a functionally equivalent 15" LCD results in 0.0283 kg of BOD surface water releases. As shown in Figure 3-14, BOD impacts for both monitor types are driven by surface water releases in the manufacturing stage, which contribute 100% of CRT impacts and 99% of LCD impacts. Note that small BOD impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. These are almost entirely offset by negative BOD values at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery. Note also that there are no BOD emissions from the U.S. electric grid during the use stage. The incineration inventory is a secondary data set that contains a different electric grid inventory than the U.S. electric grid inventory developed by the CDP.

Table 3-37 lists the materials responsible for the top 99% of the CRT BOD impacts. CRT impacts in this category are driven by BOD releases from the LPG production process, most of which is used to make LPG employed as fuel in CRT glass manufacturing. BOD releases from CRT tube manufacturing also contribute a small percentage to the total score.

Table 3-37. Top 99% of the CRT BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	BOD	Secondary	96%
Manufacturing	CRT tube manufacturing	BOD	Primary	3.3%

Table 3-38 lists the materials that contribute to the top 99% of the LCD BOD impacts. As shown in the table, LCD impacts are slightly more distributed among processes than CRT impacts, with BOD releases from four processes or process groups making up the list of top contributors. Note that BOD releases from LPG production (most of which is used to make LPG for LCD glass manufacturing) are much less for the LCD than the CRT, even though the LCD glass manufacturing inventory was derived from the CRT glass manufacturing inventory. This is because the CRT contains approximately ten times more glass than the LCD.

Table 3-38. Top 99% of the LCD BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	BOD	Primary	61%
Manufacturing	LPG production	BOD	Secondary	32%
Manufacturing	LCD panel components	BOD	Primary	4.7%
Materials processing	Natural gas production	BOD	Secondary	0.99%

3.3.11.2 Total suspended solids (TSS)

Figure 3-15 presents the CRT and LCD LCIA results for the TSS water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Tables M-27 and M-28 in Appendix M list complete results for the CRT and LCD, respectively.

The life-cycle TSS impact indicator is 0.874 kg of TSS for the CRT and 0.0615 kg of TSS for the LCD. TSS impacts for both monitor types are driven by the manufacturing stage, where 99 and 94% of impacts occur for the CRT and LCD, respectively. TSS impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. Both technologies receive a credit on TSS impacts at EOL due to an offset of electric grid emissions when the monitors are incinerated with energy recovery.

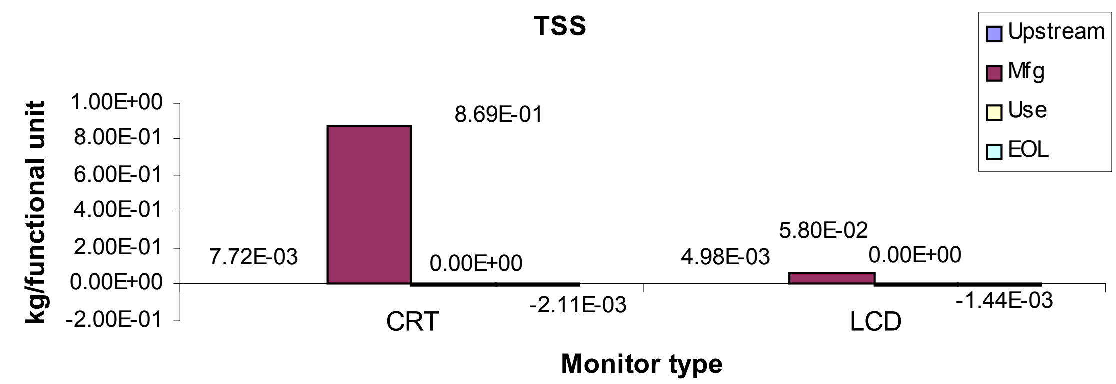

Figure 3-15. TSS impacts by life-cycle stage

Table 3-39 presents the major contributors to the CRT TSS indicator and lists the LCI data type. As with many other impact categories, the LPG production process is the single largest contributor to the CRT TSS indicator, accounting for 97% of the total score. Most of the LPG from this process is used as a fuel to produce CRT glass, but CRT energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. TSS surface water releases from the CRT glass/frit process group, CRT tube manufacturing, and fuel oil #6 production are also top contributors to the CRT TSS score. However, the contribution of these processes or process groups is small compared to that of the LPG production process.

Table 3-39. Top 99% of the CRT TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Suspended solids	Secondary	97%
Manufacturing	CRT glass/frit mfg.	Suspended solids	Primary	0.83%
Manufacturing	CRT tube manufacturing	Suspended solids	Primary	0.53%
Manufacturing	Fuel oil # 6 production	Suspended solids	Secondary	0.33%

Table 3-40 presents the top contributors to the LCD TSS impact score. Like the CRT results discussed above, TSS surface water releases from the LPG production process are responsible for the majority of LCD TSS impacts. LPG from this production process is used to produce LCD glass. Note that the actual mass of TSS releases from the LCD-related process is much smaller than those from the CRT-related process. This is because the LCD only uses about 10% as much glass as the CRT. TSS releases from the LCD monitor/module process group also account for a sizeable percentage of LCD TSS impacts.

Table 3-40. Top 99% of the LCD TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Suspended solids	Secondary	66%
Manufacturing	LCD monitor/module mfg.	Suspended solids	Primary	25%
Materials processing	PMMA sheet production	Suspended solids	Secondary	2.2%
Materials processing	Natural gas production	Suspended solids	Secondary	2.0%
Materials processing	Steel production, cold-rolled, semi-finished	Suspended solids	Secondary	1.6%
Materials processing	Aluminum production (all virgin)	Suspended solids	Secondary	1.1%
Manufacturing	LCD panel components	Suspended solids	Primary	1.0%

*Column may not add to 99% due to rounding.

3.3.11.3 Limitations and uncertainties

Both BOD and TSS indicators are calculated using a loading approach (i.e., the impact score is based on the inventory amounts) and are therefore highly sensitive to inventory data quality. CRT impact results are driven almost entirely by the LPG production inventory (a secondary data set) and are therefore subject to the limitations and uncertainties associated with secondary data. In particular, see Section 3.3.2.3 for a detailed discussion of LPG production data quality. In addition, note that LPG production impacts are almost all due to the large amount of LPG reported to be used as a fuel in CRT glass manufacturing. As note previously, CRT glass energy inputs are uncertain and are evaluated in a sensitivity analysis (see Section 3.4).

LCD impact results, on the other hand, are driven by LCI data from both primary and secondary sources and are therefore considered to be of somewhat better quality than the CRT results. However, a significant percentage of LCD water quality impacts also come from the large amount of LPG used as a fuel input to LCD glass manufacturing. These energy inputs are also uncertain and are evaluated in the sensitivity analysis in Section 3.4.

3.3.12 Radioactivity

Figure 3-16 presents the CRT and LCD LCIA results for the radioactivity impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.11. Complete CRT and LCD results are presented in Tables M-29 and M-30 in Appendix M, respectively.

The life-cycle radioactivity indicator is 38.5 million Bequerels (Bq) for the CRT and 12.2 million Bq for the LCD. Radioactivity impacts are driven by radioactive emissions from the upstream, materials processing stage for both monitor types, which contributes 99% of CRT life-cycle impacts and 98% of LCD life-cycle impacts. This result was unforeseen, since one might expect the majority of radioactive emissions to occur from the use stage, due to electricity generation at nuclear power plants. As it turns out, radioactivity impacts are being driven by data for nuclear fuel reprocessing that are included in the electric grid inventories for the steel, invar (an alloy of nickel and ferrite), and ferrite production process groups.

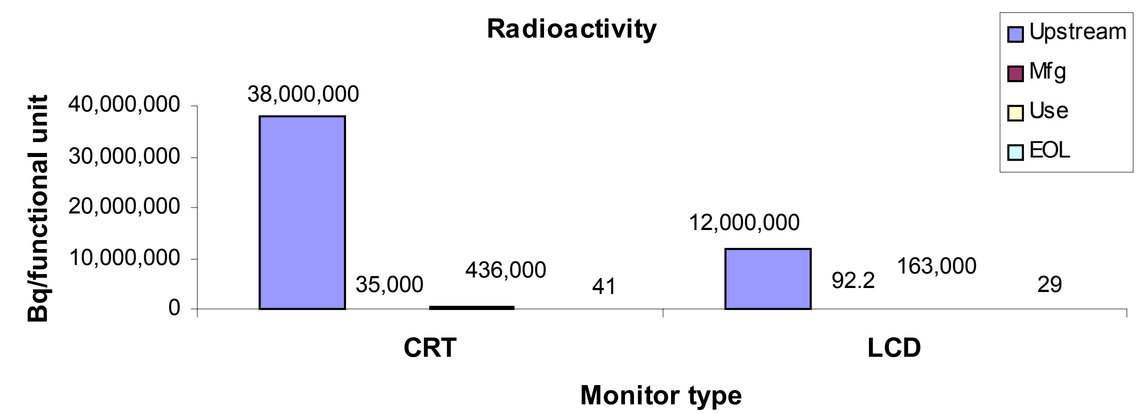

Figure 3-16. Radioactivity impacts by life-cycle stage

The LCIs for steel, invar, and ferrite were obtained from two databases developed by the former *Ecobilan Group,* an LCA consulting firm that was previously headquartered in France (see Section 2.2.1.1 for a discussion of how these databases were selected). Per *Ecobilan*, the ferrite inventory contains older data that may include radioactive emissions from electricity use. For the steel and nickel inventories, the source of both is site data in Europe, with the radioactive emissions coming from electricity in Europe, where nuclear fuel is reprocessed. In fact, the electricity data are from France for both materials, and France is one of the few countries (including Japan and the United Kingdom) that reprocesses nuclear fuel (Glazebrook, 2001). Therefore, the radioactivity impacts calculated from these inventories are more representative of impacts from countries that reprocess nuclear fuel than impacts from countries that do not.

To further illustrate this point, Tables 3-41 and 3-42 lists the materials and process groups that contribute to the top 99% of the CRT and LCD radioactivity indicator results, respectively. As shown in the tables, radioactivity impacts for both monitor types are driven by releases of plutonium-241 from steel (both monitor types), invar (CRT), and ferrite (CRT) production. Plutonium-241 is a byproduct of fuel reprocessing. Xenon -133 releases from the U.S. electric grid contribute slightly to the LCD radioactivity impacts and to a lesser degree to the CRT total impacts. Note that the actual amount of radioactivity from Xenon-133 is greater for the CRT than the LCD, but contributes a smaller percent of total impacts.

Table 3-41. Top 99% of the CRT radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	62%
Materials processing	Invar	Plutonium-241 (isotope)	Secondary	18%
Materials processing	Ferrite	Plutonium-241 (isotope)	Secondary	17%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.81%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.27%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.24%

*Column may not add to 99% due to rounding.

Table 3-42. Top 99% of the LCD radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	96%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.95%
Manufacturing	Japanese electric grid	Xenon-133M (isotope)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.42%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.38%

*Column may not add to 99% due to rounding.

Most of the radioactivity impacts are based on LCI data from secondary sources and are therefore subject to the limitations and uncertainties in secondary data, discussed previously. In addition, because radioactivity impacts are being driven by radioactive emissions from fuel reprocessing in France, they may not be representative of radioactivity impacts elsewhere. However, most of the CRT and LCD primary manufacturing data were collected from companies in Japan, where fuel reprocessing also occurs. For example, if Japanese CRT and LCD monitor and/or components manufacturers purchase steel from Japanese steel mills, the radioactivity emissions from electricity used to manufacture the steel could be similar. Japan ranked second in worldwide steel production in 2000 behind Mainland China, and third in 1999 behind Mainland China and the United States (IISI, 2001).

Note that the Japanese electric grid, which is linked to CRT and LCD production inventories, was developed from the U.S. electric grid inventory and therefore does not account for radioactive emissions from fuel reprocessing. This means that radioactive impacts from Japanese manufacturing processes that consume electricity are understated. For example, electricity used in the CRT glass/frit process group was the ninth largest contributor to the CRT energy use score, but the inventory for this process group does not account for fuel reprocessing emissions.

3.3.13 Potential Human Health Impacts

As discussed in Section 3.1.2.12, human health impacts included in the scope of this LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects to both workers and the public, and aesthetics. (Although not a health effect *per se*, aesthetics pertains to human welfare.)

Chronic health effect (cancer and noncancer) impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the chronic toxicity of a specific material (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). In this manner the inventory amount (the toxic chemical input amount for occupational health effects, and the output amount for public health effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the chemical for chronic exposure.

The CDP human health effects LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. LCI data do not have the temporal and spatial specificity needed to estimate potential dose rates, for example, nor do they contain information on engineering controls used in an occupational setting to reduce exposure. [It should be noted that more sophisticated models for evaluating human health effects in an LCA framework are being developed that use a multimedia fate, multi-pathway human exposure, and toxicological potency approach (Bare, 1999). However, such models are less comprehensive in terms of the number of chemicals for which there are data.] The limitations and uncertainties in the health effects scores are discussed further below, following the presentation of results.

3.3.13.1 Chronic occupational health effects

Figure 3-17 presents the CRT and LCD LCIA results by life-cycle stage for the chronic occupational health effects impact category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete CRT and LCD results are presented in Tables M-31 and M-32 in Appendix M.

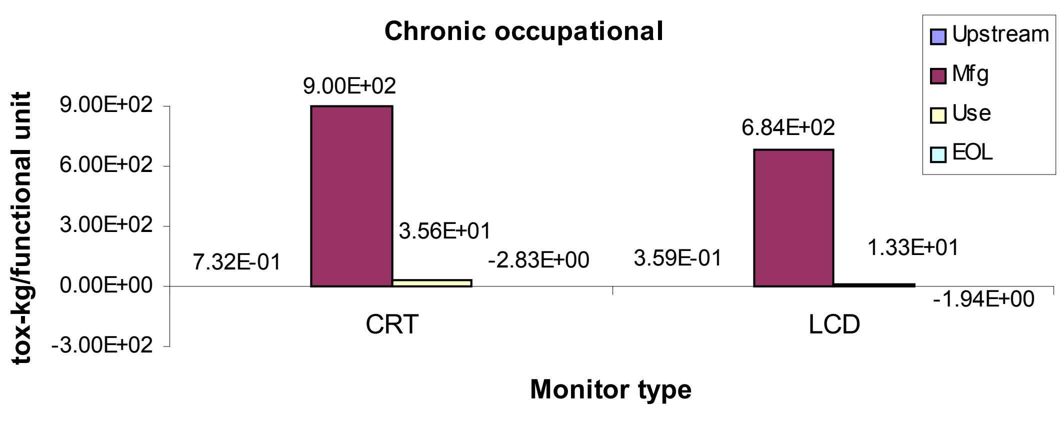

Figure 3-17. Chronic occupational impacts by life-cycle stage

The life-cycle chronic occupational health effects indicator is 934 tox-kg per functional unit for the CRT, and 696 tox-kg per functional unit for the LCD. As shown in the figure, the total score is dominated by toxic chemical inputs to the manufacturing stage, which account for 98% and 96% of CRT and LCD impacts in this category, respectively. This result was expected since inputs to the other life-cycle stages tend to be raw materials (e.g., ores, coal, etc., for the materials processing and use life-cycle stages) or finished products (e.g., the monitors themselves for the EOL stage) that are not classified as toxic materials (see Table K-9 in Appendix K for a l
list of materials excluded from the toxic classification). Both the CRT and LCD receive negative chronic occupational health effects scores at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-43 lists the materials responsible for the top 99% of the CRT chronic occupational health effects score and the LCI data type. LCI data for most of the top contributors are primary data collected from manufacturers by the CDP. In general, these data are expected to be of better quality (for the purposes of the CDP) than data from secondary sources, since they were collected to meet the goals and scope of the CDP.

Table 3-43. Top 99% of the CRT chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT glass/frit mfg.	Liquified petroleum gas	Primary	75%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	13%
Manufacturing	CRT tube manufacturing	Sulfuric acid	Primary	4.1%
Use	U.S. electric grid	Natural gas	Model/secondary	3.0%
Manufacturing	CRT glass/frit mfg.	Barium carbonate	Primary	1.8%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.81%
Manufacturing	CRT tube manufacturing	Fuel oil # 6	Primary	0.79%

*Column may not add to 99% due to rounding.

LPG inputs to the glass/frit process group, primarily from CRT glass manufacturing, contribute 75% of the CRT impacts in this category. The high impact score for LPG is mainly due to the large amount of LPG inputs to the glass/frit process group (351 kg/functional unit), which results in a high score when multiplied by the HV. No toxicity data were available for LPG. Therefore, it was assigned default HVs of one for both cancer and noncancer effects (total HV=2), representative of mean cancer and noncancer toxicity values. As noted previously, glass manufacturing energy data are uncertain and therefore evaluated in a sensitivity analysis (see Section 3.4).

Sulfuric acid used in PWB manufacturing is the next greatest contributor to the CRT chronic occupational health effects results (13%) followed by sulfuric acid used in CRT tube manufacturing (4.1%). The sulfuric acid HV is based on an inhalation NOAEL of 0.1 mg/m^3, which is significantly lower (and therefore more toxic) than the geometric mean inhalation NOAEL of 68.7 mg/m^3. Consequently, sulfuric acid impacts are driven more by its inherent toxicity for noncancer effects than the input amounts (0.18 kg per functional unit for PWB manufacturing and 0.056 kg per functional unit for CRT tube manufacturing). Sulfuric acid has no cancer slope factor and an IARC weight of evidence (WOE) classification of 3 (not classifiable for carcinogenicity), and therefore received an HV of zero for cancer effects.

Natural gas and petroleum used as fuels in the U.S. electric grid, barium carbonate used in the CRT glass/frit process group and fuel oil #6 used to manufacture the CRT tube round out the top contributors to the CRT chronic occupational health effects score. Barium carbonate has no cancer slope factor and an EPA cancer WOE of D (not classifiable), and therefore has an HV of zero for cancer effects. However, its oral NOAEL is 0.21 mg/kg-day compared to the geometric mean oral NOAEL of 11.9 mg/kg-day, which results in an HV of 57 for noncancer effects. Therefore, like sulfuric acid, the barium carbonate impacts are driven more by its inherent toxicity than the input amount (0.297 kg per functional unit). No specific toxicity data were available for natural gas, petroleum, or fuel oil #6; consequently they were assigned a default HV of one for both cancer and noncancer effects (total HV=2).

Table 3-44 lists the materials that contribute to the top 99% of the LCD chronic occupational health effects score. Like the CRT, LCI data for most of the top contributors are primary data collected from manufacturers by the CDP, and are therefore expected to be of generally better quality (for the purposes of the CDP) than data from secondary sources.

Table 3-44. Top 99% of the LCD chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Liquified natural gas	Primary	57%
Manufacturing	LCD monitor/module mfg.	Sulfuric acid	Primary	23%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	8.0%
Manufacturing	LCD glass manufacturing	Liquified petroleum gas	Primary	4.7%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	1.8%
Manufacturing	LCD panel components	Sulfuric acid	Primary	1.6%
Use	U.S. electric grid	Natural gas	Model/secondary	1.5%
Manufacturing	LCD monitor/module mfg.	Dimethylsulfoxide	Primary	1.1%
Manufacturing	LCD monitor/module mfg.	Ethanolamine	Primary	0.62%

*Column may not add to 99% due to rounding.

As shown in the table, LCD impacts in this category are dominated by LNG used in LCD monitor/module manufacturing. The high impact score for LNG is primarily due to the large amount of ancillary LNG inputs (194 kg/functional unit) in the LCD monitor/module manufacturing inventory, which results in a high score when multiplied by the HV. No toxicity data were available for LNG. Therefore, it was assigned a default, mean HV of one for both cancer and noncancer effects (total HV=2). As noted previously, only one of seven LCD module/monitor manufacturers reported using LNG as an ancillary material. Therefore, the total score for LCD chronic occupational health effects may not be representative of the industry as a whole. If we remove this application of LNG from the LCD inventory, the LCD occupational health effects result is reduced by 58 percent, from 683 tox-kg per monitor to 288 tox-kg per monitor. Note, however that other LCD monitor/module manufacturers did report using LNG as a fuel.

Sulfuric acid used in three process groups (LCD module/monitor manufacturing, PWB manufacturing, and LCD panel components) accounts for another 33% of the LCD chronic occupational health effects score. As discussed above for the CRT, sulfuric acid has a relatively low toxicity value, and therefore a high HV, which results in a high impact score for a small input amount. The LCD module/monitor manufacturing process group has the highest impact score for sulfuric acid because it has the greatest input amount (0.229 kg per functional unit).

The remaining top contributors to the LCD chronic occupational health effects score are LPG used in LCD glass manufacturing; and phosphine, dimethylsulfoxide, and ethanolamine used in LCD monitor/module manufacturing; and natural gas used as a fuel by the U.S. electric grid. As discussed earlier, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. The LPG score is based on default HVs (representative of the geometric mean toxicity values) for both cancer and noncancer effects, since no toxicity data were available for LPG.

The phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day. Thus, due to its inherently high toxicity, a relatively small input of phosphine (in this case, 0.027 kg per functional unit) results in a relatively high chronic occupational health effects score. No slope factors or cancer WOE classifications were found for phosphine, indicating a default HV of one was used, which is far outweighed by the non-cancer hazard value.

Dimethylsulfoxide is less toxic than phosphine (oral LOAEL =1.0 mg/kg-day), but has a greater input amount (0.066 kg per functional unit). However, phosphine's greater toxicity outweighs the greater input amount for dimethylsulfoxide, resulting in a higher impact score for phosphine.

No specific toxicity data were available for natural gas; consequently it was assigned a default HV of one for both cancer and noncancer effects (total HV=2).

3.3.13.2 Chronic public health effects

Figure 3-18 presents the CRT and LCD LCIA scores by life-cycle stage for the chronic public health effects category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results are presented in Tables M-33 and M-34 in Appendix M, respectively.

The life-cycle chronic public health effects score is 1,980 tox-kg per functional unit for the CRT and 902 tox-kg per functional unit for the LCD. As shown in the figure, the CRT score is dominated by toxic chemical outputs from electricity generation in the use stage, which

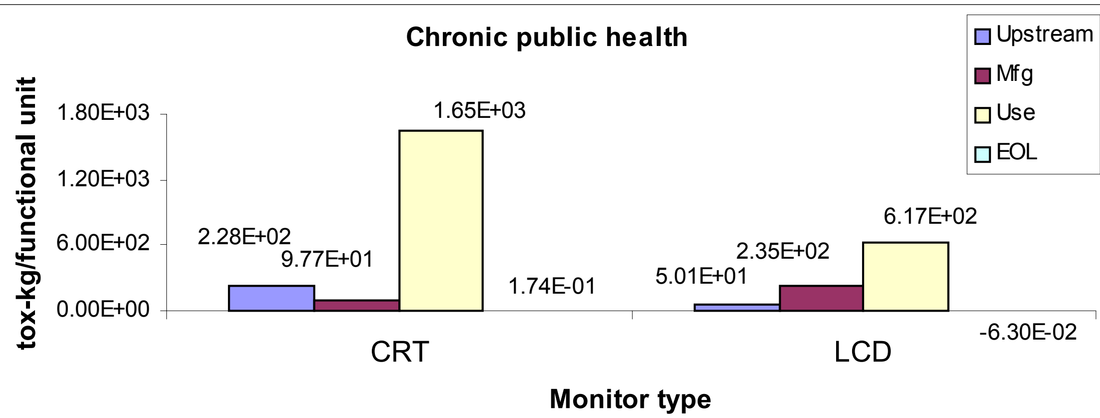

Figure 3-18. Chronic public health impacts by life-cycle stage

account for almost 84% of CRT impacts in this category. To a lesser degree, LCD chronic public health effect impacts are also driven by emissions from electricity generation in the use stage, which account for more than 68% of the total. Note that the ratio of CRT to LCD use stage public health impacts is the same as the ratio of CRT to LCD use stage electricity consumption (634 kWh/life for the CRT to 237 kWh/life for the LCD).

The materials processing stage contributes almost 12% of CRT chronic public health effect impacts and almost six percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small public chronic health effects scores at end of life. This is because most public health effect impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-45 presents the materials that contribute to the top 99% of the CRT chronic public health effects score. As shown in the table, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for more than 98% of the total. All of the SO_2 LCI data shown in the table are either from secondary data sets not developed specifically for the CDP, or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV based on an inhalation NOAEL of 0.104 mg/m^3, compared to the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, from a mass loading perspective, SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore does not contribute to the human health effects scores.

Table 3-45. Top 99% of the CRT chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.3%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.29%
Materials processing	Lead production	Sulfur dioxide	Secondary	0.23%

*Column may not add to 99% due to rounding.

Most of the sulfur dioxide emissions that contribute to the CRT chronic public health effects score are from the combustion of fossil fuels used to generate electricity. For example, the electricity required to power the monitor during the use stage accounts for the vast majority of SO_2 emissions and 83% of the CRT chronic public health effects score. Sulfur dioxide emissions from electricity consumed in the United States and Japan during the manufacturing life-cycle stage account for another 4.2% of the total score. Much of the SO_2 emissions reported in secondary data sets for the materials processing life-cycle stage may also be from electricity generation since many of these data also contain an electric grid inventory.

Table 3-46 lists the materials that contribute to the top 99% of the LCD chronic public health effects score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 93% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective, SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Table 3-46. Top 99% of the LCD chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	68%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	21%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	3.2%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.4%
Materials processing	PMMA sheet production	Sulfur dioxide	Secondary	0.96%
Materials processing	Natural gas production	Methane	Secondary	0.78%
Materials processing	Natural gas production	Benzene	Secondary	0.59%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.57%
Materials processing	Natural gas production	Carbon monoxide	Secondary	0.53%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.49%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	0.38%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.35%

*Column may not add to 99% due to rounding.

Other top contributors to the LCD chronic public health effects score include phosphine and phosphorus from LCD monitor/module manufacturing, and methane, benzene, and carbon monoxide from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day, resulting in a high HV. Thus, a relatively small output of phosphine (in this case, air emissions of 0.063 kg per functional unit) results in a relatively high chronic public health effects score.

The benzene and phosphorus chronic health effects scores are also driven more by their toxicity than the output amounts. Benzene is a known human carcinogen (EPA WOE Class A) that also causes noncancer health effects. The HV for benzene is based on its oral slope factor [0.055 (mg/kg-day)$^{-1}$] and its inhalation NOAEL for noncancer effects (1.15 mg/m^3), which together result in a high HV. (Benzene also has an *inhalation* slope factor and an *oral* NOAEL value, but these yield lower hazard values when compared to the geometric mean values.)

Phosphorus has an EPA WOE classification of D (not classifiable as to human carcinogenicity), but has a low oral NOAEL value (0.015 mg/kg-day), which also gives it a high HV.

No toxicity data were available for methane. Therefore, it received a default HV of one for both cancer and noncancer effects (HV=2 total). The HV for carbon monoxide is based on an inhalation LOAEL of 55 mg/m^3.

3.3.13.3 Chronic public health effect scores modified to exclude sulfur dioxide

Because the chronic public health effects scores for both the CRT and the LCD are dominated by SO_2 emissions, a secondary analysis was run to identify the top contributors to public health impacts when SO_2 emissions are excluded from the inventories. Results of this analysis may be more useful to manufacturers seeking to identify problematic toxic chemicals within their own manufacturing processes.

Figure 3-19 presents the CRT and LCD chronic public health effects scores by life-cycle stage when SO_2 emissions are excluded from the inventories. Under this scenario, the CRT score is reduced almost 99% from 1980 tox-kg to 26 tox-kg per functional unit, and the LCD score is reduced about 93% from 902 tox-kg to 61 tox-kg per functional unit. Note that these scores should not be used to evaluate which monitor type has higher overall impacts in this category, but they are useful for identifying life-cycle improvement opportunities that were previously obscured by SO_2 impacts.

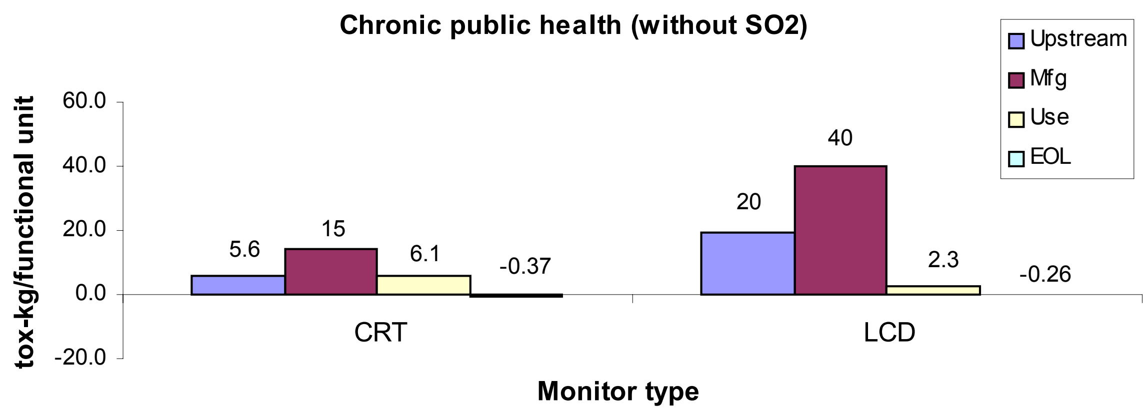

Figure 3-19. Chronic public health impacts (without SO2) by life-cycle stage

With SO_2 emissions removed from the inventories, chronic public health effect impacts are highest in the manufacturing life-cycle stage for both the CRT (56% of impacts) and the LCD (65% of impacts). The use stage is the next largest contributor for the CRT (22%), and the materials processing stage in the next largest contributor for the LCD (32%). As will be shown below, use stage impacts are significant for the CRT, even when SO_2 emissions are excluded, because of the CRT's relatively high electricity consumption during use by the consumer and the associated emissions of pollutants from U.S. power plants.

Table 3-47 presents the materials that contribute greater than one percent of CRT impacts when SO_2 emissions are excluded from the CRT inventory. Under this scenario, CRT chronic public health impacts are still being driven by emissions of criteria air pollutants,[2] including carbon monoxide, nitrogen oxides, and sulfur oxides (assuming that SO_2 emissions comprise a large part of the sulfur oxide emissions shown in the table). As shown in the table, emissions of these three pollutants or pollutant categories are responsible for some 48% of CRT chronic public health impacts when pure SO_2 emissions are excluded from the CRT inventory. Note that the majority of these emissions occur from the LPG production process, and most of this LPG is used as a fuel in CRT glass manufacturing. CRT glass manufacturing energy inputs are uncertain and evaluated in a sensitivity analysis (See Section 3.4). Other significant contributors include arsenic from lead production, methane from LPG production and the U.S. electric grid inventory, vanadium and benzene from LPG production, and titanium tetrachloride from aluminum production.

Table 3-47. Materials contributing greater than 1% of the CRT chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Carbon monoxide	Secondary	22.35%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	9.12%
Materials processing	Lead	Arsenic	Secondary	8.55%
Manufacturing	LPG production	Methane	Secondary	6.50%
Manufacturing	LPG production	Sulfur oxides	Secondary	6.21%
Use	U.S. electric grid	Methane	Modeled/secondary	4.99%
Manufacturing	LPG production	Nitrogen oxides	Secondary	4.44%
Use	U.S. electric grid	Carbon monoxide	Modeled/secondary	4.23%
Manufacturing	LPG production	Vanadium	Secondary	4.05%
Manufacturing	LPG production	Benzene	Secondary	3.32%
Materials processing	Aluminum production (virgin)	Titanium tetrachloride	Secondary	2.79%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.27%
Use	U.S. electric grid	Arsenic	Modeled/secondary	2.16%
Use	U.S. electric grid	Hydrochloric acid	Modeled/secondary	1.91%
Materials processing	Steel Prod., cold-rolled, semi-finished	Carbon monoxide	Secondary	1.16%

Table 3-48 presents the materials that contribute greater than one percent of LCD impacts when SO_2 emissions are excluded from the LCD inventory. Under this scenario, phosphine emissions from LCD monitor/module manufacturing are the dominant factor in the LCD chronic public health effects score, contributing 47% of the total. Other significant contributors include methane, benzene, carbon monoxide, and nitrogen oxides from natural gas production, and phosphorus, fluorides, tetramethyl ammonium hydroxide, and nitrogen oxides from LCD monitor/module manufacturing. Recall that the LCD monitor/module manufacturing process

[2] The criteria air pollutants are those for which U.S. National Ambient Air Quality Standards have been adopted. They are carbon monoxide, lead, nitrogen oxides, ozone, particulate matter, and sulfur dioxide.

consumes the majority of the natural gas made in the natural gas production process, where LNG is used as an ancillary material. However, only one of the seven LCD monitor/module manufacturers that provided inventory data to the CDP reported the ancillary use of LNG. Other LCD monitor/module manufactures did report the use of LNG as a fuel.

Table 3-48. Materials contributing greater than 1% of the LCD chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	46.7%
Materials processing	Natural gas production	Methane	Secondary	11.4%
Materials processing	Natural gas production	Benzene	Secondary	8.61%
Materials processing	Natural gas production	Carbon monoxide	Secondary	7.81%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	5.56%
Manufacturing	LCD monitor/module mfg.	Fluorides (F-)	Primary	4.15%
Materials processing	Natural gas production	Nitrogen oxides	Secondary	2.12%
Manufacturing	LCD monitor/module mfg.	Tetramethyl ammonium hydroxide	Primary	2.09%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	1.78%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	1.43%

3.3.13.4 Limitations and uncertainties: chronic human health effects

Most of the limitations and uncertainties in the chronic human health effects results presented here 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 are discussed below.

Structural or modeling limitations and uncertainty. 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, transformation, or degradation into account. In addition, it uses a simple surrogate value (i.e., inventory amount) to evaluate the potential for exposure, when actual exposure potential involves many more factors, some of which are chemical-specific. Other sources of uncertainty include possible omissions by the CDP 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 may also be considered limits in the toxicity data which are discussed further below.

It should also 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 can not 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. More detailed assessments of the toxicity and potential exposures to selected materials are performed in Chapter 4.

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 homogeneous 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.

Regarding uncertainties resulting from missing toxicity data, there is uncertainty 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). 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 273 chemicals classified as potentially toxic in the CDP LCA, 156 (57%) had no toxicity data for carcinogenic effects and 128 (47%) had no data for noncarcinogenic effects. Ninety-seven chemicals (36%) had no human health toxicity data whatsoever.

LCI data limitations and uncertainty. Limitations and uncertainties in the LCI data have been discussed previously and are generally related to: (1) uncertainties in data from secondary sources that may not be representative of the geographic and temporal boundaries of this LCA, and (2) uncertainties in a few of the primary data points collected specifically for this project. With regard to the latter, glass manufacturing energy inputs are particularly uncertain despite numerous attempts to resolve the uncertainty, but are responsible for a significant portion of CRT human health impacts. Glass manufacturing energy inputs are evaluated in a sensitivity analysis in Section 3.4. The amount of LNG used as an ancillary material in LCD monitor/module manufacturing is also uncertain (also despite attempts to resolve questions regarding the data), but this material contributes a significant portion of LCD occupational health impacts. As noted previously, removing this application of LNG from the LCD monitor/module manufacturing inventory would reduce the LCD chronic occupational health effects score by 68%.

3.3.13.5 Aesthetic impacts (odor)

Figure 3-20 presents the CRT and LCD LCIA results for the aesthetic impacts (odor) category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results for the CRT and LCD are presented in Tables M-35 and M-36 in Appendix M, respectively. The life-cycle aesthetic (odor) impact result is 7.58 million m^3 malodorous air per functional unit for the CRT and 5.04 million m^3 malodorous air per functional unit for the LCD. As shown in the figure, this impact category indicator is dominated by air emissions in the manufacturing stage for both the CRT (96% of total) and the LCD (98% of total). Both monitor types receive relatively minor contributions in the use and materials processing life-cycle stages, and negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

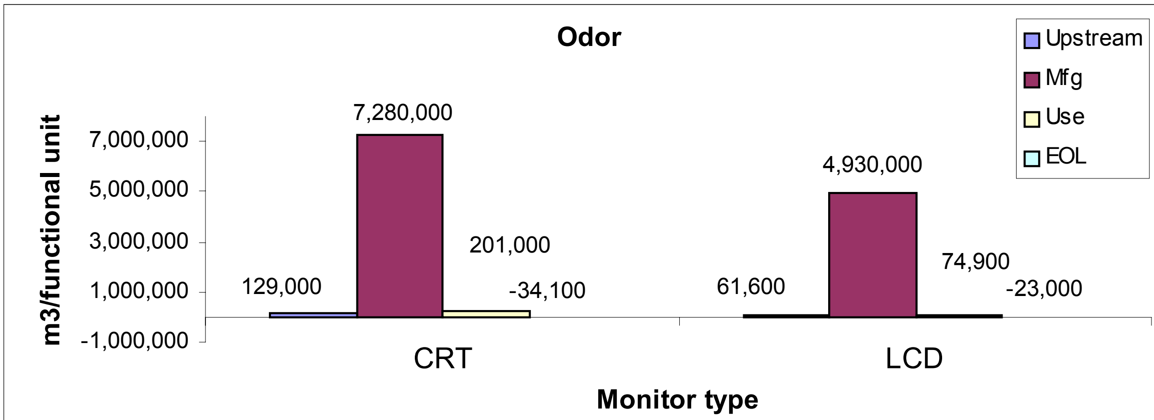

Figure 3-20. Odor impacts by life-cycle stage

Major Contributors to the CRT Aesthetics (Odor) Result

Table 3-49 lists the materials that contribute to the top 99% of the CRT aesthetic impacts result and the LCI data type. Air emissions of hydrogen sulfide from LPG production in the manufacturing life-cycle stage dominate the CRT odor impacts, contributing 94% of the total score. Hydrogen sulfide impacts are calculated based on an odor threshold value (OTV) of 0.00043 mg/m^3. [See Table K-7 in Appendix K for a list of OTVs used to calculate aesthetic (odor) impacts.] As noted previously, most of the LPG produced by this process is used as a fuel in CRT glass manufacturing, but glass manufacturing energy inputs are uncertain. The next largest contributor to the CRT is acetaldehyde emitted from the U.S. electric grid during the use stage. Acetaldehyde has a lower OTV (0.00027 mg/m^3) than LPG, and is also emitted in smaller quantities. Emissions of hydrogen sulfide from fuel oil #6 production, steel production, and ABS production are the remaining top contributors to the CRT aesthetic impacts score. LCI data for all of the top contributors are either from secondary data sets or developed by CDP researchers from secondary sources.

Table 3-49. Top 99% of the CRT aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Hydrogen sulfide	Secondary	94%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	2.5%
Manufacturing	Fuel oil #6 production	Hydrogen sulfide	Secondary	0.98%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrogen sulfide	Secondary	0.42%
Materials processing	ABS production	Hydrogen sulfide	Secondary	0.31%

*Column may not add to 99% due to rounding.

Major Contributors to the LCD Aesthetics (Odor) Result

Table 3-50 presents the materials that contribute to the top 99% of the LCD aesthetics impact score and the LCI data type. LCD impacts are dominated by air emissions of phosphine from LCD monitor/module manufacturing, which contribute 89% of the total score. OTVs reported for phosphine range from 0.014 to 2.8 mg/m^3. The lower, more sensitive value (0.014 mg/m^3) was used to calculate impacts.

Table 3-50. Top 99% of the LCD aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	89%
Manufacturing	LPG production	Hydrogen sulfide	Secondary	6.8%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	1.4%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	1.2%
Manufacturing	LCD monitor/module mfg.	Acetic acid	Primary	0.44%

*Column may not add to 99% due to rounding.

Other significant contributors include hydrogen sulfide from LPG production, acetaldehyde from the U.S. electric grid, and ammonia and acetic acid from LCD module/monitor manufacturing. Most of the LPG made in the LPG production process is used as a fuel in LCD glass manufacturing, indicating this process is ultimately responsible for LPG production impacts. However, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis (Section 3.4). LCD monitor/module manufacturing data were collected directly from manufacturers by the CDP, while the LPG production inventory was obtained from *Ecobilan.* The U.S. electric grid inventory was developed by CDP researchers from secondary sources.

Limitations and Uncertainties

Aesthetic (odor) impact scores are based on the identity and amount of odor-causing chemicals (Heijungs *et al.*, 1992; EPA, 1992), released to the air divided by their chemical-specific OTVs. An OTV is the lowest concentration of a substance in air that can be smelled based on a standardized test. Limitations and uncertainties in the aesthetics impact score stem from structural or model uncertainty (whether or not odor thresholds will actually be exceeded), OTV data uncertainty (how well published OTVs represent the odor threshold of different populations), and LCI data uncertainty.

The aesthetics impact score calculates the mass of malodorous air that could result if a chemical release occurs in a finite volume of air. It does not predict whether actual odor impacts will occur. This is because LCI data do not describe the time rate of release or whether dilution and mixing with ambient air will dilute the concentration of a pollutant to below its odor threshold. In addition, odor thresholds are highly variable because of the differing ability of individuals to detect odors. Therefore, the impact scores may not account for odors perceived by the most sensitive populations or may overstate impacts perceived by less sensitive populations. Finally, the aesthetic impact scores are subject to the limitations and uncertainties in the LCI data, since they are calculated from air emissions data in the inventories. The limitations and uncertainties in LCI data were discussed in Section 2.2.2.2, and have been discussed extensively with LCIA results for other impact categories, above.

3.3.14 Ecotoxicity

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. As discussed in Section 3.1.2.13, ecotoxicity impact categories included in the scope of this LCA include impacts to aquatic and terrestrial organisms.

Ecotoxicity impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the toxicity of a specific material to aquatic or terrestrial organisms (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). Aquatic HVs are based on acute and chronic toxicity values for fish, while terrestrial HVs are based on chronic noncancer toxicity values for mammals, usually rodents. Similar to the chronic human health impacts discussed in Section 3.3.13, the inventory amount (the toxic chemical outputs to water for aquatic toxicity effects, and the outputs to air and water for terrestrial toxicity effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the substance.

Also like the human health effects methodology, the CDP ecotoxicity LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. In addition, the methodology is limited in that it does not consider toxicity data from all types of aquatic or terrestrial species, but rather focuses on a few selected species for which more toxicity data are available. The limitations and uncertainties in the ecotoxicity scores are discussed further below, following the presentation of results.

3.3.14.1 Aquatic toxicity

Figure 3-21 presents the CRT and LCD LCIA results for the aquatic toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-37 and M-38 in Appendix M, respectively.

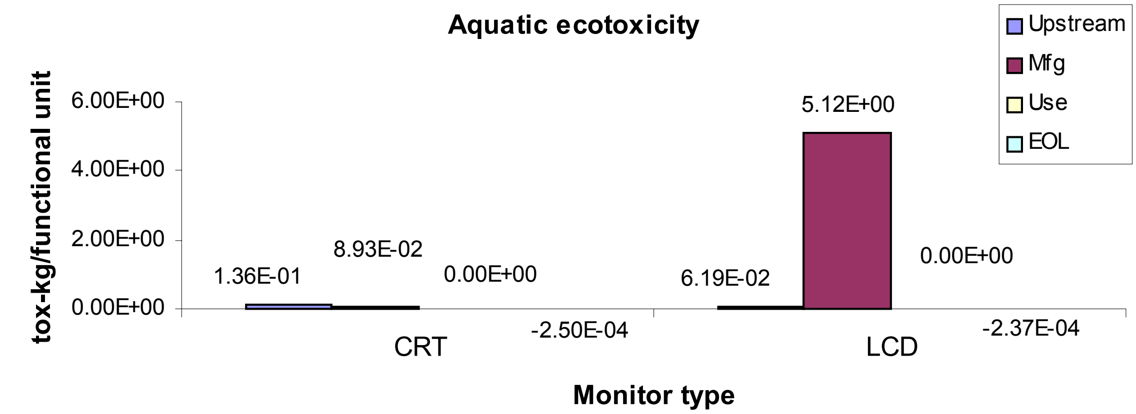

Figure 3-21. Aquatic ecotoxicity impacts by life-cycle stage

The life-cycle aquatic toxicity indicator is 0.22 tox-kg per functional unit for the CRT and 5.19 tox-kg per functional unit for the LCD. As shown in the figure, the CRT aquatic toxicity indicator is driven by water releases in the materials processing stage (64% of total), while the LCD aquatic toxicity indicator is completely dominated by water releases in the manufacturing stage (99% of total). Both monitor types receive zero scores in the use stage and small, negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

Table 3-51 lists the materials that contribute to the top 99% of the CRT aquatic toxicity impact score and the LCI data type. As shown in the table, CRT aquatic toxicity impacts are broadly distributed across a number of different process groups, with most of the top contributors responsible for less than five percent of the impacts. Most of the LCI data from which the scores were calculated are from secondary data sets, although a substantial fraction are from primary data collected to meet the goals and scope of the CDP LCA. Water releases of phosphorus from CRT tube manufacturing represents the single largest contributor to the CRT aquatic toxicity score, accounting for 26% of the total. Aquatic toxicity impacts for phosphorus are driven more by its inherent acute toxicity than the output amount. The phosphorus acute HV is calculated from a fish LC_{50} of 0.020 mg/L, which is significantly more toxic than the geometric mean value of 23.5 mg/L.

The only other specific outputs that contribute more than five percent of the CRT aquatic toxicity score are water discharges of aluminum ions (valence = +3) and copper ions (valence = +1 and +2) from aluminum production. The aluminum HV is calculated from an LC_{50} value of 36 mg/L and a NOAEL value of 3.6 mg/L, which are within an order of magnitude of the geometric mean values of 23.5 mg/L and 3.9 mg/L. Copper, on the other hand, is much more toxic to fish, with an LC_{50} value of 0.014mg/L and a NOAEL value of 0.004 mg/L. The aluminum aquatic toxicity score exceeds that of copper because it is discharged in much greater quantities.

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	26%
Materials processing	Aluminum production	Aluminum (+3)	Secondary	12%
Materials processing	Aluminum production	Copper (+1 & +2)	Secondary	9.5%
Materials processing	Invar	Copper (+1 & +2)	Secondary	5.0%
Materials processing	Invar	Aluminum (+3)	Secondary	4.4%
Materials processing	Invar	Zinc (+2)	Secondary	4.0%
Materials processing	Lead	Aluminum (+3)	Secondary	3.6%
Manufacturing	CRT tube manufacturing	Fluoride	Primary	3.1%
Materials processing	Ferrite manufacturing	Zinc (+2)	Secondary	3.0%
Materials processing	Aluminum production	Zinc (+2)	Secondary	2.9%
Materials processing	ABS production	Ammonia	Secondary	2.7%
Materials processing	Lead	Copper (+1 & +2)	Secondary	2.7%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.6%
Manufacturing	CRT tube manufacturing	Zinc (elemental)	Primary	2.3%
Manufacturing	CRT tube manufacturing	Copper	Primary	2.1%
Materials processing	Steel production, cold-rolled, semi-finished	Phosphorus (yellow or white)	Secondary	2.0%
Manufacturing	LPG production	Phenol	Secondary	1.9%
Materials processing	Steel production, cold-rolled, semi-finished	Ammonia	Secondary	1.2%
Manufacturing	LPG production	Aluminum (+3)	Secondary	1.1%
Materials processing	Lead	Zinc (+2)	Secondary	0.82%
Materials processing	Polycarbonate production	Copper (+1 & +2)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Copper (+1 & +2)	Secondary	0.45%
Materials processing	Ferrite manufacturing	Aluminum (+3)	Secondary	0.43%
Materials processing	Aluminum production	Barium sulfate	Secondary	0.40%
Materials processing	ABS production	Aluminum (+3)	Secondary	0.39%
Materials processing	Invar	Ammonia	Secondary	0.36%
Materials processing	Ferrite manufacturing	Copper (+1 & +2)	Secondary	0.31%
Materials processing	ABS production	Copper (+1 & +2)	Secondary	0.25%
Materials processing	Styrene-butadiene copolymer production	Copper (+1 & +2)	Secondary	0.24%
Materials processing	Aluminum production	Titanium tetrachloride	Secondary	0.20%
Materials processing	Polycarbonate production	Mercury compounds	Secondary	0.19%
Materials processing	Aluminum production	Strontium (Sr II)	Secondary	0.14%

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Aluminum (+3)	Secondary	0.12%
Materials processing	Ferrite manufacturing	Ammonia	Secondary	0.12%
Materials processing	Lead	Barium sulfate	Secondary	0.10%
Materials processing	Steel production, cold-rolled, semi-finished	Nitrogen dixode	Secondary	0.088%
Materials processing	ABS production	Mercury compounds	Secondary	0.088%
Materials processing	Steel production, cold-rolled, semi-finished	Zinc (+2)	Secondary	0.087%
Materials processing	Styrene-butadiene copolymer production	Mercury compounds	Secondary	0.086%
Materials processing	Steel production, cold-rolled, semi-finished	Fluorides (F-)	Secondary	0.086%
Materials processing	Aluminum production	Lead compounds	Secondary	0.076%
Materials processing	Polycarbonate production	Zinc (+2)	Secondary	0.076%
Materials processing	Invar	Strontium (Sr II)	Secondary	0.074%

*Column may not add to 99% due to rounding.

Table 3-52 lists the materials that contribute to the top 99% of the LCD aquatic toxicity impact score and the LCI data type. Unlike the CRT, LCD impacts in this category are not distributed across a number of different process groups, but dominated by phosphorus emissions from a single process group, LCD monitor/module manufacturing. Phosphorus releases from LCD monitor/module manufacturing are several orders of magnitude higher than phosphorus releases from CRT tube manufacturing (the greatest contributor to the CRT aquatic toxicity impact score). However, the LCD aquatic toxicity score for phosphorus is still driven by the inherent acute toxicity of phosphorus, rather than the release amount.

Other top contributors to LCD impacts in this category include ammonia releases from PMMA sheet production, and phosphorus emissions from LCD panel components manufacturing. No toxicity data were available for ammonia. Consequently, it was assigned a default HV of two, representative of mean acute and chronic fish toxicity values.

Table 3-52. Top 99% of the LCD aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	98%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.63%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.56%

3.3.14.2 Terrestrial ecotoxicity

Figure 3-22 presents the CRT and LCD LCIA results for the terrestrial toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-39 and M-40 in Appendix M, respectively.

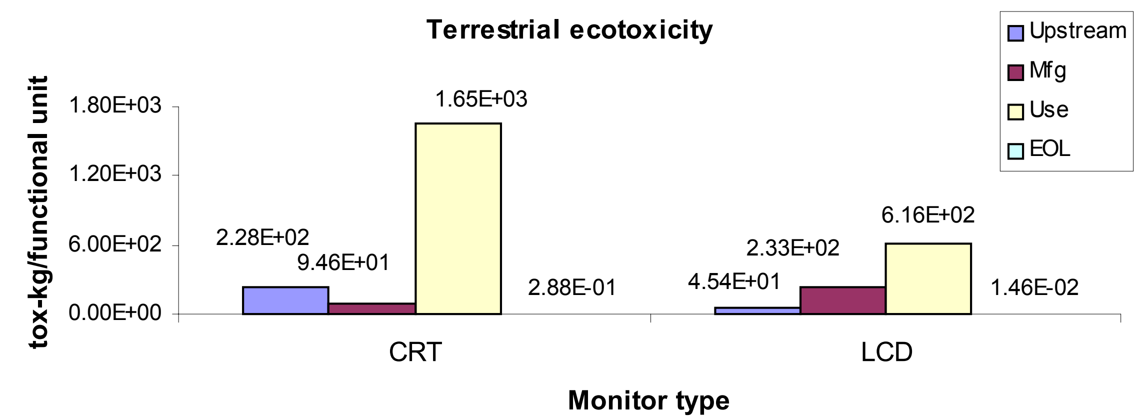

Figure 3-22. Terrestrial ecotoxicity impacts by life-cycle stage

The life-cycle terrestrial toxicity indicator is 1,970 tox-kg per functional unit for the CRT and 894 tox-kg per functional unit for the LCD. As shown in the figure, the CRT result is dominated by toxic chemical outputs from electricity generation in the use stage, which account for almost 84% of CRT impacts in this category. To a lesser degree, LCD terrestrial toxicity impacts are also driven by emissions from electricity generation in the use stage, which account for more than 69% of the total.

The materials processing stage contributes about 12% of CRT terrestrial toxicity impacts and about five percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small terrestrial toxicity scores at end of life. This is because most terrestrial toxicity impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

The terrestrial toxicity impact results are almost identical to the chronic public health effects results presented previously (see Section 3.3.13). Recall that human health and terrestrial toxicity impacts are calculated using the same noncancer toxicity values (and the same inventory data), with the main difference being that toxicity data on carcinogenic effects are excluded from the terrestrial toxicity impact calculations. However, human health and terrestrial toxicity impacts are almost identical because: (1) impacts in both categories are dominated by emissions of sulfur dioxide from electricity generation (see Tables 3-53 and 3-54 below for top contributors to the CRT and LCD terrestrial toxicity impacts), and (2) sulfur dioxide has a high hazard value for noncancer effects and a hazard value of zero for cancer effects.

Table 3-53 presents the materials that contribute to the top 99% of the CRT terrestrial toxicity impact score. As already noted, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for slightly less than 99% of the total. Most of these emissions are from the combustion of fossil fuels to generate electricity. All of the SO_2 LCI data are either from secondary data sets not developed specifically for the CDP or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV, based on an inhalation NOAEL of 0.104 mg/m^3 and the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, as noted in the section on human health effects (3.3.13), from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore did not contribute to the terrestrial toxicity impact category.

Table 3-53. Top 99% of the CRT terrestrial toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.4%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.27%

* Column may not add to 99% due to rounding.

Table 3-54 lists the materials that contribute to the top 99% of the LCD terrestrial toxicity impact score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 92% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV, due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Other top contributors to the LCD terrestrial toxicity score include phosphine and phosphorus from LCD monitor/module manufacturing, and carbon monoxide and methane from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine, phosphorus, and benzene scores are driven more by their inherent toxicity than their output amounts.

Table 3-59. Baseline and sensitivity analysis results—manufactured life

		CRT			LCD		
Impact category	**Units/ Monitor**	**Baseline**	**Manu-factured**	**% change**	**Baseline**	**Manu-factured**	**% change**
Renewable resource use	kg	1.31e+04	4.83e+04	268%	2.80e+03	4.30e+03	53.5%
Nonrenewable resource use	kg	6.68e+02	2.58e+03	286%	3.64e+02	6.12e+02	68.0%
Energy use	MJ	2.08e+04	7.70e+04	270%	2.84e+03	5.71e+03	101%
Solid waste landfill use	m3	1.67e-01	6.86e-01	312%	5.43e-02	1.79e-01	230%
Hazardous waste landfill use	m3	1.68e-02	6.05e-02	260%	3.60e-03	3.60e-03	0.00%
Radioactive waste landfill use	m3	2.00e-04	8.00e-04	328%	1.00e-04	3.00e-04	194%
Global warming	kg-CO2 eq.s	6.95e+02	2.90e+03	317%	5.93e+02	1.17e+03	97.3%
Ozone depletion	kg-CFC-11 eq.s	2.05e-05	8.27e-05	304%	1.37e-05	2.66e-05	94.1%
Photochemical smog	kg-ethene eq.s	1.71e-01	6.20e-01	262%	1.41e-01	1.47e-01	4.22%
Acidification	kg-SO2 eq.s	5.25e+00	2.19e+01	317%	2.96e+00	7.29e+00	146%
Air particulates	kg	3.01e-01	1.13e+00	277%	1.15e-01	1.87e-01	63.4%
Water eutrophication	kg-phosphate eq.s	4.82e-02	**1.74e-01**[a]	260%	4.96e-02	4.96e-02	0.02%
BOD	kg	1.95e-01	7.02e-01	260%	2.83e-02	2.83e-02	0.02%
TSS	kg	8.75e-01	3.15e+00	260%	6.15e-02	6.15e-02	0.02%
Radioactivity	Bq	3.85e+07	1.14e+08	197%	1.22e+07	1.28e+07	4.49%
Chronic health effects, occupational	tox-kg	9.34e+02	3.39e+03	263%	6.96e+02	7.41e+02	6.47%
Chronic health effects, public	tox-kg	1.98e+03	8.56e+03	333%	9.02e+02	2.98e+03	230%
Aesthetics (odor)	m3	7.58e+06	2.74e+07	262%	5.04e+06	5.30e+06	5.00%
Aquatic toxicity	tox-kg	2.25e-01	8.10e-01	260%	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.54e+03	333%	8.94e+02	2.97e+03	232%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the CRT indicator is now greater than the LCD.

As shown in Table 3-59, under the manufactured life scenario CRT impacts exceed those of the LCD in every impact category except aquatic toxicity. CRT impacts were expected to be greater than those of the LCD in most impact categories for the following reasons:

- Under the baseline scenario CRT impacts exceeded those of the LCD in every category but water eutrophication and aquatic toxicity.
- The manufactured life scenario assumes more CRTs are manufactured than LCDs during the manufactured life lifespan, which results in greater impacts.
- The manufactured life use stage is longer than the baseline, effective life use stage, and the CRT consumes more electricity during use than the LCD.

By looking at the percent change in impact scores from the baseline to manufactured life for a monitor type we can better understand which aspect of the life-cycle is driving impacts. For example, CRT impacts increased by roughly 260% in several impact categories, which is the increase from manufacturing or disposing of an additional 2.6 monitors. Energy impacts increased by more than 260% due to the additional increase in electricity consumption during use. The CRT chronic public human health effects category increased by some 330%. This is explained by the increase in SO_2 emissions in the use stage and the high HV for SO_2, which has a proportionately greater effect on overall impacts than increased outputs of other pollutants with lower HVs in other life-cycle stages.

LCD impacts increased only slightly from the baseline to the manufactured life scenario in some impact categories, but increased up to 230% in others. Most of the LCD impact categories with less than one percent increase are for impacts related to water discharges (e.g., water eutrophication, aquatic toxicity, etc.). This is because the most significant change to the LCD inventory from the baseline to the manufactured life scenario was in the use stage, and few water discharges are reported in the U.S. electric grid inventory. On the other hand, the chronic public health effects and terrestrial toxicity impact categories show the greatest increase. These results are driven by air emissions of SO_2 from U.S. power production, which increased significantly with the longer lifespan.

To further illustrate how the longer lifespan (and additional manufacturing requirements, mainly for the CRT) in the manufactured life scenario is affecting impacts, Figures 3-24 and 3-25 compare the energy impacts and public chronic health effects, respectively, of both monitor types under the baseline and manufactured life scenarios. As shown in Figure 3-24, CRT energy impacts are still dominated by the manufacturing stage in the manufactured life scenario. This is mainly due to the large amount of LPG used to manufacture 3.6 sets of CRT glass. On the other hand, LCD energy impacts during the use stage exceeded those in manufacturing by a factor of about 2.6 in the baseline scenario, but are ten times greater in the manufactured life scenario. This is due to the longer lifespan for a single LCD in the manufactured life scenario.

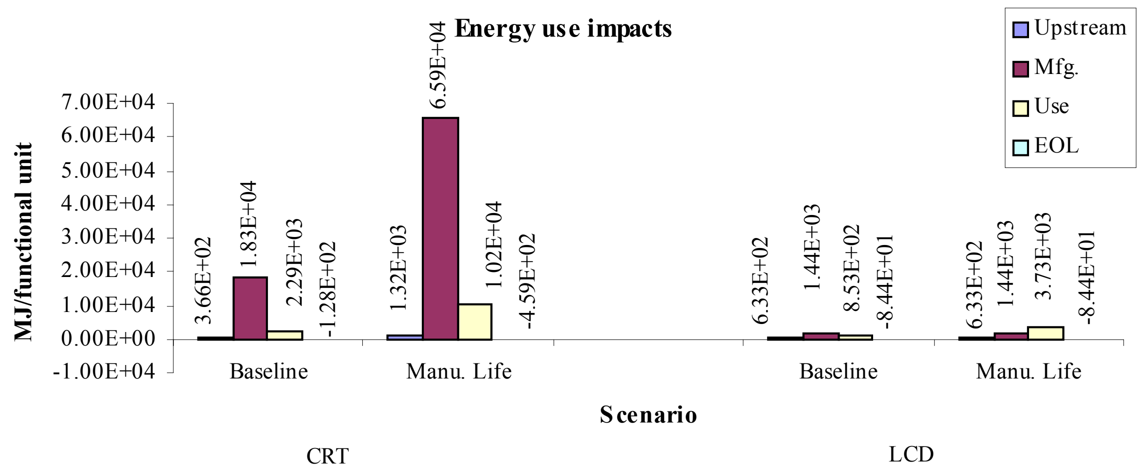

Figure 3-24. Energy use: baseline and manufactured life sensitivity results

Figure 3-25 shows that CRT chronic public health impacts are similarly distributed in the baseline and manufactured life scenarios. However, a greater percentage of LCD chronic health impacts are in the use stage under the manufactured life scenario than the baseline due to the longer use stage.

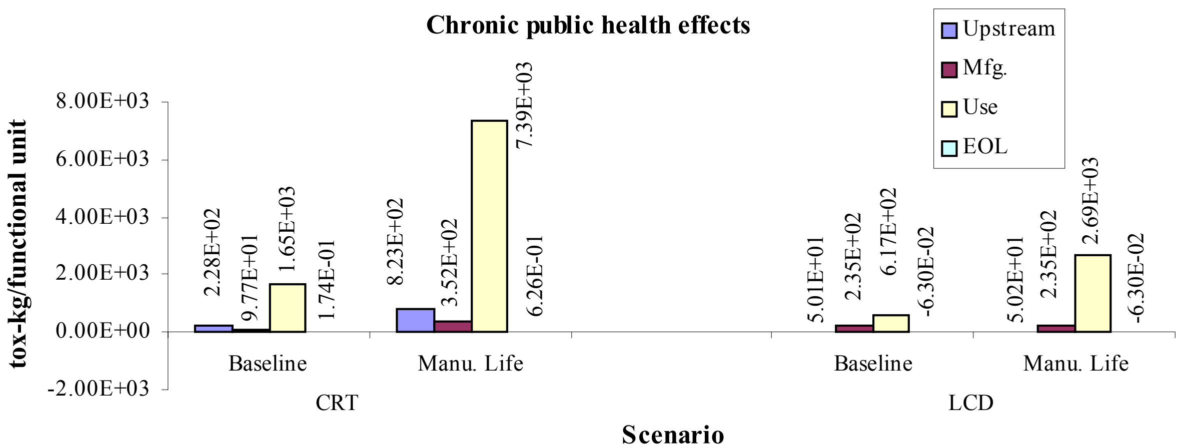

Figure 3-25. Chronic public health effects: baseline and manufactured life sensitivity results

3.4.2 Modified Glass Energy Scenario

One area of relatively large uncertainty and variability in the primary data supplied for the project was the glass manufacturing data. Both the CRT and LCD glass data were based on data supplied by CRT lead oxide (PbO) glass manufacturers, since no LCD glass manufacturers were willing to provide data to the project. To represent an LCD glass inventory, lead (Pb) materials in the CRT glass inventory were removed. Based on conversations with industry members, it was assumed that the same amount of energy per kilogram of glass produced is used to generate LCD and CRT glass. In addition, large variability among the three data sets collected resulted in a large degree of uncertainty in the glass inventory. Finally, a number of the CRT impact category results are being driven by the glass energy data or by the production process for producing the large amount of LPG used as a fuel in glass manufacturing. Consequently, the glass manufacturing inventories for both LCD and CRT glass were modified and life-cycle impacts were recalculated.

To conduct the sensitivity analysis, the energy input data for glass manufacturing were modified by removing, from the average, data that appeared unusually large, and that might be inconsistent with general industry statistics. However, industry statistics are greatly lacking when specifically considering specialty glasses such as CRT and LCD glass. Modifying the energy inputs greatly reduced the fuel energy amounts reported for the glass production process.

The baseline scenario, based on averaged primary data from manufacturers, assumed that the total energy to produce a kilogram of CRT or LCD glass was 1,560 MJ (433 kWh) of energy, with only 0.3% of that as electrical energy. The sensitivity analysis scenario assumes 16.3 MJ (4.5 kWh) per kilogram of glass produced, with approximately 30% as electrical energy. The majority of the fuel energy in the baseline scenario was from LPG. The actual input amounts are not presented here to protect the confidentiality of data provided by glass manufacturers.

Under the sensitivity (modified glass energy) scenario, only the manufacturing stage is affected, since the production of the fuels used during manufacturing is included in the manufacturing life-cycle stage. All impact categories, not only energy, are also affected because the inputs and outputs from fuel production and electricity generation processes affect each of the impact categories evaluated in this study.

Table 3-60 shows the baseline impact results and the revised impact results based on the modified glass energy inputs. The overall life-cycle impact results are highly sensitive to the energy consumption values from glass manufacturing. Under the modified glass energy scenario, the nonrenewable resource use, global warming, photochemical smog, BOD, TSS, chronic occupational health effects, and odor impact categories reversed direction such that the LCD had greater impacts within each impact category than the CRT in the overall life cycle. Note that the percent change in CRT results in most impact categories is much greater than that of the corresponding LCD results. This is because the CRT uses approximately ten times more glass than the LCD and therefore, the CRT results are much more sensitive to the glass manufacturing data than are the LCD results.

Table 3-60. Baseline and sensitivity analysis results—modified glass energy

		CRT			LCD		
Impact category	**Units/Monitor**	**Baseline**	**Glass energy**	**% change**	**Baseline**	**Glass energy**[a]	**% change**
Renewable resource use	kg	1.31e+04	2.67e+03	-79.6%	2.80e+03	2.43e+03	-13.4%
Nonrenewable resource use	kg	6.68e+02	2.35e+02	-64.8%	3.64e+02	**3.49e+02**	-4.14%
Energy use	MJ	2.08e+04	3.02e+03	-85.5%	2.84e+03	2.04e+03	-28.0%
Solid waste landfill use	m3	1.67e-01	1.23e-01	-26.0%	5.43e-02	5.27e-02	-2.82%
Hazardous waste landfill use	m3	1.68e-02	1.54e-02	-8.13%	3.60e-03	3.60e-03	-1.35%
Radioactive waste landfill use	m3	2.00e-04	2.00e-04	0.12%	1.00e-04	1.00e-04	0.01%
Global warming	kg-CO2 eq.s	6.95e+02	5.23e+02	-24.8%	5.93e+02	**5.87e+02**	-1.01%
Ozone depletion[b]	kg-CFC-11 eq.s	2.05e-05	1.97e-05	-3.75%	1.37e-05	1.37e-05	-0.18%
Photochemical smog	kg-ethene eq.s	1.71e-01	5.59e-02	-67.3%	1.41e-01	**1.37e-01**	-2.84%
Acidification	kg-SO2 eq.s	5.25e+00	4.02e+00	-23.4%	2.96e+00	2.92e+00	-1.45%
Air particulates	kg	3.01e-01	1.72e-01	-42.9%	1.15e-01	1.10e-01	-3.97%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.10e-03	-91.5%	4.96e-02	4.80e-02	-3.17%
BOD	kg	1.95e-01	7.00e-03	-96.4%	2.83e-02	**2.16e-02**	-23.8%
TSS	kg	8.75e-01	2.06e-02	-97.6%	6.15e-02	**3.09e-02**	-49.7%
Radioactivity	Bq	3.85e+07	3.16e+07	-17.9%	1.22e+07	1.22e+07	0.00%
Chronic health effects, public	tox-kg	1.98e+03	1.97e+03	-0.56%	9.02e+02	9.01e+02	-0.02%
Chronic health effects, occupational	tox-kg	9.34e+02	2.30e+02	-75.4%	6.96e+02	**6.63e+02**	-4.74%
Aesthetics (odor)	m3	7.58e+06	1.09e+04	-99.9%	5.04e+06	**4.79e+06**	-4.99%
Aquatic toxicity	tox-kg	2.25e-01	2.18e-01	-3.07%	5.19e+00	5.19e+00	0.01%
Terrestrial toxicity	tox-kg	1.97e+03	1.97e+03	-0.42%	8.94e+02	8.94e+02	-0.01%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the LCD indicator is now greater than the CRT.
[b] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

The energy impacts for the baseline and modified glass energy scenarios are presented in Figure 3-26. In the baseline scenario, over 18,000 MJ of energy were consumed per CRT monitor during manufacturing. Almost 83% of this was from the glass/frit process group, mainly from glass manufacturing energy alone. When the glass energy inputs are reduced under the modified scenario, total energy use in the CRT manufacturing stage decreases some 97% to just under 500 MJ, and the use stage dominates the overall life-cycle energy impacts at approximately 2,300 MJ per functional unit (i.e., per monitor). The 97% decrease in manufacturing stage energy use is due to the reduced glass manufacturing fuel inputs and the consequent reduction in energy inputs to the fuel production process.

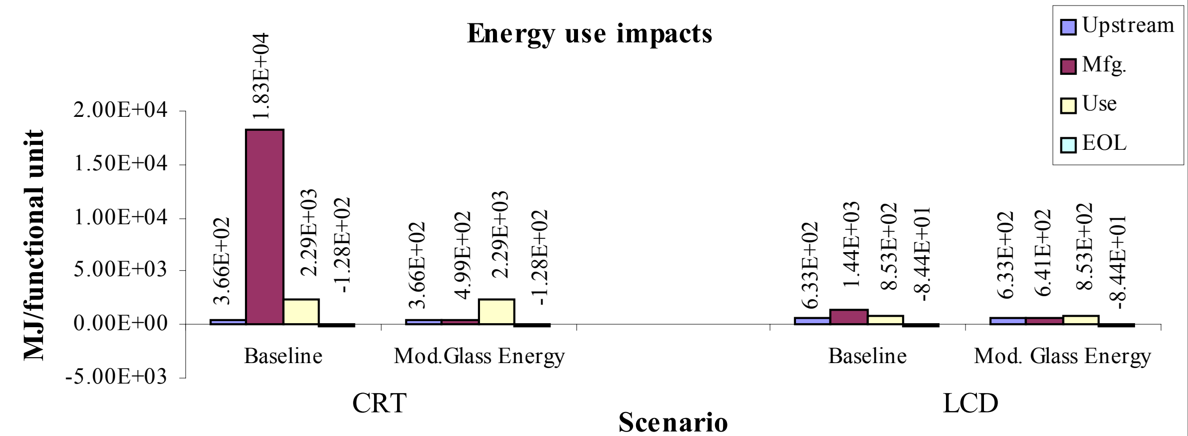

Figure 3-26. Energy impacts: baseline and modified glass energy sensitivity results

The modified glass energy scenario has a lesser, but still significant, effect on the distribution of LCD energy impacts across life-cycle stages. Under the sensitivity scenario, the LCD manufacturing stage energy consumption is reduced 55% from 1,440 MJ per monitor to about 640 MJ per monitor, and the use stage becomes the biggest energy consumer at about 850 MJ per monitor.

Global warming is one of the impact categories in which the CRT has the greater impacts than the LCD under the baseline scenario, but the LCD has the greater impacts under the sensitivity analysis. Figure 3-27 shows the global warming impacts for both monitor types under the baseline and modified glass energy scenarios. Under the latter scenario, CRT global warming impacts in the manufacturing stage are reduced some 85%, but LCD impacts are only reduced 2.5%. Again, this illustrates the greater sensitivity of CRT impact results to glass energy inputs. Also, as discussed in Section 3.3.5, a large part of LCD global warming impacts are driven by sulfur hexafluoride emissions from LCD monitor/module manufacturing, which are unaffected by the revised glass energy scenario.

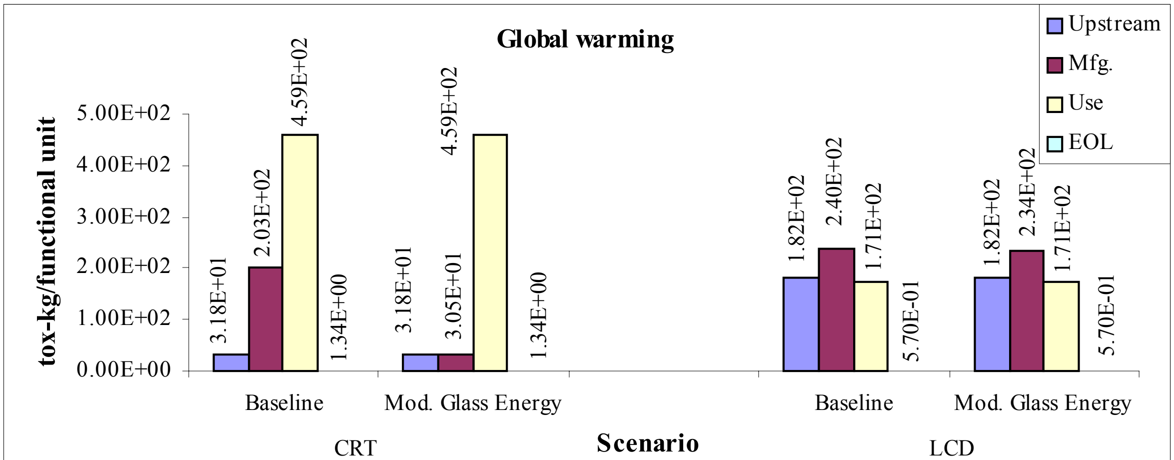

Figure 3-27. Global warming: baseline and modified glass energy sensitivity results

3.4.3 Modified LCD Module Energy Scenario

LCD monitor/module manufacturing energy was another area of relatively large uncertainty and variability in the inventory data. As discussed in Section 2.7.3.3, total energy inputs reported in six data sets received from LCD monitor/module manufacturers in Japan and Korea ranged from 330 MJ to 7,310 MJ, with a mean and standard deviation of 2,269 MJ and 2,906 MJ, respectively. The manufacturing energy data reported in two of the data sets were found to be outliers and removed from the averages used in the baseline inventory. However, for this sensitivity analysis, the outliers were added back in to the averages. Thus, to apply the modified LCD manufacturing energy scenario to the LCD profile, the following modifications were made to electricity and fuels:

- changed the electric energy inputs to the LCD monitor/module manufacturing process group from 82.1 kWh (253 MJ) per monitor to 70.1 kWh (217 MJ) per monitor,
- changed the fuel oil # 4 inputs from 0.25 kg to 0.30 kg per monitor,
- changed the kerosene inputs from 0.35 kg to 0.23 kg per monitor,
- changed the LPG inputs from 0.68 kg to 0.45 kg per monitor,
- changed the LNG inputs from 3.8 kg to 45 kg per monitor, and
- changed the natural gas inputs from 0.99 to 0.70 kg per monitor.

Note that one LCD monitor/module manufacturer also reported using a large amount of LNG as an ancillary material. However, this input amount is not affected by the sensitivity analysis, which only deals with inputs used as an energy source.

Table 3-61 presents the baseline impact results and the revised LCD impact results based on the modified LCD module energy scenario. It also shows the baseline CRT results. Under the modified LCD energy scenario, LCD impacts in ten categories actually decrease slightly, due to the slight decrease in average electrical energy consumed during LCD monitor/module manufacturing. However, impacts in six categories increase slightly, and impacts in four categories (nonrenewable resource use, energy use, photochemical smog and chronic occupational health effects) increase by more than 10%. As expected, life-cycle energy impacts are the most affected by this sensitivity analysis, due to the increased fuel consumption during manufacturing. However, under this scenario, none of the impact category results reversed direction from the baseline such that the LCD now has greater impacts than the CRT or vice versa, where the baseline LCD impacts were greater than the CRT.

Table 3-61. Baseline and sensitivity analysis results—LCD modified module energy

Impact category	Units/Monitor	CRT	LCD		
		Baseline	Baseline	Mod. energy	% change
Renewable resource use	kg	1.31e+04	2.80e+03	2.78e+03	-0.69%
Nonrenewable resource use	kg	6.68e+02	3.64e+02	4.06e+02	11.4%
Energy use	MJ	2.08e+04	2.84e+03	4.68e+03	64.9%
Solid waste landfill use	m3	1.67e-01	5.43e-02	5.47e-02	0.74%
Hazardous waste landfill use	m3	1.68e-02	3.60e-03	3.60e-03	-0.01%
Radioactive waste landfill use	m3	2.00e-04	1.00e-04	1.00e-04	-3.88%
Global warming	kg-CO2 eq.s	6.95e+02	5.93e+02	6.17e+02	4.05%
Ozone depletion[a]	kg-CFC-11 eq.s	2.05e-05	1.37e-05	1.37e-05	-0.26%
Photochemical smog	kg-ethene eq.s	1.71e-01	1.41e-01	1.61e-01	13.7%
Acidification	kg-SO2 eq.s	5.25e+00	2.96e+00	3.00e+00	1.48%
Air particulates	kg	3.01e-01	1.15e-01	1.19e-01	3.85%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.96e-02	4.96e-02	0.00%
BOD	kg	1.95e-01	2.83e-02	2.83e-02	-0.12%
TSS	kg	8.75e-01	6.15e-02	6.13e-02	-0.30%
Radioactivity	Bq	3.85e+07	1.22e+07	1.22e+07	-0.09%
Chronic health effects, occupational	tox-kg	9.34e+02	6.96e+02	7.66e+02	10.1%
Chronic health effects, public	tox-kg	1.98e+03	9.02e+02	8.82e+02	-2.14%
Aesthetics (odor)	m3	7.58e+06	5.04e+06	5.04e+06	0.01%
Aquatic toxicity	tox-kg	2.25e-01	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.94e+02	8.74e+02	-2.25%

[a] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

Figure 3-28 presents the LCD baseline and sensitivity analysis results for the energy use impact category, the category with the greatest percent change from the baseline to the modified LCD module energy scenario. Under this scenario, LCD energy use impacts in the manufacturing stage increased almost 230% from 1,440 MJ per functional unit to 3,280 MJ per functional unit. However, total life-cycle energy use impacts increased only 65%. This sensitivity analysis did not affect consumption rates outside of the manufacturing stage.

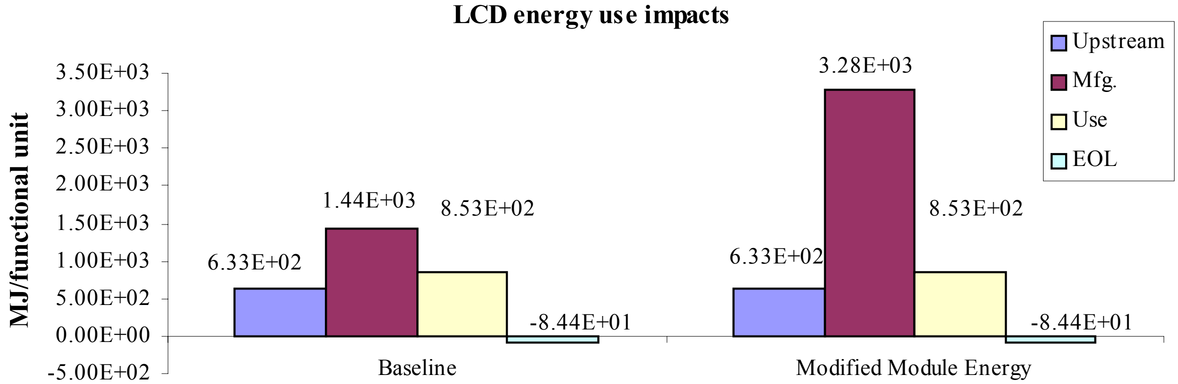

Figure 3-28. Energy use: LCD baseline and modified module energy sensitivity results

Figure 3-29 shows the effects of the sensitivity analysis on LCD chronic occupational health effects, another impact category with a relatively large percentage change. As shown in the figure, the manufacturing stage impact score in this category increased about ten percent, from 684 tox-kg per monitor to 755 tox-kg per monitor, due to the increase in fuel inputs. The chronic occupational health effect impacts were less sensitive than energy impacts because health effects results are calculated using a scoring approach that considers the inherent toxicity of a chemical instead of a simple loading approach (as is used for energy impacts). No toxicity data were available for LNG, the input with the greatest change in quantity. Therefore, the LNG HV is representative of a mean toxicity value.

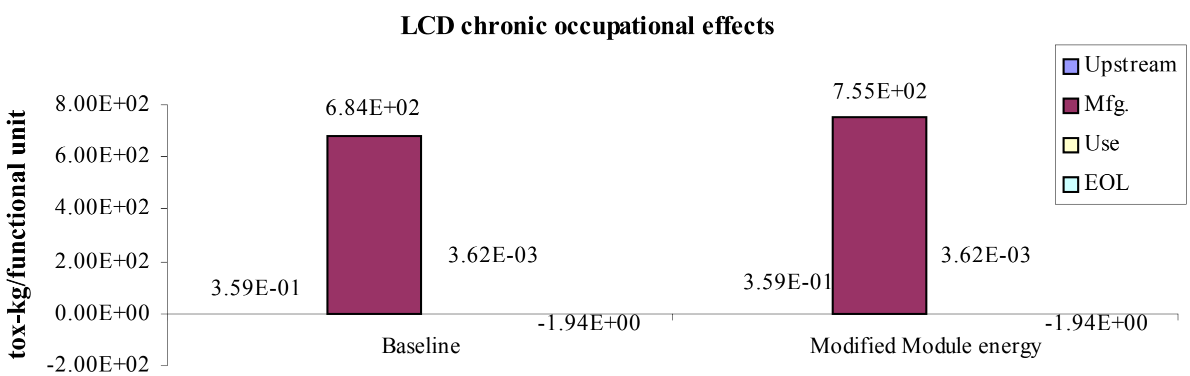

Figure 3-29. Chronic occupational effects: LCD baseline and modified module energy sensitivity results

3.4.4 Modified LCD EOL Dispositions Scenario

Finally, because very few desktop LCDs have reached their end of life, and usually only if they have been damaged in some way, very little is known about the EOL disposition of LCDs. In the baseline scenario it was assumed that a certain percent of EOL LCDs are incinerated, recycled, remanufactured, landfilled as solid waste, and landfilled as hazardous waste. (See Section 2.7.3 and Appendix I for an explanation of how EOL disposition percentages were determined.) To address uncertainties in the allocation of disposition percentages, this sensitivity analysis qualitatively evaluates a different set of final disposition numbers, as follows:

- change percent recycled from 15% to 0%,
- change percent remanufactured from 15% to 40%,
- change percent landfilled (solid waste) from 50% to 40%.
- do not change fraction incinerated (15%) or fraction sent to a hazardous waste landfill (5%).

Thus, under the modified EOL disposition scenario, recycling and solid waste landfilling impacts would decrease, remanufacturing impacts would increase, and incineration and hazardous waste landfilling impacts would not change. However, in attempts made to obtain remanufacturing data, it was found that remanufacturing processes spanned a wide range of activities, from as little as replacing button tops to as extensive as testing and replacing PWBs or transformers. Given the broad range of possibilities, and because few desktop LCDs have reached their end of life, no single set of operations could be identified to adequately represent remanufacturing activities that could be incorporated in our model. Remanufacturing data were, therefore, excluded from the assessment.

As shown in the baseline LCIA results (Section 3.3), LCD EOL dispositions have little effect on overall life-cycle impacts under the baseline scenario. In fact, the only impact categories in which an EOL process was a top contributor to overall impacts were the hazardous waste landfill use impact category, where the portion of a monitor landfilled contributed 97% of impacts, and the solid waste landfill use category, where the portion of a monitor landfilled contributed 3.5% of impacts. As noted above, hazardous waste landfill use impacts would not change under the modified LCD EOL dispositions scenario, but solid waste landfill impacts would be expected to decrease slightly. In a preliminary quantitative analysis of this scenario, LCD life-cycle solid waste landfill impacts were found to decrease less than one percent, and life-cycle impacts in other impact categories decreased less than 0.1%. Thus, the modified LCD EOL dispositions scenario would have only a minor effect on LCD life-cycle impacts and would not change comparative CRT and LCD results.

3.4.5 Summary of CRT and LCD Sensitivity Analysis Results

The results of the sensitivity analyses are useful to manufacturers who want to understand how uncertainty in the inventory affects impacts. This information can be used to identify areas for additional study or potential improvement opportunities. As discussed in Sections 3.4.1 through 3.4.2, it appears that CRT life-cycle impacts are highly sensitive to the glass energy data, and less sensitive to the lifespan assumptions (lifespan assumptions greatly affect the magnitude of CRT life-cycle impacts, but they do not greatly affect the distribution of impacts among life-cycle stage). LCD impacts are less sensitive to the glass energy data and in fact are not greatly affected by any of the sensitivity analysis scenarios, except the longer lifespan under the manufactured life scenario.

Sensitivity results are also useful to interested members of the public who may be evaluating the relative impacts of different monitor types and are interested in whether the CRT or LCD has greater life-cycle impacts in any given impact category. Table 3-62 presents the monitor type with greatest impacts by impact category and by scenario. This information helps us determine whether major assumptions (e.g., the monitor lifespan and LCD EOL distribution assumptions) or uncertain data (e.g., glass energy data and LCD monitor manufacturing energy) are driving results. As shown in the table, the modified glass energy scenario is the only scenario that significantly changes the results from the baseline CRT and LCD comparative results. Under this scenario, life-cycle impact results in seven categories reverse direction from the baseline assessment, such that the LCD has greater impacts than the CRT. Therefore, under this scenario, a total of nine out of 20 categories are greater for the LCD than the CRT, compared to two out of 20 categories under the baseline scenario. The only other scenario that affects these results is the manufactured life scenario, when impacts in the water eutrophication category are greater for the CRT than the LCD.

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modifed LCD EOL distribution[a]
Renewable resource use	CRT	CRT	CRT	CRT	CRT
Nonrenewable resource use	CRT	CRT	LCD	CRT	CRT
Energy use	CRT	CRT	CRT	CRT	CRT
SW landfill use	CRT	CRT	CRT	CRT	CRT
HW landfill use	CRT	CRT	CRT	CRT	CRT
RW landfill use	CRT	CRT	CRT	CRT	CRT
Global warming	CRT	CRT	LCD	CRT	CRT
Ozone depletion [b]		[b] [b]	[b] [b]		
Photochemical smog	CRT	CRT	LCD	CRT	CRT
Acidification	CRT	CRT	CRT	CRT	CRT
Air particulates	CRT	CRT	CRT	CRT	CRT
Water eutrophication	LCD	CRT	LCD	LCD	LCD
Water quality, BOD	CRT	CRT	LCD	CRT	CRT
Water quality, TSS	CRT	CRT	LCD	CRT	CRT
Radioactivity	CRT	CRT	CRT	CRT	CRT
Chronic health effects, occupational	CRT	CRT	LCD	CRT	CRT
Chronic health effects, public	CRT	CRT	CRT	CRT	CRT
Aesthetics (odor)	CRT	CRT	LCD	CRT	CRT

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modifed LCD EOL distribution[a]
Aquatic toxicity	LCD	LCD	LCD	LCD	LCD
Terrestrial toxicity	CRT	CRT	CRT	CRT	CRT

[a] Based on a qualitative evaluation, not quantitative results.

[b] CRT impacts are greater than LCD impacts in this category when all data are included in the inventories, including data for substances that have been phased out. However, LCD impacts are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

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