Life Cycle Environmental Assessment of Paint Processes

Stella Papasavva, Sheila Kia, Joseph Claya,† and Raymond Gunther†—General Motors*

The environmental impact of three different automotive paint scenarios: (a) solventborne primer-waterborne basecoat-solventborne clearcoat, (b) powder primer-waterborne basecoat-solventborne clearcoat, and (c) powder primer-waterborne basecoat-powder clearcoat were investigated. Scenarios (a) and (b) are in production by the U.S. automotive industry and scenario (c) is a potential future goal. The scenarios modeled assume a greenfield plant, considering a mid-size sport utility vehicle that is painted in two separate colors. A complete life cycle analysis of the materials and processes was carried out using commercial state-of-the-art software. The analysis showed that a transition from solvent-based to powder-based coatings for the primer and clearcoat leads to an improvement in the environmental performance of the paint processes. The decrease in total energy consumption, water usage, and sludge generation is 22%, 34%, and 27%, respectively. The paint scenario comprised of powder primer-waterborne basecoat-powder clearcoat will minimize the environmental impacts of the painting processes for all the metrics examined in this study.

INTRODUCTION

The automotive painting operation is an energy- and materials-intensive operation and contributes most to the environmental emissions, compared to any other manufacturing process of a vehicle. Environmental concerns along with economic considerations for cleaner technologies led to the transition from solventborne to waterborne to powder paint coatings over the past decade to reduce plant volatile organic compound (VOC) emissions and the need for abatement equipment.

Life Cycle Assessments (LCA) are widely used for the evaluation of the environmental emissions associated with the manufacturing, use, and end of life of materials and processes.[1,2] It is a useful tool in the long-term investment decision making of corporations that seek innovative solutions to their environmental and financial problems.[3] LCA provides a holistic view of the environmental emissions associated with the manufacturing of materials and processes because it is based on the inventory of all environmental emissions involved. The environmental LCA analysis is evaluated based on industrial ecology principles, taking into account all energy and material flows throughout the production, use, and end of life of a product.[4] This is the basis of the Design for the Environment (DfE) concept, on which many corporations base their decisions for the selection of environmentally reliable and cost effective materials and processes.[5]

Previous studies that addressed environmental impact analysis of automotive painting did not consider an indepth life cycle analysis evaluation of the materials and processes involved in a typical assembly plant.[6-8] For example, in a recent study[6] the LCA assessment of the General Motors Orion Assembly Center (Lake Orion, MI) was carried out by examining the facility and management operations. Harsch et. al[7] focused on the comparison of powder, waterborne, and solventborne clearcoats. Dobson[8] examined the environmental trade-offs associated with lowering the VOC content of a plant.

The major goal of this study was to thoroughly evaluate the environmental emissions of the traditional solvent-based coatings as compared to those for alternative coatings based on water or powder, all in a greenfield automotive plant. In order to evaluate the emissions based on the LCA approach we followed the EPA SETAC (Society of Environmental Toxicology and Chemistry) guidelines in which a complete inventory of all materials that

Presented at the 78th Annual Meeting of the Federation of Societies for Coatings Technology, on October 18-20, 2000, in Chicago, IL.
*Research and Development Center, Warren, MI, 48090.
†World Wide Facilities, General Motors.

Table 1—Scenarios

Scenarios/Code	Primer	Basecoat	Clearcoat
(1)	*Primer*	*Waterborne basecoat*	*Solvent clearcoat*
SP1-WB1-SC1	*Solventborne*	WB1: White (Polyester)	SC1: (Acrylic)
	SP1: (Acrylic)		
(2)	*Primer powder*	*Waterborne basecoat*	*Solvent clearcoat*
PP1-WB1-SC1	PP1: (Acrylic)	WB1: White (Polyester)	SC1: (Acrylic)
PP1-WB2-SC1	PP1: (Acrylic)	WB2: Pewter (Polyester)	SC1: (Acrylic)
PP2-WB1-SC1	PP2: (Polyester)	WB1: White (Polyester)	SC1: (Acrylic)
(3)	*Primer powder*	*Waterborne basecoat*	*Powder clearcoat*
PP2-WB1-PC2	PP2: (Polyester)	WB1: White (Polyester)	PC2: (Acrylic)

includes resource extraction and energy requirements is considered.[9,10]

Three paint scenarios were compared as shown in *Table* 1:

(1) solventborne primer-waterborne basecoat-solventborne clearcoat, which is considered the baseline;

(2) powder primer surfacer-waterborne basecoat-solventborne clearcoat; and

(3) powder primer surfacer-waterborne basecoat-powder clearcoat.

Within scenario (2) we looked at two different colors, white and pewter, as well as two powder primer formulations, acrylic and polyester. The nomenclature of each scenario is presented in *Table* 1 (column 1).

Although, scenarios (1) and (2) are common in the U.S., scenario (3) may be a potential arrangement for automotive paint in future operations. The powder clearcoat is currently being investigated by the Low Emission Paint Consortium (LEPC) of the United States Consortium for Automotive Research (USCAR).

For the purposes of this study it was assumed that each scenario operates in a greenfield plant following all the standard processes essential to the operation. The LCA of the paint process consists of: (a) LCA of the materials required to paint the vehicle, and (b) LCA of the paint operation in a plant. We did not consider the fate of the painted vehicle body at the end of its lifetime. The reason is that there are no quantifiable processes that account for the separation of the paint from the metal in the shredder. Often the paint is never separated from the parts and the metal is treated with the paint on it. More importantly, the end of life LCA will be similar for all scenarios.

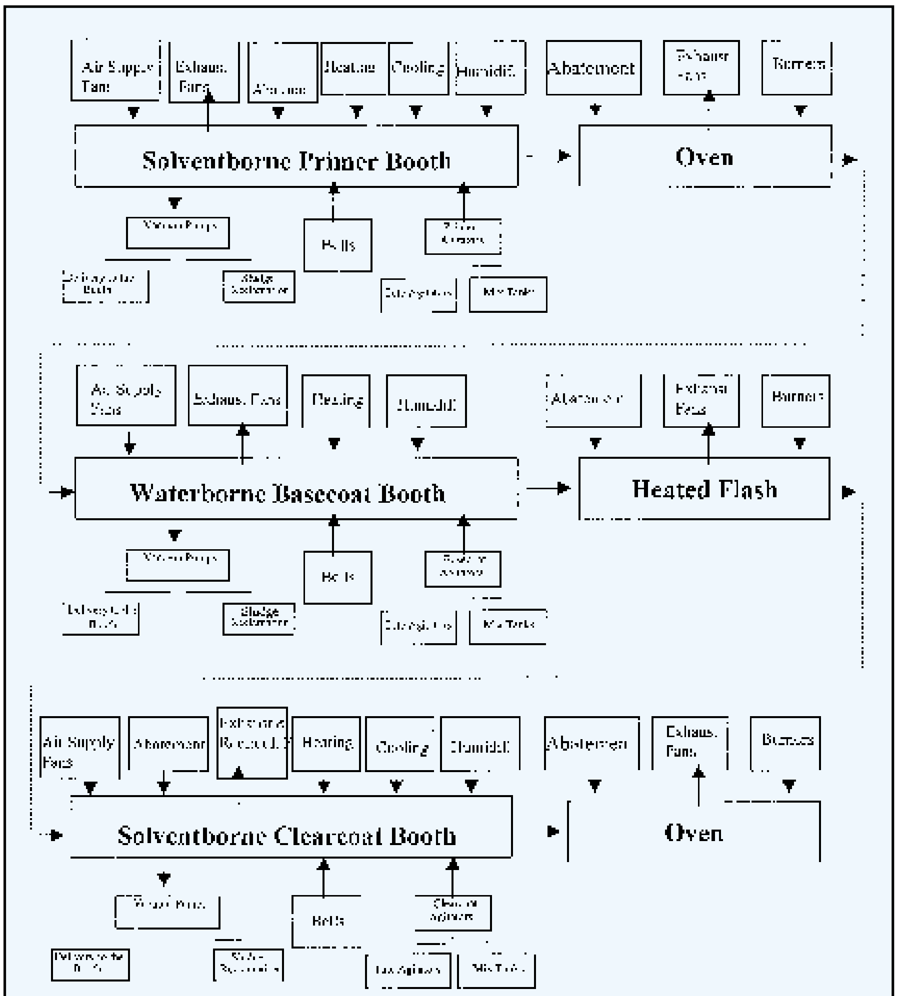

Figure 1—Processes for Scenario 1: Solvent-Water-Solvent

We made the assumption that the phosphate and the electrodeposition processes were identical for all scenarios and thus they were not included in this study. The vehicles being studied were SUVs of typical size, such as Chevy Blazers.

We made this study a generic one based on assumptions that allow the comparison of the three scenarios to be possible. The results of the analysis provided the energy and water requirements as well as the air, water, and solid waste emissions per job.

In this paper we first provide a detailed discussion of the processes involved in the paint operation for each scenario and its corresponding LCA. This is followed by the LCA of the materials. The results from the total LCA of the entire paint operation, which includes the materials and the processes, are then provided, followed by the overall performance of the scenarios and the conclusions.

LCA OF PROCESSES

Figures 1-3 outline diagrammatically the paint processes involved in each one of the scenarios. In accordance with the SETAC guidelines,[9] we developed inventories of the environmental emissions associated with each individual process element. The boxes assigned to the booths also include the observation zones.

Methodology

To compare the results among the three scenarios, we based our calculations on three generic greenfield plants. We did not gather data from actual plants since: (a) there is no plant that operates with the PP2-WB1-PC2 scenario, (b) most automotive plants paint different size vehicles, (c) plants may be subjected to different environmental regulations, and (d) the energy they purchase comes from a mix of different fuels, which results in different environmental emissions. In this study we considered a USA average fuel mix scenario for the generation of electricity, which according to reference 21 consists of 13% nuclear, 19% hydroelectric, 12% natural gas, 19% fuel oil, and 37% coal. We overcame these inherent difficulties by making our study a generic one operating on the conditions given in *Table* 2.

The environmental emissions for each process were assessed by considering: (a) the emissions generated from the production of energy (electricity and natural gas) required to run the capital equipment for each scenario as presented in *Figures* 1-3, (b) the air, water, and solid emissions generated from each process, and (c) the energy and emissions associated with the production of raw materials required for the production of electricity and natural gas. The energy required for running the conveyors was not considered because: (a) it is not easy to collect this information, (b) the energy is expected to be insignificant compared to the total energy captured in the inventory, and (c) it is the same for all three scenarios.

The energy required to run the fans was estimated theoretically using the following horsepower formula[11]:

$$HP = \frac{CFM \ (SP - TP)}{6356 \ \eta_s} \quad (1)$$

where HP is horsepower, CFM is the inlet fan capacity in cfm units, (SP–TP) is the fan static pressure with SP being the outlet pressure and TP the inlet pressure of the fan, and η_s is the static efficiency. The efficiency of the fan is 70%. The airflow capacity is based on the Bill of Process requirements for the various application processes. We consider that the powder and solventborne primer booths operate with one line, whereas the waterborne basecoat, solventborne clearcoat, and powder clearcoat booths have three lines each. Each line has two 10-bell stations, which are fully automated. The air driven in each 10-bell station is about 3,000 l/min, compressed at 90 psi. The powder primer booth operates with three one-agitator hoppers and four feed hoppers that feed the applicators. The solvent primer booth is equipped with three color keyed tote agitators, three color keyed mix tanks, and seven color specific mix tanks. The waterborne basecoat booth operates with 10 tote agitators and 10 mix tanks and the solvent clearcoat booth has two tote agitators and two mix tanks. Beneath the booths, various pumps deliver the booth water to the booths and circulate the sludge generated. For the powder primer and clearcoat applications, the powder is pumped to the booths and applied onto the vehicle at a 95% Effective Transfer Efficiency (E.T.E). We define E.T.E as the sum of the effective usage (powder applied onto the vehicle) and the overspray powder reclaimed for reapplication. The other 5% of powder is included in the waste stream (as industrial waste).

The energies for heating, cooling, and humidification requirements were estimated by considering the operating conditions of each spraybooth including air volume, air pressure drop, booth temperature, relative humidity, air recirculation along with the outdoor air temperature, relative humidity, and hours of occurrence. The energy required was estimated from the following formula:

$$BTU/hr = (CFM/\rho) * 60 * (H_{makeup} - H_{ambient} - T_{rise\ fan} * C_p) \quad (2)$$

Where *CFM* is the booth makeup air volume, ρ is the density of the makeup air, H_{makeup} is the enthalpy of makeup

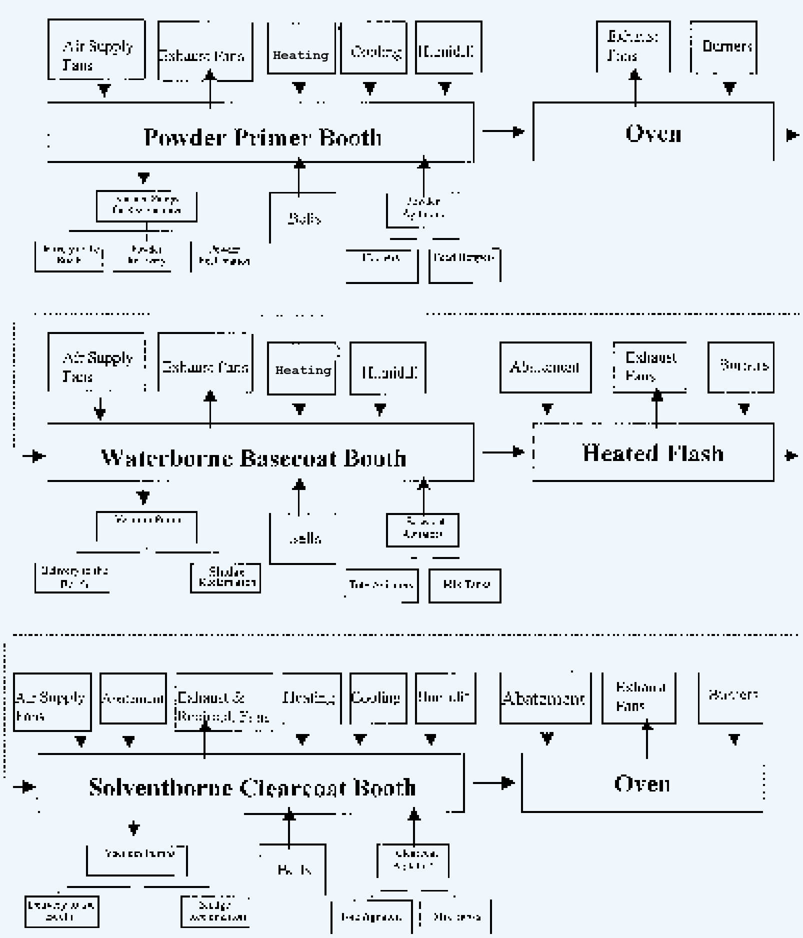

Figure 2—Processes for Scenario 2: Powder-Water-Solvent

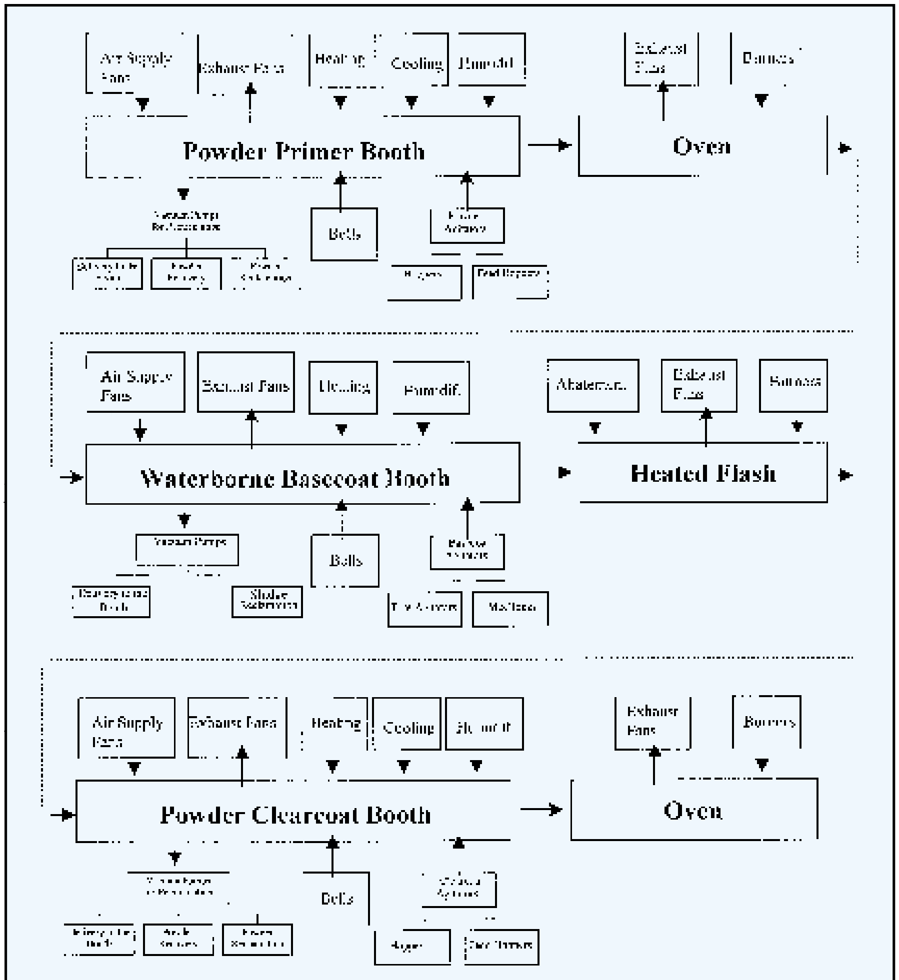

Figure 3—Processes for Scenario 3: Powder-Water-Powder

air to maintain booth conditions, $H_{ambient}$ is the enthalpy of the ambient air, $T_{rise\ fan}$ is the temperature rise caused by the system fan, and C_p is the heat capacity of air. A heating or cooling requirement is indicated by a positive or negative value, respectively. To generate the annual energy, weather data was arranged in 5°F bins with mean coincident wet-bulb temperatures and hours of occurrence by eight-hour periods of the day using the following formula:

$$Bin\ Energy = hours\ of\ occurrence * BTU/hr \tag{3}$$

where *BTU/hr* is from equation (2) utilizing the appropriate conditions. Annual heating/cooling requirement is then the sum of all bins with positive/negative values, respectively.

The ovens consist of eight zones and are heated with natural gas. The natural gas requirements in units of ft^3/job were estimated considering the following formula:

$$NaturalGas_{ovens} = (T_{(oven)} - 70^\circ F) * (length)_{oven} * 65 * \left(\frac{1}{0.85}\right) * \left(\frac{1}{1000}\right) \tag{4}$$

where *T* is the oven temperature, 65 is the loss of energy in BTU per unit of temperature (°F) per foot, 0.85 is the thermal efficiency of the oven, and 1000 is the energy content of 1ft^3 of natural gas. The ovens that correspond to the powder booths operate at 350°F and those of the liquid-based coatings operate at 265-275°F. Each zone has one 30-HP pump that operates with electricity. There is also one 60-HP pump for the exhaust and one 10- HP for the burner.

The VOC emissions were estimated using oven solvent loading information used to establish the quantity of VOCs emitted from the various process zones. The following factors were then used to determine the total emissions:

- 1% of the VOCs sprayed in a conventional booth remains in the paint sludge;
- 85% of the VOCs released in a wet spray application zone for solvent-based paint go through an abatement device and the other 15% are released into the atmosphere unabated; and
- the abatement equipment consists of a carbon concentrator with a collection efficiency of 90% and the Regenerative Thermal Oxidizers (RTO) with a destruction efficiency of 95%.

The VOC abatement methods utilized in this study included a carbon concentrator with RTO for solvent-based primer and clearcoat spraybooth systems and RTOs for solvent-based coatings ovens and waterborne heated flash. The thermal oxidation process that destroys VOCs leads to the conversion of these hydrocarbons into CO_2 and H_2O emissions. We have estimated the amount of the CO_2 generated by assuming the surrogate heptane to represent all VOCs.

The abatement requirements of the booths and ovens for each scenario are presented in *Table* 3. For a worst case scenario, we have also carried out calculations when all ovens are abated for odor and VOC control. Discussion of these data will be presented later.

Table 2—Operating Conditions of the Generic Plant

Vehicle type	SUV
Jobs/hour	60
Hours/day	16
Days/year	235
Jobs/year	225,600
Energy production	USA Average Fuel Mix Scenario

Table 3—Abatement Requirements for the Booths and Ovens

Scenarios	Booths			Ovens
	Primer	Basecoat	Clearcoat	—
SP1-WB1-SC1	Yes	No	Yes	Yes/All
PP1-WB1-SC1	No	No	Yes	Topcoat[a]
PP2-WB1-SC1	No	No	Yes	Topcoat[a]
PP2-WB1-PC2	No	No	No	Basecoat (Heated flash)

(a) The basecoat heated flash and clearcoat booth ovens are abated.

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Figure 4—Atmospheric emissions from the paint processes in different scenarios.

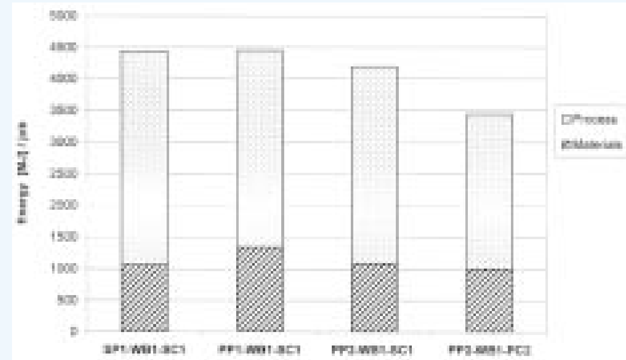

Figure 5—Total energy consumption per job for each paint scenario.

Atmospheric Emissions

Figure 4 plots the emissions of CO, NOx, SOx, PM, and VOC, released in association with the paint process. Here we have to differentiate the atmospheric emissions that are associated with the plant operations and those with the production of electricity outside the plant.

- The SOx emissions are exclusively generated during the production of electricity, outside the plant.
- The CO, NOx, PM, and VOCs emissions are generated during both the paint process inside the plant and the production of electricity outside the plant. The plant contribution to NOx and CO emissions is due to the combustion of natural gas. Estimated emissions according to AP42 guidelines are 45.36 grams NOx and 38.10 grams CO per MCF (thousand cubic feet). Thus, the plant contribution to the:

—NOx emissions are 25.4-28.1 grams from the total of 1,253-1,570 grams.

—CO emissions are 21.3-23.6 grams from the total of 109-159 grams.

—PM emissions are about 60 grams from the total of 776-1,010 grams. The PM emissions occur at the basecoat booths where a scrubber operates at 99.99% efficiency.

—VOC abated emissions are 1.2 - 2.0 kg from the total of 1.273 - 2.140 kg. The net abatement efficiency of the equipment is 60.2% for the SP1-WB1-SC1 scenario, 62.5% for the PP2-WB1-PC2 scenario, and 52.3% for the others.

As *Figure* 4 shows, for each of these emissions the lowest values correspond to the PP2-WB1-PC2 scenario and the highest to the SP1-WB1-SC1.

LCA OF THE MATERIALS

We considered two different powder primer formulations from two suppliers (DuPont and Seibert Inc.). Both primers are used at various automotive assembly plants and are based on acrylic (DuPont) and polyester chemistry (Seibert Inc.). For the waterborne basecoat we considered two different colors, white and pewter, from DuPont. These two are the supplier's highest selling colors. The acrylic clearcoats examined are the powder from Seibert and the solventborne from DuPont.

Table 4 lists the ingredients of the paints involved in different scenarios. The material requirements per job is also provided in *Table* 4.

All the powder, waterborne, and solventborne automotive finishes use the same basic chemical categories, resins and crosslinkers (binder system), pigments, and modifying additives. The role of the additives is to enhance the mechanical and chemical properties (e.g., light stabilizers that protect the polymers from UV breakdown) of the paint. The material composition,[12-16] energy used for manufacturing of 1 kg of each paint formulation, and the quantity of the packaging material (plastic bags) used to transport 1 kg of the paint have been taken into consideration in the materials LCA. Subsequently, we have estimated energy requirements and associated environmental emissions for the amount of each coating required per SUV application.[17]

A detailed discussion of the LCA for the manufacturing of each paint formulation is provided elsewhere[17,18] and the results are incorporated in the next section for each of the paint scenarios.

TOTAL LIFE CYCLE ENVIRONMENTAL ASSESSMENT

Energy Consumptiion

In this section we present the results of the combined emissions of processes and materials: energy and water requirements, air, water, solid waste, and carbon dioxide equivalent emissions. *Figure* 5 shows the total amount of the energy consumed for each paint case study using the white waterborne basecoat. The findings show that among all scenarios: (a) the least amount of energy (3,447 MJ) is required by the PP2-WB1-PC2, (b) the highest energy (4,451

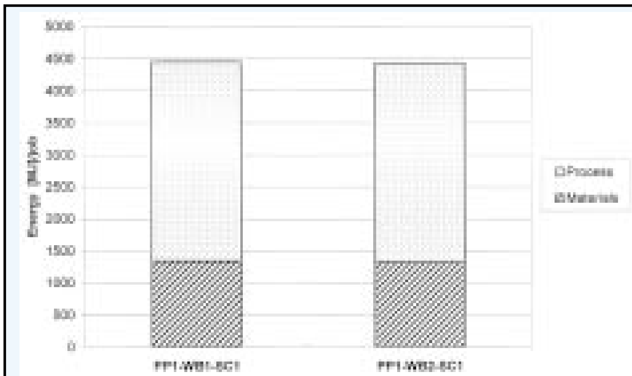

Figure 6—Total energy consumed per job for white and pewter basecoats.

Table 4—Material Ingredients and Coating Requirements for Each Paint Formulation Considered in Each Scenario[a]

	Powder Primer		Solventborne Primer
	Acrylic	Polyester	Polyester
Material	Quantity	Quantity	Quantity
Titanium dioxide	0.05	0.08	0.19
Sand	0.01		0.015
Carbon black	0.01	0.005	0.005
Polyester resin	0.02		0.2
DGEBA[b]	0.02		
Benzoin	0.01	0.005	
Barium sulfate	0.02	0.1	
Methacrylic polymer	0.72	0.05	
DDDA[c]	0.13	0.01	
PMMA[d]	0.01		0.036
Polyurethane		0.66	
Acrylic/Si polymer		0.01	
Calcium metasilicate		0.05	
Naptha			0.085
EGME[e]			0.06
Benzene			0.005
Toluene			0.025
Xylenes			0.09
Formaldehyde			0.02
Iron			0.015
Melamine formaldehyde			0.11
Ethylbenzene			0.025
N-butyl alcohol			0.07
Cumene			0.01
MTS[f]			0.004
Methyl isobutyl ketone			0.02
2-Heptanone			0.015
Material requirements	0.33[h]	0.24[h]	0.24[h]

Waterborne Basecoat		
	White	Pewter
Material	Quantity	Quantity
Water	0.4	0.57
Titanium dioxide	0.21	
Naptha	0.04	0.07
Polyurethane	0.03	0.02
Polyester resin	0.07	
Melamine formaldehyde	0.04	0.05
EGME[e]	0.07	0.08
2-Hexyloxyethanol	0.02	
PMMA	0.1	0.14
Sand		0.02
Aluminum		0.03
Material requirements	2.2[i]	2.2[i]

	Solventborne Clearcoat	Powder Clearcoat
	Acrylic	Acrylic
Material	Quantity	Quantity
Naptha	0.03	
Xylenes	0.18	
Methanol	0.02	
Melamine formaldehyde	0.12	
Ethylbenzene	0.01	
N-Butyl alcohol	0.14	
Cumene	0.01	
MTS[f]	0.05	
Butyl acetate	0.03	
PMMA	0.42	
PDMS[g]		0.01
Benzoin		0.005
Acrylic/Si polymer		0.01
Methacrylic polymer		0.72
DDDA		0.22
Material requirements	1.05[h]	0.33[i]

(a) All values are in weight %, except for water in liters
(b) DGEBA: Bisphenol a diglicidyl ether polymer
(c) DDDA: 1,12 Dodecanedioic acid
(d) PMMA: Polymethylmethacrylate
(e) EGME: Ethylene glycol monobutyl ether
(f) MTS: 3-Methacryloxypropyl-trimethoxy-silane
(g) PDMS: Polydimethylcyclosiloxane
(h) Actual value (gal/job)
(i) Estimated value (gal/job)

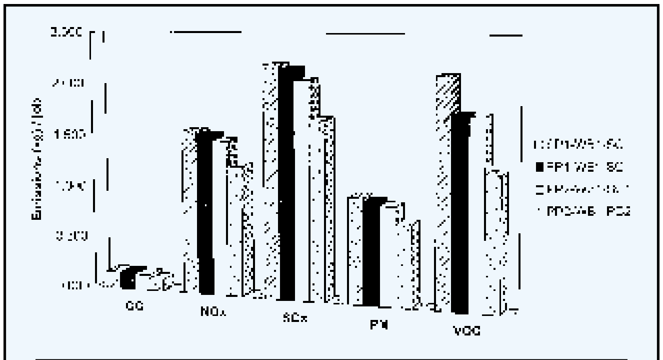

Figure 7—Total atmospheric emissions.

MJ) by the PP1-WB1-SC1 and SP1-WB1-SC1 (4,443 MJ) scenarios, and (c) the energy consumption for PP2-WB1-SC1 is (4,195 MJ).

The comparison of the total energy requirements for the white (4,451 MJ) and pewter painted vehicles (4,434 MJ) is presented in *Figure* 6. The findings show that it takes about the same amount of energy to manufacture the two colors.

Atmospheric Emissions and Global Warming Contribution

Some gases, such as CO_2, CH_4, and N_2O, contribute to the enhancement of the greenhouse effect when released into the atmosphere. The basic principle that lies behind this mechanism is that the emissions of greenhouse gases, which occur from industrial and natural processes, prevent the infrared radiation emitted from the earth's surface to escape into space.[19] As a result, the greenhouse gases act as a shield that help bounce part of the infrared radiation back to the earth, leading to an increase in the atmosphere's temperature, known as global warming. In order to assess the relative contributions to the global warming of different greenhouse gases with respect to a reference molecule, which is chosen to be CO_2, the Global Warming Potential (GWP) index has been developed.[19] Because different gases have different lifetimes and vanish from the atmosphere at different rates, a common time frame that will be used for the estimation of the GWP is necessary. This time frame is called the integrated time horizon (ITH). The GWP values we considered here are based on a 100-year ITH. The contribution of all greenhouse gases to global warming is expressed in terms of CO_2 equivalent emissions.

Table 5—Water Requirements for the Evaporation and Blowdown

	SP1-WB1-SC1	PP1-WB1-SC1	PP2-WB1-PC2
Blowdown (gal/min)	20.00	14.12	6.76
Evaporation (gal/min)	13.35	13.07	8.43

Figures 7 and 8 present the total atmospheric and carbon dioxide equivalent emissions. The fraction of CO_2 emissions to the total equivalent emissions is 95% in all scenarios. Both figures follow the same trend, which shows that the PP2-WB1-PP2 scenario outperforms the others.

Water Consumption

In the water life cycle assessment we have taken into consideration the water requirements for:

(a) industrial synthesis of the materials;

(b) make-up water to the booth water system that compensates for evaporative and blowdown losses;

(c) generation of electricity;

(d) extraction of the raw materials and fossil fuels; and

(e) humidification and cooling of the booth areas.

The amount of water in (gal/min) required for the evaporation and blowdown for each scenario is presented in *Table* 5. Water evaporation is estimated assuming adiabatic cooling of the spraybooth air through the eliminator section of wet booths to an exhaust relative humidity of 90%. Blowdown for the SP1-WB1-SC1 scenario is estimated at 20 gal/min from current experience. Blowdown for the other scenarios is factored from the SP1-WB1-SC1 scenario on the basis of the length of wet eliminator employed. The values have been estimated considering the entire paint operation. The values used for evaporation and blowdown in this study correspond to a 24-hr booth water system operation because the water is running round the clock.

Figure 9 presents the total water consumption for each scenario. It is observed that the total water consumption is least for the PP2-WB1-PC2 scenario. Also water consumption is less for the polyester powder primer in scenario PP2-WB1-SC1 than the acrylic one (PP1-WB1-SC1).

The water consumption contributors for each scenario are presented in *Figure* 10. In this figure Booth 1 is defined to be the Primer Booth, Booth 2 the Basecoat Booth, and Booth

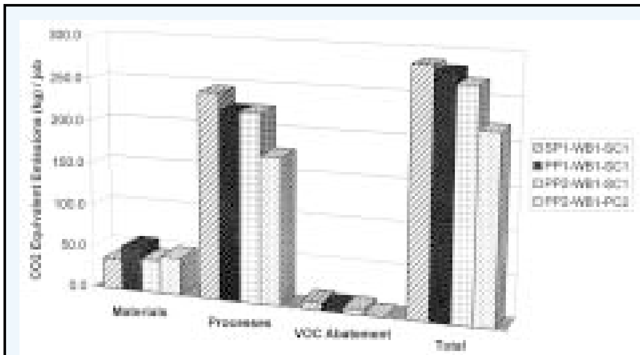

Figure 8—Total carbon dioxide equivalent emissions.

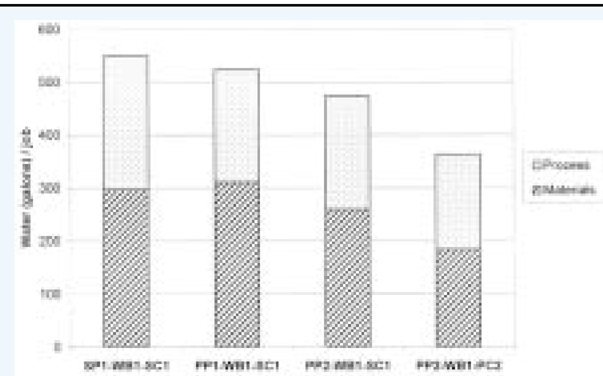

Figure 9—Total water consumption.

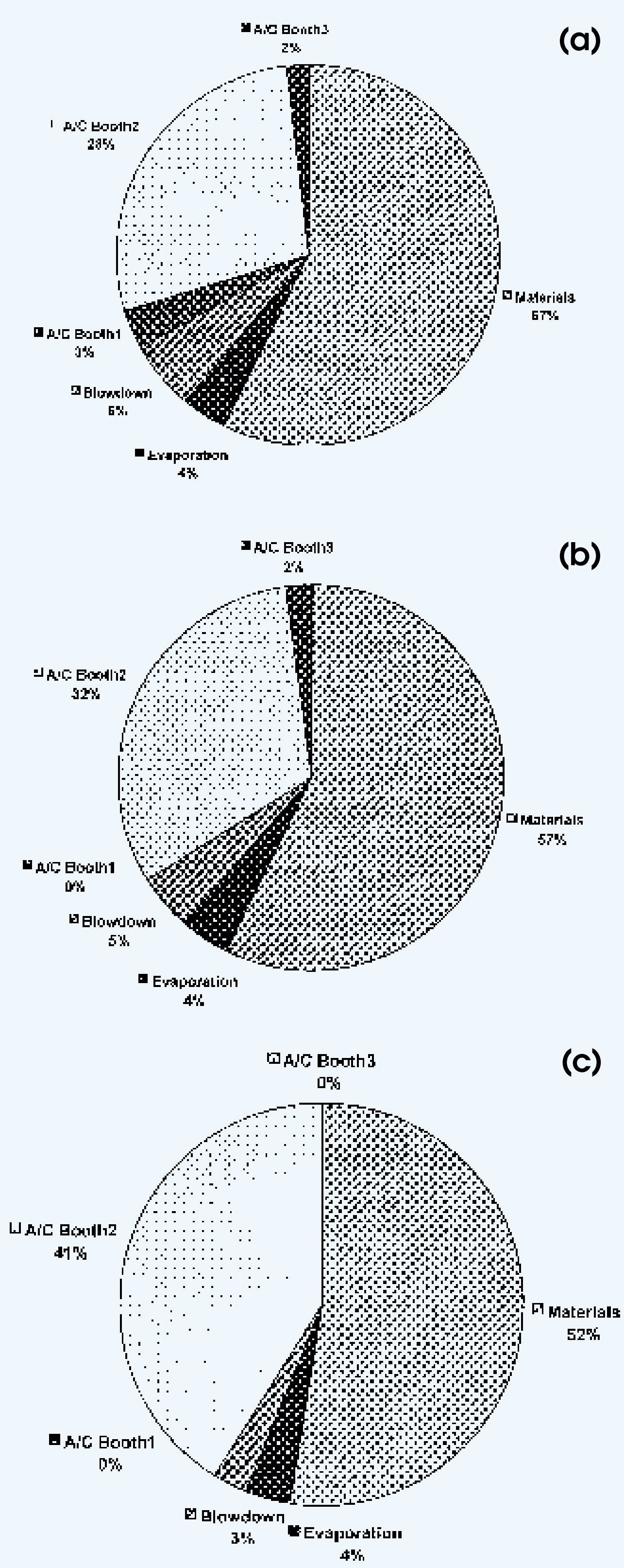

Figure 10—Water consumption contributors for different scenarios: (a) SP1-WB1-SC1, (b) PP2-WB1-SC1, (c) PP2-WB1-PC2.

3 the Clearcoat Booth. The findings show that the water consumption for the production of the materials contributes between 52 and 57% of the total. The second most important contributor is the air conditioning requirements of the basecoat booth, accounting for 28 to 41% of the total.

Water Emissions

The water emission categories obtained with the LCA Boustead database[10] are defined as follows:

Total solids: materials left after evaporation and drying the sample.

Suspended solids: materials removed from a sample filtered through a standard glass fiber filter.

Dissolved solids: the difference between the total and suspended solids.

Hydrocarbons and dissolved organics: compounds containing carbon and hydrogen in various combinations, found especially in fossil fuels. Because of government and industrial interest in fossil fuels and its conservation issues, hydrocarbons are reported separately from other organic compounds.

BOD_5: measure of the amount of oxygen utilized or consumed in the biochemical oxidation of organic matter in five days.

COD: measure of the amount of oxygen required to oxidize all compounds in water, both organic and inorganic.

Although the Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) contribute to regional environmental pollution that may have different adverse ecological impacts in different geographical regions of the world, it is still important to present the aggregate emissions. In the metals category, Na and Pb emissions are taken into consideration although several other metal categories are reported in the LCA output, such as arsenic, but in minute quantities (<1 mg).

Figure 11 presents the water emissions for the materials and processes. Due to graphic space limitations the nomenclature of the scenarios changed slightly. SWS corresponds to SP1-WB1-SC1, P1WS to PP1-WB1-SC1, P2WS to PP2-WB1-SC1, and PWP to PP2-WB1-PC2. As *Figure* 11 shows, the majority of the emissions are attributed to the industrial synthesis of the materials.

Solid Waste Emissions

Similar to the other environmental emissions, the solid wastes consist of those associated with the production of materials and those emitted during the paint process. The wastes emitted from the production of materials and those generated during the production of energy that run the processes are grouped into categories that are defined by the Boustead database as follows:

Regulated wastes: anything that requires specialized handling outside the realm of common landfills. If special handling is required then the waste has been relegated to the regulated waste category.

Inert wastes: those wastes that are common landfill components such as paper, glass, plastics, etc. Most of this has come from packaging wastes.

Mineral wastes: this has been used mostly to capture wastes from mining operations.

Mixed industrial: any waste that does not fall in any of the previously named categories.

Paint solids: this category was defined by us to denote the amount of solids generated from the powder coating applications. We keep this category as a distinct one because the wasted powder does not enter the wet waste stream of the sludge. The contribution of this waste to the total is less than one percent. In addition to these wastes, sludge is generated during the paint process.

In *Table* 6 we present the theoretical estimate of the sludge generated by each scenario considering 70 and 35.6%, solid content of the sludge. The latter is a more realistic scenario, reflecting the condition at a GM plant. According to the GM engineers, sludge with solid content of 70% is possible, but requires extra dewatering equipment and manpower. Higher solid content for sludge is generally more desirable to reduce the volume of sludge generated and the associated landfill costs. Also, we considered the effect of the two basecoat colors on sludge generation because the amount of solids, by weight percent, varies among them.

For the PP1-WB1-SC1 scenario, we compared our estimated sludge generation with actual values provided by a GM plant. Such comparison needs to be carefully considered because at the plant: (1) there is a multicolor operation and the solid content of each color contributes to the sludge, and (2) the sludge reported includes: the sludge from the electrodeposition, phosphate process, and that generated by a powertrain plant, which shares the same sludge treatment system with the paint operations. Considering these factors, the sludge generated at the GM plant is found to be 23 lb per job. According to the plant engineers, the sludge produced during the ELPO and phosphate processes is about three pounds and that produced from the other plants is not significant. Therefore, about 20 lb per job of sludge is generated during the prime and topcoat operations. This compares well with the estimated range for sludge per job. As *Table* 6 shows, the estimated sludge is 22.6 lb for the white color and 13.92 for the pewter, at 35.6% solid content.

Figure 12 shows the total solid wastes generated for each scenario for the white and pewter colors using 35.6% sludge solid content. It is observed that the highest amount of sludge is generated by the SP1-WB1-SC1 scenario and the lowest by the PP2-WB1-PP2 for both colors. In all scenarios, most of the solid waste emissions are due to the process.

Sensitivity Analysis

Powder Oven Abatement: All the calculations presented thus far consider oven abatement only for the solvent primer oven in scenario 1 (see *Table* 3). Powder prime ovens (scenarios 2 and 3) are generally not abated because powder coating emits very little VOCs. To see the sensitivity we reran the calculations assuming abatement for prime ovens in all scenarios. The results are shown in *Table* 7.

As *Table* 7 indicates, the amount of VOC emissions (up to the first decimal place in kg units)[20] is essentially the same with or without oven abatement. It is observed that the utility requirements are very sensitive to the primer oven abatement selection options.

For the PP1-WB1-SC1 scenario, the usage increases by 12% and 14% for the electric and gas requirements, respectively. The change is more significant for the PP2-WB1-PC2 scenario where the electric usage increases by 44% and the gas by 40%. Although the results indicate a direct relationship between utility requirements and prime oven abatement, the added contribution to the total energy is only two to seven percent. The increase in environmental emissions would be proportional to the energy changes.

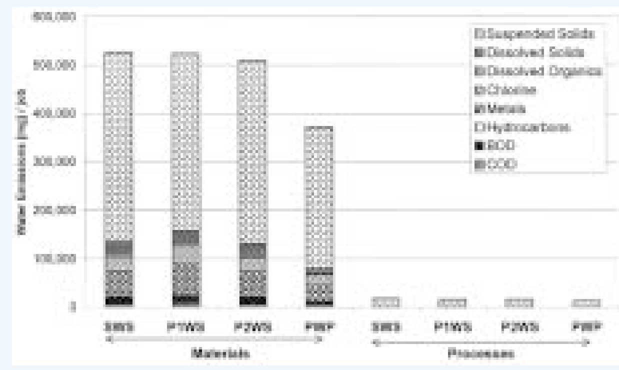

Figure 11—Total water emissions.

Reclaim of Powder Coatings: The study assumed 95% E.T.E. This is feasible if powder is sprayed in dry booths and reclaimed effectively. In fact, the 95% E.T.E is observed in powder prime applications at GM plants. However, it may be argued that the transfer efficiency for powder clear would be much less 95% (no reclaim). To see the sensitivity we assumed 60% E.T.E for powder clearcoat in scenario 3.

The results show that the amount of powder clearcoat required per job increases by 28.5%, with respect to the values estimated with 95% E.T.E, from 0.330 to 0.462 gal per job. Accordingly, the energy to manufacture the powder increased by 26% from 406 to 551 MJ. The paint solids emissions increased from 0.06 to 0.77 kg, a thirteen-fold increase.

The process energy requirements for the PP2-WB1-PC2 scenario with 60% E.T.E will remain the same. The change in the materials energy will lead to a four percent increase in total energy from 3,447 to 3,592 MJ. With this insignificant change in total energy requirements, scenario 3 still uses less energy than the others (see *Figure* 5).

Film Thickness of Acrylic Powder Primer: The study assumed 3.0 mils film thickness for the acrylic powder primer and 2.2 mils for the polyester. We evaluated the changes in material usage, energy requirements, and solid waste generation. Assuming the same film thickness of 2.2 mils for acrylic primer. The findings show that amount of powder required decreased by 27% from 0.33 to 0.24 gallons per job, energy to manufacture the powder decreased by 29% from 385 to 275 MJ, and solids in the sludge decreased by 28% from 0.07 to 0.05 kg.

The process energy requirements for the PP1-WB1-SC1 scenario will remain the same. The change in the materials energy will lead to a two percent decrease in total energy from 4,451 to 4,341 MJ. All other LCA emissions will change proportionally. This indicates that the polyester powder still uses less energy than the acrylic.

OVERALL ENVIRONMENTAL PERFORMANCE OF THE SCENARIOS

The life cycle assessment of the three different paint scenarios has revealed some trends in their environmental

Table 6—Sludge Calculation

Sludge Calculation (Considering 70% Solid Content of the Sludge)

		Paint/Job (gal)	T.E[a] (%)	Waste Paint/Job (gal)	Weight of Paint (lb/gal)	Waste Paint/Job (lb)	Weight Solids (%)	Solids in Waste (lb)	Solid content of Sludge (%)	Sludge (lb)
Primer powder	(DuPont)	0.33	95	0.02	9.4	0.16	100	0.16	100	0.16
Primer powder	(Seibert)	0.24	95	0.01	11.1	0.14	100	0.14	100	0.14
Primer solventborne	(DuPont)	0.27	70	0.08	9.85	0.81	60.93	0.49	70	0.70
Basecoat waterborne (White)	(DuPont)	2.13	30	1.49	10.02	14.94	41.69	6.23	70	8.90
Basecoat waterborne (Pewter)	(DuPont)	2.26	30	1.58	8.51	13.46	23.31	3.14	70	4.48
Clearcoat solventborne	(DuPont)	1.05	65	0.37	8.17	3.00	60.52	1.82	70	2.60
Clearcoat powder	(Seibert)	0.46	60	0.18	9.26	1.71	100	1.71	100	1.71

Sludge generated for White	lb/job	kg/job	Sludge generated for Pewter	lb/job	kg/job	
SP1-WB1-SC1	12.20	5.53	SP1-WB1-SC1	7.78	3.53	The value accounts for the sludge generated from each booth.
PP1-WB1-SC1	11.49	5.21	PP1-WB1-SC1	7.08	3.21	From the basecoat and clearcoat booths.
PP2-WB1-PC1	8.90	4.04	PP2-WB1-PC1	4.48	2.03	The value accounts for the sludge generated from the basecoat booths.

Sludge Calculation (Considering 35.6% Solid Content of the Sludge)

		Paint/Job (gal)	T.E[a] (%)	Waste Paint/Job (gal)	Weight of Paint (lb/gal)	Waste Paint/Job (lb)	Weight Solids (%)	Solids in Waste (lb)	Solid Content of Sudge (%)	Sludge (lb)
Primer powder	(DuPont)	0.33	95	0.02	9.4	0.16	100	0.16	100	0.16
Primer powder	(Seibert)	0.24	95	0.01	11.1	0.13	100	0.13	100	0.13
Primer solventborne	(DuPont)	0.27	70	0.08	9.85	0.80	60.93	0.49	35.6	1.37
Basecoat waterborne (White)	(DuPont)	2.13	30	1.49	10.02	14.94	41.69	6.23	35.6	17.50
Basecoat waterborne (Pewter)	(DuPont)	2.26	30	1.58	8.51	13.46	23.31	3.14	35.6	8.82
Clearcoat solventborne	(DuPont)	1.05	65	0.37	8.17	3.00	60.52	1.82	35.6	5.10
Clearcoat powder	(Seibert)	0.33	95	0.02	9.26	0.15	100	0.15	100	0.15

Sludge generated for White	lb/job	kg/job	Sludge generated for Pewter	lb/job	kg/job	
SP1-WB1-SC1	23.97	10.87	SP1-WB1-SC1	15.28	6.93	The value accounts for the sludge generated from each booth.
PP1-WB1-SC1	22.60	10.25	PP1-WB1-SC1	13.92	6.31	From the basecoat and clearcoat booths.
PP2-WB1-PC1	17.50	7.94	PP2-WB1-PC1	8.82	4.00	The value accounts for the sludge generated from the basecoat booths.

(a) T.E. = Transfer Efficiency; Note that T.E. for powder primer and clearcoat is the Effective T.E, (E.T.E).

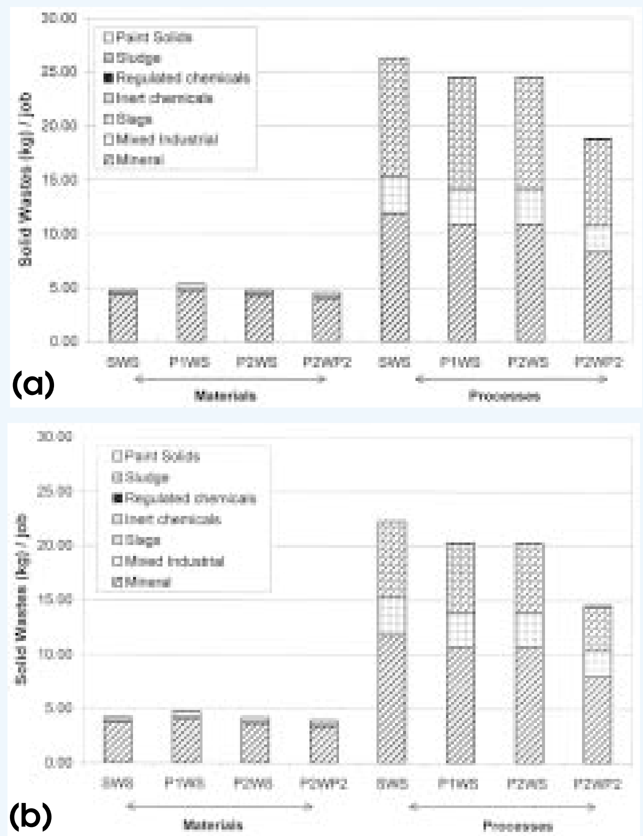

Figure 12—Solid wastes generated from materials production and paint operations: (a) White Color, (b) Pewter Color.

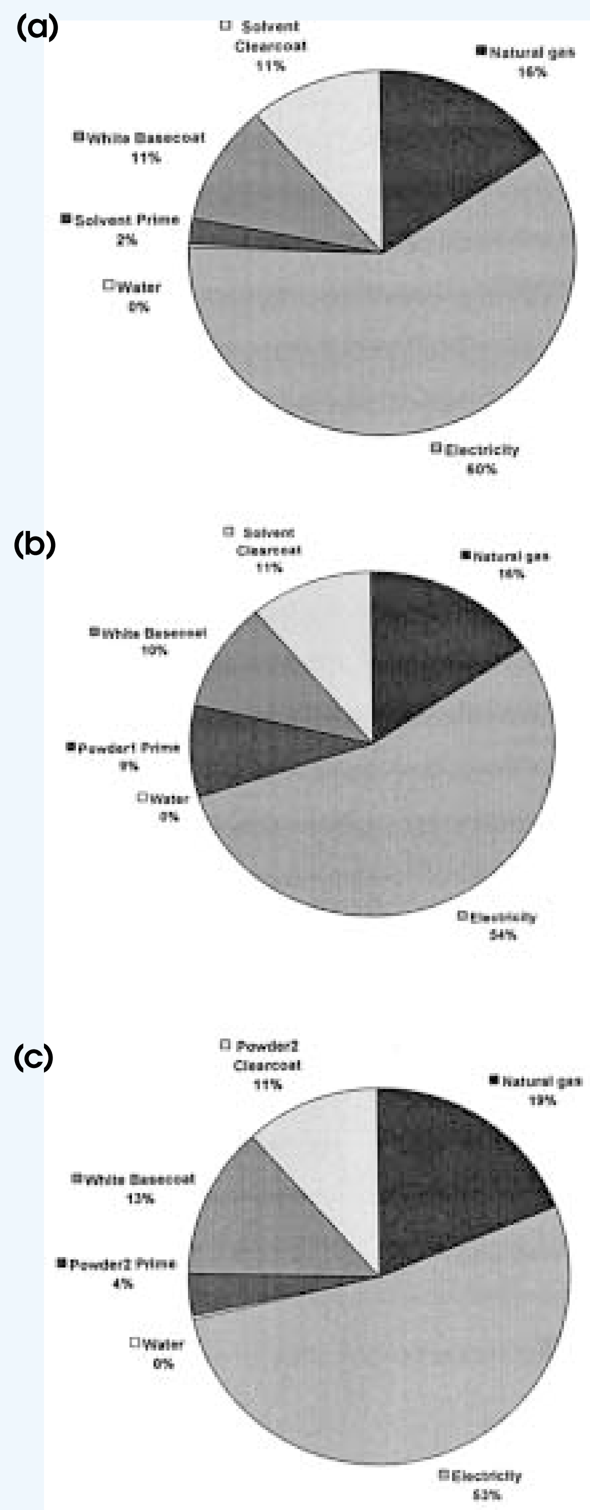

Figure 13—Energy consumption contributors for different scenarios: (a) SP1-WB1-SC1, (b) PP1-WB1-SC1, (c) PP2-WB1-PC2.

emissions that will help in selecting paint materials and processes. However, it is important to emphasize that life cycle inventories, as those obtained in this analysis, provide only part of the information for decision making. This is because the inventories do not evaluate the total environmental impacts of the emissions. If we think that each one of the emission categories presented here represents an index, then it will be more meaningful to associate global environmental impacts for some indices, such as Global Warming Potential (GWP) and Ozone Depletion Potential (ODP).[19] For these indices it is meaningful to aggregate all the emissions that occur from each plant, considering that the plants may be geographically scattered around the globe. The total aggregate value has a meaning because the emissions are well mixed into the atmospheric environment and the associated impacts (global warming and ozone depletion) have global character.

The precursors for stratospheric ozone depletion are CFCs and HCFCs and none of these chemicals contribute to the emissions reported in this study. Therefore, the ODP index is of no concern to us. However, the CO_2 equivalent emissions (impact on global warming) which occur pri-

Table 7—Sensitivity of Utility Requirements and VOC Emissions per Job with or without Primer Oven Abatement

Scenario	Electric Usage (kWh/job)		Gas Usage (MCF/job)		VOC Emissions (kg/job)	
	Abated	Non-Abated	Abated	Non-Abated	Abated	Non-Abated
PP1-WB1-SC1	26	23	0.21	0.18	1.7	1.7
PP2-WB1-PC2	9	5	0.10	0.06	1.2	1.2

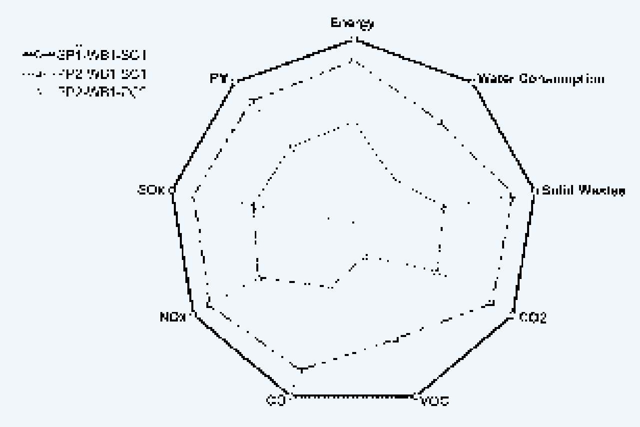

Figure 14—Summary of the environmental performance.

marily during the production of energy (electricity and heat) using fossil fuels, are significant. Therefore, besides choosing the best scenario, PP2-WB1-PC2, to reduce energy requirements and the associated emissions, energy conservation measures and an increase use of renewable forms of energy can further reduce the CO_2 equivalent emissions for all scenarios. Considering that 70-76% of the total energy (natural gas and electricity) consumed per job is attributed to the paint process, as shown in *Figure* 13, such energy measures can have a significant impact in the environmental performance of each scenario. As a result, the CO, Nox, and SOx will also be reduced simultaneously for reasons that have already been explained.

The environmental impacts of CO, NOx, and SOx have local and regional character and cannot be aggregated at a global level. It is also meaningless to talk about the aggregate environmental impacts of these gases as well as those emitted from water and solid wastes. This is because the regional ecosystems in which the air, water and solids wastes are discharged have different ecological properties and tolerances.

Figure 14 summarizes the environmental performance of the three scenarios in a single chart. The attributes considered are energy, water consumption, solid wastes, CO_2 equivalent emissions, VOC, CO, NOx, SOx, and PM. For each attribute, the basis is taken to be that for the SP1-WB1-SC1 scenario and those of the other scenarios are scaled to that. It is observed that scenario PP2-WB1-PC2 is associated with the least environmental impact in every respect. For example, the energy usage and CO_2 equivalent emissions are less by 22 and 24%, respectively, compared to those found in scenario SP1-WB1-SC1.

CONCLUSIONS

Life Cycle Assessment was used to evaluate three paint processes and their associated materials. The analysis shows that a transition from solvent-based coatings to powder-based for the primer and clearcoat leads to an improvement in the environmental performance of the paint processes. The decrease in: (a) total energy consumption is 22% (from 4,443 to 3,447 MJ), (b) water usage is 34% (from 549 to 363 gallons), and (c) sludge generation is 27% (from 10.87 to 7.94 kg). The decrease in all air emission categories follows the pattern in the energy usage. More than 50% of the total energy is used in the painting processes. This energy usage together with the greenhouse gas emissions can be reduced in all scenarios by using less fossil fuels and more renewable forms of energy.

ACKNOWLEDGMENTS

The authors acknowledge the valuable comments and suggestions by Peter Gribble at Seibert Inc., Buck D. McKinney at DuPont Inc., Sue Brassiano at GM WWF, Leo Shorek, Judy Reidi, Dean Doherty, David Dobias, Patrick Schoening, and Gary Hildebrand at GMNA Paint Engineering, David Kloppenburg, Ed Beckley, Roger Johnson, Mary P. Turney, and Dick Stadtler GM Plant Engineers, and Martin A. Ferman and Ronald L. Williams at GM R&D.

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