EPA/600/R-01/058

Life Cycle Design of In-Mold Surfacing Film

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3M Demonstration Project

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Assistance Agreement # CR 822998-01-0

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1. Notice

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II. Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the abilities of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future. The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on the methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This work was sponsored by the National Risk Management Research Laboratory (NRMRL) of the U.S. Environmental Protection Agency. Since 1990, NRMRL has been at the forefront of development of Life Cycle Assessment as a methodology for environmental assessment. In 1994, NRMRL established an LCA team to organize individual efforts into a comprehensive research program. In addition to project reports, the LCA team has published guidance manuals, including “Life Cycle Assessment: Inventory Guidelines and Principles (EPA/600/R-92/245)” and “Life Cycle Design Framework and Demonstration Projects (EPA/600/R-95/107).”

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

III. Abstract

This life cycle design project was a collaborative effort between the Center for Sustainable Systems (formerly National Pollution Prevention Center) at the University of Michigan, 3M Corporation, and the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency. The primary objective of this project was to apply life cycle design tools to a new product introduced by 3M. In-mold surfacing film (ISF) is an alternative color-coating system to the traditional paint coating process. It has been tested for application on body side molded (BSM) plastic parts on automobiles. In contrast to painting processes, ISF is manufactured at 3M and is shipped to tier 1 (relative to Original Equipment Manufacturers (OEM), i.e. automobile manufacturers) suppliers for application into BSM parts. ISF is a layered product consisting of clear coat, color coat, adhesive, and a Thermoplastic Polyolefin (TPO) backing. A Polyethylene Terepthalate (PET) liner is used during manufacturing, but is removed before the film is die. The analysis is performed for 12.2 g of die cut ISF film applied to a BSM part of surface area of 399 cm^2. The material production inventories of Poly Vinylidene Fluoride (PVDF), acrylic, PET, and TPO, which constitute the ISF, were evaluated as part of the analysis.

The scope of the LCD study encompasses manufacturing, application, use and retirement stages. In contrast to painting operations, where the majority of environmental burdens are concentrated in the paint shops of tier 1 suppliers or at the OEM facility, the environmental burdens for ISF application are shifted upstream from tier 1 suppliers to 3M. The overall material efficiency based on solids and coating solvents as input material from manufacturing to application is 19%. The total life cycle energy requirement for the paint film was determined to be 11.8 MJ/ISF and the total life cycle solid waste generated per ISF was 62 g. The use phase results in a majority of the life cycle environmental burden in terms of energy (54%) and CO_2 emissions (63%); however, the use phase contributes only 29% of the total life cycle solid waste. The majority of life cycle cost occurs during manufacturing (81%). Based on the results of this life cycle environmental and cost inventory, metrics for design analysis are proposed. Different life cycle performance metrics required to meet the OEM specifications are also presented

This report is submitted in partial fulfillment of Cooperative Agreement number CR822998-01-0 by the National Pollution Prevention Center at the University of Michigan under the sponsorship of the U.S. Environmental Protection Agency. This work covers a period from November 10, 1994 to March 30, 1996.

IV. Contents

V. Acknowledgment

We wish to thank 3M and members of the 3M life cycle design project team for collaborating with the National Pollution Prevention Center. Thomas Zosel played a key role in initiating this project. Mick Sawka served as project leader and was very instrumental in gathering data for the environmental, cost, and performance analyses. In particular, he provided a very detailed manufacturing process flow diagram and data set. Gary Crecelius provided management support and critical feedback on the life cycle design approach. Ed Price participated in discussions of technical issues relating to the streamlined life cycle inventory analysis. Wing-Wah Yeung helped in selecting the specific 3M automotive film for this investigation. We also wish to acknowledge Jonathan Bulkley and Sabrina Spatari, of NPPC, for review and technical editing of this document.

1. Project Description

1.1 Introduction

Integration of environmental considerations into the design process represents a complex challenge to designers, managers and environmental professionals. A logical framework including definitions, objectives, principles and tools is essential to guide the development of more ecologically and economically sustainable product systems. In 1991, the US. Environmental Protection Agency collaborated with the University of Michigan to develop the life cycle design framework (Keoleian and Menerey 1993; Keoleian and Menerey 1994; Keoleian, Koch, and Menerey 1995; Koch and Keoleian 1995). This framework is documented in two publications: Life Cycle Design Guidance Manual (Keoleian and Menerey 1993) and the Life Cycle Design Framework and Demonstration Projects (Keoleian, Koch, and Menerey 1995).

Two demonstration projects evaluating the practical application of this framework have been conducted with AlliedSignal and AT&T. AT&T applied the life cycle design framework to a business phone (Keoleian, Glantschnig, and McCann 1994) and AlliedSignal investigated heavy duty truck oil filters (Keoleian 1995). In these projects environmental, performance, cost, and legal criteria were specified and used to investigate design alternatives. A series of new demonstration projects with Dow Chemical Company, Ford Motor Company, General Motors Corporation, United Solar and 3M Corporation have been initiated with Cleaner Products through Life Cycle Design Research Cooperative Agreement CR822998-01-0. Life cycle assessment and life cycle costing tools are applied in these demonstration projects in addition to establishing key design requirements and metrics. This report provides a description of the 3M project that investigated the life cycle design of in-mold surfacing films. An overview of the life cycle design framework is provided in Appendix D of this document.

1.2 Project Origin / Team

The life cycle design project with 3M was launched in November of 1994. Initial meetings with the 3M group focused on defining project objectives and scope as well as picking a specific 3M film product for a life cycle design (LCD) study. After several meetings with 3M, a paint film designed to be applied to exterior plastic automobile parts was targeted for this study. 3M was interested in studying how the LCD framework and tools could be applied to its ongoing pollution prevention program. Members of the 3M group participating in this study are indicated Table 1-1.

Table 1-1. 3M Core Team Members for the Life Cycle Design Project

Division	Team Member
Paint Replacement and Coating Supervisor	Gary Crecelius
Senior Product Development Engineer	Mick Sawka
Senior Environmental Scientist	Ed Price
Pollution Prevention Manager	Thomas Zosel
Market Development	Wing-Wah Yeung

1.3 Product Selection

In-mold surfacing film (ISF), also referred to as injection molded paint film, was selected by 3M for this life cycle design study. The other candidate products were thermoformed paint film and blackout/colorout film. Injection molded paint film was chosen for the following reasons:

- 3M is striving to reduce the environmental burden of its products through its Pollution Prevention Pays program
- 3M can use this demonstration project to test LCD as a decision making tool for future cleaner product design
- Since production of the paint film has not begun, LCD results can potentially be used to improve stages of the production process which result in significant environmental burden
- 3M envisions that paint film potentially has a large market due to durability (peel off, cracking, and chipping) problems associated with paint applied to plastic parts

1.4 Product Significance

3M is targeting paint film for application on injection molded plastic parts. Presently 3M is pursuing orders for in-mold surfacing films for external automotive applications and is preparing to begin full-scale production. The potential paint film market for North American automobiles is approximately $300 million (3M 1995). Sales of paint film for body side molded (BSM) parts could potentially amount to $50 million. Currently about 12 million individual BSM parts are produced each year in North America.

1.5 Objectives

The objectives of this project are to develop a set of tools that can be used by 3M product and process engineers to more effectively integrate environmental requirements into product system design and analysis. Current design techniques are often limited by lack of an organized methodology to evaluate environmental burdens throughout the life cycle of a product. This project sought to address such limitations by developing practical metrics for evaluating life cycle environmental, cost and performance criteria. Specific objectives were:

- Evaluating primary energy and waste for material production, manufacturing, application, use and retirement stages
- Estimating cost at different life cycle stages
- Identifying process improvements which will reduce environmental burden

2. Systems Analysis

2.1 Product Composition

In-mold surfacing film (ISF) is a 3M product that is shipped to tier 1 suppliers in die-cut form for application on automotive body side molded (BSM) parts. ISF is a layered product consisting of clear coat, color coat, adhesive and TPO. A PET liner is used during manufacturing for film application but is removed before the film is die cut. The film is cut into an appropriate size for each BSM part and excess film is trimmed off. In this study, all data were gathered and evaluated for a prototype BSM part with a surface area of 399 cm^2. Taking into account trimming and yield losses of about 37%, the die-cut ISF for this application has a surface area of 637 cm^2 (5.7 cm x 111.7 cm).

The mass of die-cut ISF for one prototype BSM part was calculated with a model that assumed 50,000 four-door vehicles with 200,000 prototype molded parts requiring 207,254 die-cut pieces of ISF having a mass of 4017 kg. Thus, 19.4 g of die-cut ISF is required for each prototype BSM part. Figure 2-1 is a diagram of the layers in ISF.

Figure 2-1. Cross-section of 3M ISF (PET Liner is removed prior to application)

Table 2-1 provides the mass of applied ISF on one prototype BSM part. Many of the film constituents are applied as liquid materials, however, only final solid composition is shown here.

Table 2-1. Composition and Mass of ISF Molded on One Prototype BSM Part

Film Layer	Thickness (mm)	Constituents	Mass (g / film)
PET liner	51	PET	2.7†
Clear coat	51	PVDF	2.5
		Acrylic	0.8
Color coat	38	PVDF	1.7
		Acrylic	0.6
		Pigment	0.7
Adhesive	8	Adhesive resin	0.4
TPO film	152	TPO	5.5
Total			12.2†

†The PET liner is removed prior to application, therefore, the mass of the liner is not included in the total presented here.

The mass of ISF on one prototype BSM part was also calculated by taking into account trimming and applications losses of 37%. This means that an initial mass of 19.4 g, prior to molding, is required for the final 12.2 g on each BSM part. It is important to note that the PET liner (2.7 g), which is stripped from the film prior to die cutting, is not included in these values.

2.2 Scope

The initial scope of the project was to perform a comparative assessment of ISF and paint applied on external plastic automobile parts. Some of the typical applications considered were BSM parts, fascia, bumpers, grill panels and mirror holders. The scope of the study was subsequently narrowed to ISF applied on a prototype BSM part because of the difficulties in gathering energy and waste data from paint manufacturing and application facilities.

2.3 Boundaries and Assumptions

The boundary for this project includes material production, manufacturing, application, use and retirement as explained in Table 2-2.

Table 2-2. Boundary and Assumptions of the In-Mold Surfacing Film (ISF) System

LC Stage	Boundary and assumptions
Material production	• The material production inventory was calculated using confidential data sources and (Boustead 1993),(Boustead 1994),(Boustead 1995). • Material production energy did not include pigment production energy. • Data for PVC production (Boustead 1994) was used as a surrogate for PVDF production.
Manufacturing	• Process energy and waste for unit operations were obtained from 3M's engineering model (3M 1995; 3M 1996), which were assumed to reasonably represent actual operating conditions. Die-cutting energy was not available; however, 3M sources have indicated that these are on the same order of magnitude as stripping and slitting operations. • Environmental data were provided by 3M for 207,254 pieces of die cut ISF which have a total mass of 4017 kg. Therefore, environmental data per film was obtained by dividing data from individual unit operations by 4017 kg. • The manufacturing stage consists of manufacturing and lamination unit operations for clear coat, color coat, adhesive and TPO film. • It was assumed that the PET liner was disposed of after one use. • Environmental data for the production of a mineral spirit coating solvent were estimated by using the environmental data for the production of refined petroleum products (Franklin Associates 1992). In this study, it is assumed that 50% of the energy contained in coating solvent emissions is recaptured for another use during thermal oxidation and 50% is lost. Thus only 50% of combustion energy for the coating solvents is allocated to the ISF system. • 95% reclamation of cleaning solvents was assumed in the manufacturing plant. Environmental burden for the production of cleaning solvents was not considered in this analysis due to lack of data. The mass of cleaning solvents reclaimed per mass of coating solvents used is about 0.009. Therefore, neglecting the cleaning solvents in the inventory analysis will not result in a significant error in this analysis. • Environmental burden for transportation between material production and manufacturing facility was not considered.
Application	• The contribution of ISF to the cycle time of BSM molding was assumed to be 10 seconds. • Injection molding energy for the BSM part was assumed to be 75 kW/kg (3M 1993). • The 3M model (3M 1995) was assumed to reasonably represent the scrap generated from edge trim and yield loss. • An average 800-mile distance was assumed from the manufacturing plant to the application plant. Transportation energy using diesel trucks was obtained from (Franklin Associates 1992).
Use	• Use phase environmental data for ISF was evaluated from fuel consumption and washing data. • The ISF part was modeled over the eight-year service life of the vehicle. • A 6.6% rule for correlating weight reduction to fuel consumption reduction was used to determine fuel consumed. • ISF contribution to vehicle emissions was obtained by assuming that emissions were proportional to vehicle mass; the allocation rule is accurate for CO_2 but for other gases the relationship is nonlinear. • A cleaning schedule of 1 mechanical wash every four months was assumed for the first eight years of the film's life with no washing thereafter. • Energy and cost required to clean the surface area of a BSM film was assumed to be proportional to the external surface area of the entire car. • The energy required for touch up paint operation during paint application is neglected.
Retirement	• Two different scenarios were considered : - ISF disposed to landfills (shredding, separation, transportation and landfill disposal energy, and waste included) - ISF recovered as part of a BSM part and recycled (dismantling, regrinding, transportation energy, waste, and cost included) • Efficiency of recycling ISF into BSM regrind was assumed to be 95%.

2.3 ISF System Description

The life cycle product system for ISF consists of product, process and distribution subsystems for the following life cycle stages: material production, manufacturing, application, use and retirement as shown in Figure 2-2.

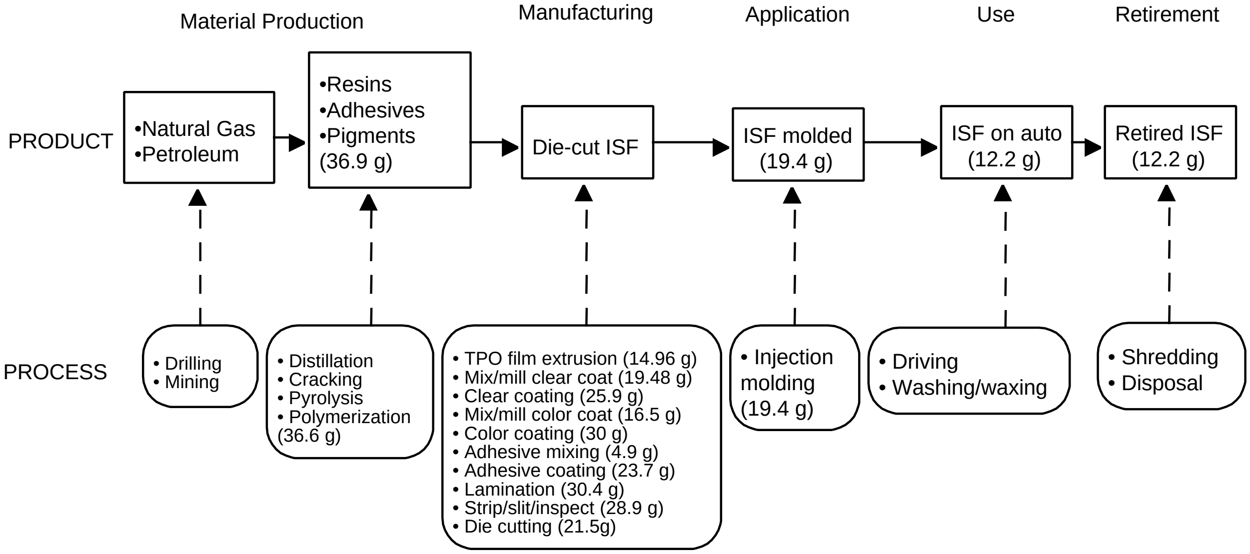

Figure 2-2. Flow Diagram for ISF

The product component for the film in the manufacturing stage consists of a clear top coat, color coat, adhesive layer, and a TPO backing sheet as illustrated in Figure 2-1. The ISF manufacturing process consists mainly of coating these layers, one on top of the other, onto a PET casting liner and then die cutting the film to fit the particular part. Details of the manufacturing process are shown in Figure 2-3 to illustrate different unit operations.

The clear coat is the first to be applied. Clear coat solution is made of PVDF and acrylic resin dispersed in mineral spirits. This solution is coated directly onto a roll of PET casting liner by passing the PET liner through a series of rollers. The wet, clear-coated PET liner then passes through a drier. Solvents are combusted in a thermal oxidizer.

Next, the color coat solution is applied on the clear-coated PET liner by passing it through a series of rollers as described above. Color coat solution consists of PVDF, acrylic resin and pigment dispersed in mineral spirits. The wet clear/color coat layer is then passed through a drier.

Next, a solution of adhesive resin and mineral spirit is applied over the color coat and dried. The final layer is TPO, which is extruded.

At this point, the film is in roll form and ready for trimming and inspecting. In the stripping/slitting/inspection step, the PET liner is removed and the edges of the rolls are trimmed to eliminate parts of the film that weren't sufficiently covered. In this step, any film with imperfections not previously detected is removed. Acceptable film is now ready to be die cut for specific applications. This cut film is sent to tier 1 suppliers who apply the film during injection molding of parts.

Energy is required for every step of this process, and waste is also produced at each step. In terms of waste, some amount of coating solution is always lost due to spillage and other reasons. The mixing stage also requires cleaning solvents to clear old solution from the equipment. Solid waste results from product that doesn't meet specifications at each stage, edge trimming and yield loss, and trimming during die cutting. Drying each layer involves blowing off solvents which produces gaseous waste. These VOCs are burned in a thermal oxidizer that returns some energy to the process. Solid waste is handled by either selling it to power companies to burn for producing electricity or disposing it in landfills.

ISF, consisting of a clear coat, color coat, adhesive layer and TPO layer, is applied by placing it in an injection molding die with the clear coat layer facing the die. Molten resin for the BSM part is injected into the die and bonds with the TPO layer of the ISF. Upon cooling, the film is securely attached to the BSM part.

The prototype BSM part used in this study would ultimately be attached to a vehicle. The use process for ISF involves driving the vehicle, cleaning, washing and waxing. In retirement, film is either disposed to landfills or recovered along with BSM parts and reground for recycling into new BSM parts or other applications.

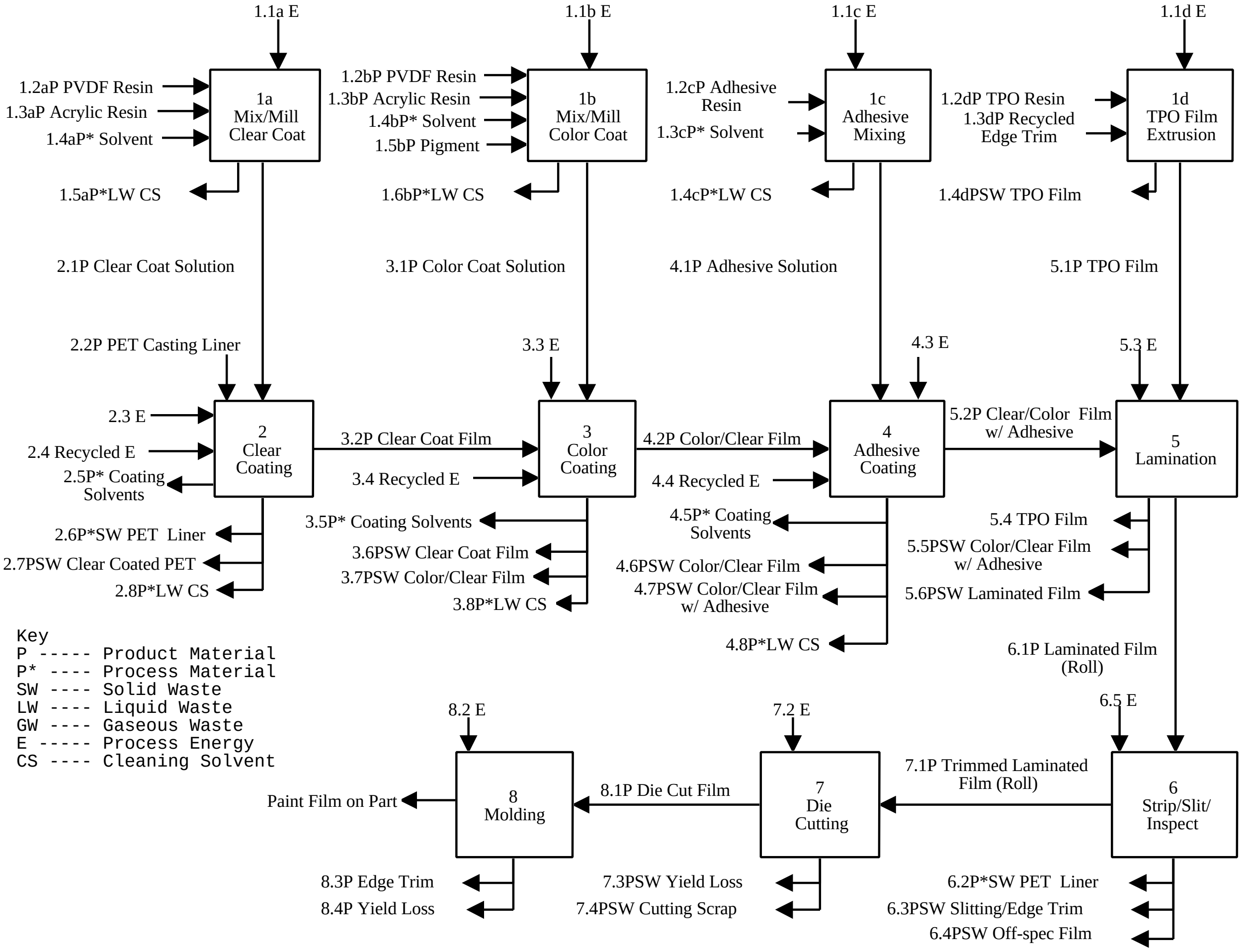

Figure 2-3. ISF Manufacturing and Application Process

3. Data Collection and Analysis

3.1 Methodology

In this chapter, environmental, cost and performance data are evaluated for different stages of the life cycle of ISF. A spreadsheet describing details of the data analysis and methodology is presented in Appendix B. Environmental data in the material production stage were calculated using the best available life cycle inventory data for TPO, PVDF, PET, and Acrylic. These four materials comprise 94% of the total mass of ISF raw materials. The remaining 6% is made up of pigments and adhesive; no data was available for these materials. Film manufacturing data were supplied by 3M (3M 1996; 3M 1995; 3M 1993). The University of Michigan core team members obtained primary data from 3M core team members, who in turn collected data from other divisions within 3M and their suppliers. Most environmental data provided by 3M were based on numerical models of specific processes. Environmental data in the use phase were obtained from fuel economy and emissions data for an average light duty passenger car (US EPA 1995) and car washing data obtained from (Lighthouse Car Wash 1995). In the retirement stage, shredding and transportation energy and waste were evaluated from (McGlotholin 1995; APC 1994; Franklin Associates 1992).

Manufacturing, application, use and retirement costs were also evaluated. Manufacturing and application costs were provided by (3M 1993). In the use phase, fuel cost (Lockhart 1995) and washing cost (Lighthouse Car Wash 1995) were evaluated. Retirement cost was estimated from the retirement spreadsheet model of APC (APC 1994) and data obtained from NSWMA (NSWMA 1995).

Performance metrics evaluated in the manufacturing and application phase were material throughput and cycle time (3M 1996). In the use phase, performance metrics consisted of OEM specifications for the ISF.

3.2 Environmental Data

A streamlined inventory analysis for material production, manufacturing, application, use and retirement are described in the following subsections.

3.2.1 Material Production

Table 3-1 shows the mass of film materials processed for manufacturing ISF film for one prototype BSM part.

Table 3-1. Mass of Material Inputs for One Prototype BSM Part

Material Inputs	Mass (g)	
TPO resin	15.0	
PVDF resin	9.6	
PET liner	6.4	
Acrylic resin	3.2	
Pigments	1.7	
Adhesive resin	0.7	
Total Product Materials		36.6
Coating solvents	25.8	
Total Process Materials		25.8
Total		62.4

Only the product materials listed in Table 3-1 constitute the final ISF. For this reason the production of the coating solvents was not included as part of the material production analysis, however, production of these materials was included in the manufacturing analysis.

The Ullmann's Encyclopedia of Chemical Technology defines TPO as "a simple blend of a-olefin rubber in a crystalline polyolefin resin" (Ullmann 1985). Many commercially available polymers fit this definition of TPO. For the purposes of this study it was assumed that the TPO used in ISF consisted of EPDM rubber (53%) in PP (43%) (Ullmann 1985). In order to estimate the life cycle inventory for TPO production environmental data for EPDM and PP were averaged according to their relative weights in this mixture. Environmental data for EPDM production was taken from a confidential source and data for PP production was obtained from (Boustead 1993). No data was available for PVDF manufacturing, PVC manufacturing is believed to provide a reasonable approximation of the material production inventory for PVDF (Kroschwitz 1990). Material production data for PVC was taken from (Boustead 1994). Life cycle inventory data for PET production was taken from (Boustead 1995). The source of the inventory data for acrylic is confidential. These environmental data were combined according to mass to determine the inventory profile for ISF material production. No data were available on the pigment or adhesive used in the ISF. The burdens for production of these materials were neglected.

3.2.2 Manufacturing

Environmental burden for manufacturing ISF was estimated using a 3M model that is based on the process variables indicated in Tables 3-2 to 3-4. Table 3-2 shows that clear coat and color coat solution both use about 40% solids in mineral spirits and require similar sized ovens for drying. Adhesive coating is 15% solids in mineral spirits and uses a drying oven that is approximately 3.7 times smaller in length than the oven for clear/color coating. Drying temperature is 149° C for all these processes. Overall power consumption includes power required to heat the dilution air, evaporate solvent, heat the base layer to the desired temperature and heat the solid film layer. Power required for skin loss is also included. Power required to heat the dilution air is about 88 to 93% of the total power consumed for clear, color and adhesive coating operations and is therefore the most important energy metric in the manufacturing stage.

Table 3-2. Clear, Color and Adhesive Coating Process Variables for ISF to Coat 207,254 BSM parts

Process Variables	Top Coat Layer Metrics		
	Clear coat[1]	Color coat[2]	Adhesive coat[3]
Top coating solution (% solids in mineral spirits)	40	40	15
Caliper of dry top coat layer (μm)	51	38	8
Caliper of dry base coat liner (μm)	51	102	138
Density of solid top coat layer (kg / m^3)	1630	1970	1150
Density of solid base coat liner (kg / m^3)	1340	1480	1620
Top coat layer coverage (kg / cm^2)	830	730	1000
Mineral spirits coverage (kg / cm^2)	1220	1120	490
Oven length (m)	55	55	15
Length of oven walls (m)	1.8	1.8	1.8
Drying time (min)	3	3	0.27
Line speed/rate (m/s)	0.3	0.3	0.9
Coating width (m)	1.29	1.27	1.27
Rate of solvent evaporation (kg / s)	0.049	0.043	0.056
Assumed overall oven exhaust solvent concentration (% lower flammability limit, LFL)	20	20	20
Drying temperature (°C)	149	149	149
LFL (% v/v)	0.8	0.8	0.8
Vapor density for mineral spirits (kg / m^3)	4.6	4.6	4.6
Exhaust flow rate (m^3 / s)	6.6	5.9	7.6
Ambient air temperature (°C)	10	10	10
Power required to heat dilution air (kW)	1109	986	1268
Heat of vaporization for mineral spirits (MJ / kg)	0.36	0.36	0.36
Power required to evaporate solvent (kW)	18	16	20
Power required to heat the base coat (kW)	6.2; 249 C	13.4; 249 C	41; 149 C
Power required to heat solid top coat layer (kW)	7.5	6.7	1.6
Heat transfer coefficient (W/m^2 °C)	4.7	4.7	4.7
Skin temperature (°C)	49	49	49
Plant air temperature (°C)	21	21	21
Power required due to skin loss (kW)	96.5	96.5	27
Total power (kW)	1237	1118	1358

[1] Corresponding base coat is PET liner

[2] Corresponding base coat is PET liner + clear coat

[3] Corresponding base coat is PET liner + clear coat + color coat

Table 3-3. Process Variables for Mixing and Milling Coating Solution

Process Variables	Top Coat Layer Metrics		
	Clear coat	Color coat	Adhesive coat
Power required for mixing kettle (kW)	22	22	22
Mixing time (min)	60	60	60

Tables 3-3 and 3-4 show that the mixing and run time for clear, color and adhesive mix/mill operations is 1 hour and has an electrical power requirement of 22 kW. The line speed for clear coating and color coating operations is 60 fpm, whereas the line speed for adhesive coating is 175 fpm.

Table 3-4. Process Variables for Different Unit Operations

Unit operations	Cycle time[1] (hr)	Line Speed (m/s)	Power[2] (kW)	Total Energy (MJ)	Input Mass (kg)	Energy density (kJ / kg)
1.1a Mix/mill clear coat (electricity)	1	N/A	22	79.2	4037	19.6
1.1b Mix/mill color coat (electricity)	1	N/A	22	79.2	3424	23.1
1.1c Adhesive mixing (electricity)	1	N/A	22	79.2	1011	78.3
1.1d TPO film extrusion (electricity)	21.7	0.23	26	2031.1	3102	654.8
2.3 Clear coating (gas oven)	13.8	0.30	1237	61454.2	5369	11446.1
3.3 Color coating (gas oven)	13.1	0.30	1118	52724.9	6223	8472.6
4.3 Adhesive coating (gas oven)	4.3	0.89	1358	21021.8	4919	4273.6
5.3 Lamination (electricity)	9.7	0.38	11	384.1	6306	60.9
6.5 Strip/slit/inspect (electricity)	13.9	0.25	11	550.4	5991	91.9

[1] Cycle time for processes indicated by 1.1a, 1.1b and 1.1c includes mixing time only, for all other processes the cycle time includes running time only

[2] Interpreted as power delivered in energy used per seconds

Overall energy for film manufacturing includes energy for different unit operations. Electricity is used for mixing/milling clear and color coat, adhesive mixing, TPO film extrusion, lamination, stripping/slitting/inspecting and die cutting. Among the various unit operations, mixing/milling requires the lowest energy, while clear and color coating together account for about 83% of total processing energy. Adhesive coating accounts for another 15% of the total processing energy.

Electricity energy consumed for manufacturing ISF for one prototype BSM part was calculated to be 0.0156 MJ per ISF. Clear coating, color coating and adhesive coating operations use natural gas as a fuel for the drying oven. Together, these three operations use about 0.65 MJ of natural gas energy per die cut film.

The manufacturing energy calculation also includes energy for the production of coating solvents. About 25.8 g of coating solvents are used per ISF. Coating solvents used are mineral spirits that are generally accepted to be simple petroleum distillate products. For this reason, Franklin Associates data for the production of refined petroleum products was used to provide the environmental data for mineral spirits (Franklin Associates 1992). Refined petroleum products have an average precombustion energy of 7.14 MJ/l and combustion energy of 34.87 MJ/l. Coating solvents are combusted in thermal oxidizers. 3M stated that the energy recovered from combustion of solvents is used in another application, but the amount recovered is unknown.

In this analysis it was assumed that 50% of solvent energy is recovered and credited to the ISF system during manufacturing. Using this allocation rule, material production energy for the mineral spirits used in the production of ISF was 24.6 MJ/l. Assuming a density of 0.74 g/l for mineral spirits (based on the density of gasoline), the total primary energy for solvent production per ISF was evaluated to be 0.86 MJ.

About 85 mg of cleaning solvents are used for the production of one ISF. The cleaning solvents are reclaimed in the plant. The amount of solvents reclaimed is not known. 95% reclamation of cleaning solvents was assumed in this analysis. With this assumption, only 5% cleaning solvents will end up as water effluents. Hence, 5% (0.05 mg) of new input cleaning solvent was required. The environmental burden for the production of 5% virgin cleaning solvents was not evaluated in this analysis.

The equivalent primary energy for electricity and natural gas usage was evaluated by incorporating appropriate efficiency factors (0.89 for natural gas and 0.32 for electricity). The primary energy equivalent for electricity consumption was 2.1 MJ and for natural gas consumption, the primary energy was calculated to be 0.73 MJ per ISF die cut film. Thus the total primary manufacturing energy, including solvent production, is 1.64 MJ per ISF die cut film.

Waste and emissions from manufacturing processes include product, process and energy production waste. Product waste involves scrap loss for different manufacturing unit operations. The percentage scrap loss for different unit operations is shown in Table 3-5.

Table 3-5. Percentage Scrap Loss from Different Manufacturing Operations

Unit Operations	Scrap Type	% Scrap by Type	% Scrap per Unit Operations
TPO film extrusion	• TPO film	25.0	25.0
Clear coating	• Clear coated PET	2.7	2.7
Color coating	• Color coated film	0.9	4.2
	• Color/ clear coated film	3.3	
Adhesive coating	• Color/clear film with adhesive	1.7	1.7
Lamination	• Laminated film	5.0	5.0
Strip/slit/inspect	• PET liner	18.3	25.5
	• Slitting/edge trim	3.1	
	• Quality waste	4.1	
Die cutting	• Film weed	10.0	10.0

About 47% of input solid materials for film manufacturing end up as scrap. Taking into account solvents, 69% of input materials end up as waste consisting of 59% solids and 41% solvents. The strip/slit/inspect and film extrusion operations each generate about 25% scrap; they are the major sources of manufacturing scrap.

The final destination of scrap materials generated during manufacturing was not considered in this analysis. It is believed that much of the scrap generated at the manufacturing facility is incinerated off-site, however, the environmental burdens for transportation and incineration of scrap were not included in the analysis. All scrap generated during manufacturing is treated as solid waste.

Air emissions in the manufacturing stage include emissions from thermal oxidizers and emissions related to natural gas and electricity production. Thermal oxidizers are used to oxidize solvent emissions in clear, color and adhesive coating operations. About 1.33 kg of coating solvents (mostly hydrocarbons) are used per kg of film. This results in 0.026 kg of solvent use per ISF die cut film. The mass of air emissions was calculated from inlet and outlet conditions of air in thermal oxidizers as shown in Table 3-6.

The mass flow rate of hydrocarbon at the inlet is 223 g/s and the mass flow rate at the outlet is 3 g/s. Therefore, this thermal oxidizer is believed to have a destruction efficiency of 98.4%. The volume flow rate of air at the outlet is 81 m^3 / s. Assuming the density of air to be 1.013 kg / m^3, the mass flow rate of air at the outlet was calculated to be 82 kg/s.

Table 3-6. Inlet and Outlet Conditions of Air in Thermal Oxidizers

Gases	Inlet concentration (%)	Outlet concentration (%)
Moisture	2.7	3.2
O_2	20.7	19.7
CO_2	0.2	0.8

Table 3-6 shows that CO_2 concentration in air increases by 0.6% at the outlet of a thermal oxidizer, which can be attributed to the oxidation of the hydrocarbons present in the coating solvent. Based on the mass flow rate of air, calculated above, the mass flow rate of CO_2 produced during oxidation is calculated to be 0.49 kg/s. This value is in reasonable agreement with the value that can be calculated assuming the hydrocarbons combusted are decane. Stoichiometric combustion of decane would yield 0.67 kg/s of CO_2 from the outlet of the thermal oxidizer.

The total cycle time for all coating operations is 31.2 hr., so the mass of CO_2 emitted from thermal oxidizers was calculated to be 921 kg. The mass of hydrocarbon at the inlets of thermal oxidizers was found to be 25,049 kg and the mass of hydrocarbon at the outlets of thermal oxidizers was calculated to be 344 kg.

CO_2 and HC emissions were calculated based on 25.7 kg of coating solvents entering oxidizer inlets per ISF. Table 3-7 shows emissions from thermal oxidizers.

Table 3-7. Emissions from Thermal Oxidizers

Gases	Emissions	
	g / kg HC at inlet	g / ISF
CO_2	36.76	0.95
HC	13.73	0.35

3.2.3 Application

ISF is applied to BSM parts by placing die cut films in molds with the clear coat facing the mold surface. Resin for the BSM part is injected into the mold where it securely bonds with the TPO layer in the film. The energy for film application was evaluated from 3M's internal sources (3M 1996). Power required for injection molding the 399 cm^2 prototype BSM part used in this analysis is 75 kW/kg (3M 1996). Cycle time for molding this BSM part with ISF was estimated by 3M to be 30 seconds. An internal 3M study showed that the cycle time for molding a different, 450 cm^2 surface area, BSM part without ISF is 45 seconds and the cycle time for molding the same BSM part with ISF is 55 seconds. For this reason, it was assumed that the ISF under study contributes 10 seconds to cycle time during application.

The electrical energy for film application was obtained as the product of power density (kW/kg), cycle time (seconds) and mass (kg) of the film. Overall energy for film application includes the electricity for molding and diesel energy required to transport the film from a 3M facility to tier 1 suppliers. An energy density of 2.05 MJ/ton-mile (Franklin Associates 1992) and an average distance of 800 miles was assumed in this analysis. The primary energy equivalents of electricity and diesel energy were evaluated by incorporating appropriate efficiency factors (0.32 for electricity and 0.84 for diesel).

Both emissions and waste in film application include product and energy waste. Product waste involves solid waste from edge trimming and yield loss. Per 1000 g of film, about 363 g of scrap are generated due to edge trimming and 35 g of scrap are generated due to yield loss. Thus about 39.8% of film material is lost as scrap during film application. The environmental burden for incinerating film scrap was not included in this analysis.

3.2.4 Use

Use phase environmental burden includes vehicle fuel consumption and emissions attributable to the weight of the film, cleaning associated with the film and waste associated with vehicle fuel production. The contribution of the film to vehicle fuel consumption was calculated from data shown in Table 3-8 for an average vehicle.

Table 3-8. Weight and Fuel Economy Data for an Average Road Vehicle

Parameter	Metrics
Test weight	3200 lb or 1451 kg
Fuel economy	21.6 mpg or 10.89 l / 100 km
Weight to fuel economy correlation	10% weight reduction ✤ 6.6% fuel consumption reduction
Life of film	100,000 miles or 160,900 km

source: (US EPA 1995)

The contribution of the film to vehicle fuel consumption ($F_{(l)}$) was obtained using the following correlation:

$$F_{(l)} = M_{ISF} \times L \times \left[\frac{FC_{(l)}}{M_V}\right] \times \frac{\Delta f}{\Delta M} \qquad (3.1)$$

where,
$F_{(l)}$ = fuel (liters) used over the life of ISF (L)
M_{ISF} = mass of the ISF (0.0122 kg)
M_V = test weight (mass) of vehicle (1451 kg)
$\frac{\Delta f}{\Delta M}$ = fuel consumption correlation with mass (0.66)
$FC_{(l)}$ = fuel consumption for the vehicle under study (0.1089 liters/km)
L = life of ISF (160,900 km)

Using equation 3.1 the contribution of ISF to an average vehicle's lifetime (160,900 km) fuel consumption was calculated to be about 0.097 liter (0.026 gal). One liter of gasoline contains 42 MJ of primary energy comprised of 34.87 MJ of combustion energy and 7.16 MJ of precombustion energy (Franklin Associates 1992). The fuel energy use attributed to the film over the assumed vehicle lifetime of 160,900 km was found to be 4.1 MJ.

Air emissions and waste were evaluated as the sum of combustion and precombustion emissions and waste. Combustion emissions for an average road vehicle are shown in Table 3-9.

Table 3-9. Emissions Data for Average On-Road Vehicle

Air emissions	g / mile
CO_2	363.0
CO	23.0
HC	3.1
NO_x	1.6

Based on standard EPA emission models which assume an average properly maintained car on the road in 1995 operating on typical gasoline in normal summer weather
source: (US EPA 1995)

The mass of air emissions over the life of ISF for one prototype BSM part was obtained from the mass of air emissions per vehicle miles traveled using EQ (3.2).

$$m_e = m_{e'} \times FE_{(gal)} \times F_{(gal)} \qquad (3.2)$$

where,
m_e = mass (kg) of air emissions over the life of ISF
$m_{e'}$ = mass of air emissions per mile (kg / mile - see Table 3-9)
$FE_{(gal)}$ = fuel economy in miles per gallon (21.6 mpg)
$F_{(gal)}$ = fuel (gallons) used over the life of ISF (0.026 gal)

Precombustion wastes (air emissions, waterborne waste and solid waste) per 1000 gallons of gasoline were obtained from the Franklin database (Franklin Associates 1992). The Franklin waste data were multiplied by gasoline used in gallons per ISF to obtain waste in kg per ISF. Total use phase waste was obtained by summing precombustion and combustion waste.

Environmental data for cleaning assumes that vehicles are washed every four months during the first eight years of their life. Data were calculated, per ISF, by assuming that energy and waste are proportional to the surface area cleaned. The surface area for an average car is 16.25 m^2 and the surface area of the film covering the BSM part is 399 cm^2. Thus energy and waste per film were obtained by multiplying per car data by 0.00245. Energy for car washing was evaluated from the following data obtained from (Lighthouse Car Wash 1995) and Detroit Edison (electricity cost in July 1995).

- Number of car wash per year = 100,000
- Electricity bill per year = $35,000
- Electricity rate = $0.0995 / kWh

The energy per car wash was calculated as 3.5 kWh. All data were converted to primary energy by incorporating appropriate efficiency factors. Overall waste and emissions in the use phase were evaluated as the sum of waste due to cleaning (washing waste and waste associated with electricity production) and combustion and precombustion emissions for fuel use attributable to the film.

3.2.5 Retirement

Warranty information about ISF damaged due to weathering or accident is not available because this ISF is not yet used on an actual vehicle. Therefore, in this analysis, the ISF was assumed to be retired when the car is retired.

The retirement stage assumes no BSM part recovery at dismantlers or during shredding. In this case, ISF is transported along with the vehicle hulk from dismantlers to the shredders, where it becomes part of automotive shredder residue (ASR) and is disposed of in a landfill. An average distance of 100 miles was assumed between dismantlers and shredders (APC 1994). The average distance from shredders to landfills was assumed to be 200 miles (APC 1994). Transportation is by diesel tractor-trailer and the average energy for transportation was assumed to be 2.05 MJ/ton-mile (Franklin Associates 1992). Shredding energy of 0.097 MJ / kg (42 BTU/lb) (McGlotholin 1995) was used in this analysis. Waste factors for electricity and diesel fuel use were obtained from Franklin (Franklin Associates 1992).

3.3 Cost Data

Costs were evaluated for 3M and other life cycle stakeholders including tier 1 suppliers, users and end-of-life managers.

3.3.1 Manufacturing

The manufacturing cost for different unit operations could not be obtained directly from 3M. The cost of a similar processed film was obtained from an unpublished 3M study (Neidermair 1993) which used a base cost of $21.50 per m^2 of film. This cost includes both material and manufacturing cost of the film. Therefore, the cost for 637 cm^2 of film was $1.37.

3.3.2 Application

Film application cost includes costs for molding equipment, tooling, machining and labor. Various individual application costs were obtained from 3M's internal study. The overall application cost per ISF film was estimated to be 20 cents.

3.3.3 Use

Use cost is the sum of fuel cost and cleaning cost. Fuel cost was evaluated for 0.026 gallon of lifetime fuel use at $1.17/gallon and was found to be 3 cents. An average cleaning cost of $3 per car wash for every four months was assumed in this analysis. For a total 24 washes over an 8-year period (no further washes were assumed after 8 years), total car washing cost is $72. The total washing cost for the lifetime of the film was obtained as the ratio of the surface area of the film to the surface area of the car; it was calculated as 17.6 cents. The overall cost in the use phase associated with the film was therefore 20.6 cents. This analysis indicates that for a small exterior part such as ISF, washing cost is about 6 times higher than fuel cost.

3.3.4 Retirement

Retirement cost was obtained by evaluating transportation and shredding cost. Transportation cost used in this analysis is $0.12/ton-mile (APC 1994). The total distance transported was assumed to be 200 miles (100 miles each from dismantlers to shredders and shredders to landfills) (APC 1994). Therefore the total transportation cost was 0.03 cent per film. Shredder processing cost was estimated to be $33.50/hulk and the weight of a hulk is 1425 kg (Kar and Keoleian 1996). Therefore, shredder processing cost was calculated to be 0.03 cent per film. An average landfill tipping fee is $30.25/ton (NSWMA 1995). This results in a total landfill disposal cost of 0.04 cents per film. The overall retirement cost for film was calculated to be 0.1 cent per film.

3.4 Performance Data

3.4.1 Manufacturing

Performance parameters in the manufacturing stage are process throughput, cycle time and equipment life related to different unit operations. Process throughput represents input and output of product material for a particular unit operation. Performance data for ISF manufacture are presented in Table 3-10. These data are evaluated from the detailed material balance model presented in Appendix C.

Table 3-10. Performance Data for ISF Manufacturing

Unit Operations	Process Throughput					Cycle time (hours)
	Input		Output		Material Efficiency (%)	
	Type	Qty (kg)	Type	Qty (kg)		
TPO film extrusion	TPO resin	3102.12	TPO film	2326.93	75	21.7
Mix / mill clear coat	PVDF resin Acrylic resin Coating solvent	1211.09 403.70 2422.63	Clear coat solution	4037.42	100	1.0
Clear coating	Clear coat solution PET casting liner	4037.42 1331.75	Clear coat film	2799.12	52	13.8
Mix / mill color coat	PVDF resin Acrylic resin Pigment Coating solvent	770.20 256.73 343.46 2054.32	Color coat solution	3423.71	100	1.0
Color coating	Clear coat film Color coat solution	2799.12 3423.71	Color / clear film	3908.15	63	13.8
Adhesive mixing	Adhesive resin Coating solvent	151.50 859.56	Adhesive solution	1011.05	100	1.0
Adhesive coating	Color / clear film Adhesive solution	3908.15 1011.05	Color / clear film w adhesive	3978.91	81	4.3
Lamination	TPO film Color / clear film w adhesive	2326.93 3978.91	ISF film (jumbo)	5990.14	95	9.7
Strip / slit / inspect	In mold surfacing film	5991.04	ISF film (roll)	4463.35	75	13.9
Die cutting	ISF film (roll)	4463.35	ISF die cut parts	4017.01	90	N/A
TOTAL		44846.74		35955.79	80	

Mixing and milling operations for the clear coat, color coat, and adhesive has a material efficiency close to 100% because these operations involve combining input materials. Film lamination also has a very high material efficiency (95%) followed by die cutting (90%) and adhesive coating (81%). Extrusion and strip/slit/inspect stage operations each have a material efficiency of 75%. Clear coating has the lowest material efficiency (52%), while color coating has a material efficiency of 63%. These low efficiencies are the result of solvent loss in drying.

3.4.2 Application

Performance in the application phase encompasses material throughput, cycle time, equipment life and adhesion efficiency. A total of 207,254 die cut ISF pieces are required for 200,000 BSM parts. This results in an application efficiency of 96.5%. In going from die cutting to molding, each ISF component is reduced from 19.4 g to 12.2 g. This step has the lowest materials efficiency (37%) in the entire process. The cycle time is approximated from a 3M internal study on a similar BSM part of surface area 450 cm^2 (3M 1993). For this part, the cycle times with and without ISF are, 55 and 45 seconds. Therefore, the contribution of ISF to the cycle time is 10 seconds. The cycle time for the BSM part molding with ISF of surface area 639 cm^2 was reported to be 30 seconds (3M 1995). The cycle time data for the BSM part without this ISF was not available. A set up time of 2 hours and depreciation time of 4 years was obtained from a 3M internal study (3M 1993).

3.4.3 Use

In the use phase, performance is associated with the ability of ISF to remain functional in extreme operating environments as well as aesthetically appealing throughout the vehicle's operating life. Use phase performance data were determined by OEM performance specifications. Table 3-11 illustrates the performance specifications of Chrysler, Ford and GM.

Table 3-11. OEM Performance Specifications of ISF During Use

Category	OEM	Test name	Performance Requirements
Weather resistance	Chrysler	463PB-34-01 463PB-22-01	No peeling, cracking, loss of adhesion, discoloration or other detrimental effect for the following conditions: QUV-1000 hrs, weatherometer-240 hrs, fadeometer - 240 hrs; no cracking, checking or film failure when exposed in Florida 5 degree south for 3 months and then subjected to 10 test cycles.
	Ford	SAE J1545 FLIM BI 160-01 SAE J 1960	After the following exposures the part must meet the requirements: 24 months Florida, 5 deg south, Xenon arc weatherometer, 2500 kJ / m^2
	GM	GM 9163P	No indication of deterioration, embrittlement, delamination, objectionable shrinkage, blistering, haziness or color or gloss change. 2% or less shrinkage following Florida and Arizona exposure, materials should be exposed to 300000 langleys exposure oriented 45 deg facing south in Arizona and 5 deg facing south in Florida; exposure to cycle A
Humidity resistance	Chrysler	463PB-9-01	There shall be no blistering, whitening or loss of adhesion between strata which is greater than 0.8 mm from the scribed lines
Chemical resistance	Chrysler	463PB-6-01, 7-0, and 8-01	Acid , solvent and water and soap resistance
	Ford	FLIM BI 155-01 FLIM BI 113-01	Resistance to waxing and dewaxing; water, soap, underbody coating spotting, brake fluid (1 hr.), 10% H_2SO_4 by weight (4 hr.), albumin in DI water, honey, 0.75% $CaSO_4$, transmission fluid, motor oil and grease, windshield washer fluid, cleaners, removers and fuel
	GM	GM 9501 P	Gasoline, windshield washer solvent and detergent resistance
Heat resist.	Chrysler	463PB-36-01	Discoloration less than specified level
	Ford		No change in appearance (warpage, deformation, cracks, delamination or other failure) when subjected to an oven maintained at 80 +/- 2° C for 7 days; evaluate after conditioning at 23 +/- 2° C
Impact resistance	Chrysler	463PB-19-01	No loss of adhesion, flaking, or chipping on initial impact; adhesion loss on aged impact shall be less than 0.8 mm and on cold impact to 2.3 mm
	Ford	FLIM BO151-01	No shattering or breaking for drop ball method 2
Hardness	Chrysler	463PB-37-01	Hardness standards for standard baked enamel, acid catalyst enamel and double baked enamel
	Ford		Subject the material to a temperature of -40 +/-2° C for 15 minutes and 70 +/- 2° C for 5 minutes; evaluate after conditioning at 23 +/- 2° C
Polishing	Chrysler	463PB-34-01	Satisfactory polishing performance such as ease of sanding, freedom from scaling, ease of removing sand scratches and minimal color change after polishing
Overspray blistering	Chrysler	463PB-9-01	No blistering, lifting, dulling, or loss of adhesion in the oversprayed area
Chip resist.	Ford	SAE J400	Stone shot resistance
Appearance	Chrysler	463PB-38-01, 11-01 & 12-01	Distinctness of image (DOI) - no significant detrimental effect on DOI after 10 days of aging; gloss; no fogging for the coating
	Ford	FLIM BI 109-01 FLIM BI 110-01	Color, gloss and surface finish
	GM	GM 9220P	Color, pattern and gloss
Adhesion	Chrysler	463PB-15-01	No adhesion loss between paint strata > 0.8 mm from scribed lines
	Ford	FLIM BI 106-01	Flaking less than 5%
	GM	PSTC 1	Minimum bond strength of 350 N / m

4. Results and Discussion

In this chapter, the methodology described in Chapter 3 is used to evaluate environmental and cost metrics for the 3M in-mold surfacing film. Only environmental and cost results are discussed in detail here because the film must meet all performance parameters described in Chapter 3 prior to production.

4.1 Environmental Metrics

Results of the streamlined life cycle inventory analysis are summarized in Table 4-1, and discussed in the following sections.

Table 4-1. Total life cycle inventory results for ISF on a BSM part

Energy Consumption	11.8 MJ
Solid Waste	0.06 kg
Airborne Emissions	
CO2	553 g
CO	12.9 g
HC	4.1 g
NOx	3.3 g
Particulates	0.8 g
SOx	2.5 g
Waterborne Emissions	
BOD	0.02 g
COD	0.08 g
Suspended Solids	0.07 g
Dissolved Solids	1.9 g
Metals	0.04 g

4.1.1 Energy

Figure 4-1 shows life cycle primary energy for ISF applied to one prototype BSM part. The use phase accounts for about 57% of total life cycle energy, followed by material production (27%), manufacturing (14.5%) and application (1.5%). Cleaning energy comprised of about 36% of the use phase energy, the remaining 64% can be attributed to fuel energy consumption for transportation of the ISF over the vehicle life (160,900 km). Retirement energy is negligible compared to other life cycle stages. Production of the coating solvent results in about 52% of the manufacturing energy.

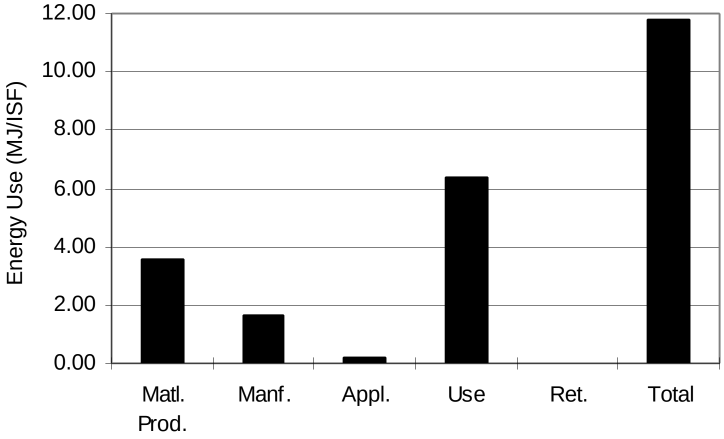

Figure 4-1. ISF life cycle energy by stage

As Figure 4-2 shows, the material production stage is dominated (56% of the total material production energy) by TPO, which constitutes 41% of the mass of materials processed in that stage. A majority of the energy required for ISF manufacturing goes into the color (31%) and clear (35%) coating processes.

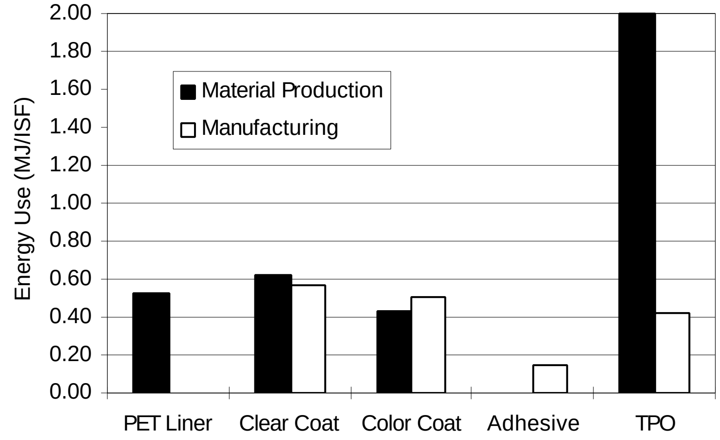

Figure 4-2. Material production and manufacturing energy for each coating layer of ISF (None of the energy consumed in the manufacture of ISF is attributed to the PET liner; Material production energy use for the adhesive is not known, and is assumed to be negligible).

4.1.2 Solid waste

Figure 4-3 illustrates the life cycle solid waste associated with ISF. A total of 62 g of solid waste is generated per ISF for one prototype BSM part. No single stage produces a majority of the life cycle solid waste. The manufacturing and use phases account for 31% and 29% of the waste, respectively. A majority of the use phase solid waste comes from the generation of electricity for washing the surface of the ISF. This analysis assumed that ISF is disposed of in a landfill at the end of its useful life. Solid waste from the disposal of the end-of-life film contributes 19% of the total life cycle solid waste.

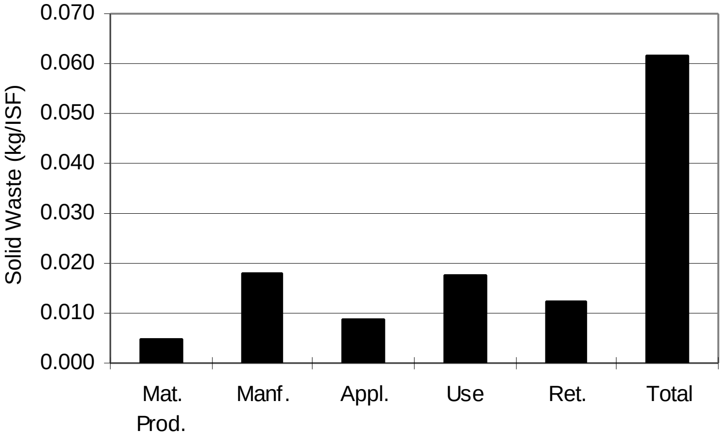

Figure 4-3. Life cycle solid waste by stage for ISF

4.1.3 Material Efficiency

A considerable amount of scrap is generated during manufacturing and application of ISF. During manufacturing, about 47% of input solid material is lost as scrap. During application, about 40% of the film is lost as trimming and yield loss. Material efficiency of the ISF is defined as follows:

$$h_o = \text{Overall material efficiency} = \frac{\text{Mass of molded ISF output}}{\text{Mass of material input}} = h_m \times h_a \qquad (4.1)$$

where,

$$h_a = \text{Application efficiency} = \frac{\text{Mass of molded ISF output}}{\text{Mass of ISF die cut}} \qquad (4.2)$$

and

$$h_m = \text{Manufacturing efficiency} = \frac{\text{Mass of ISF die cut}}{\text{Mass of material input}} \qquad (4.3)$$

Considering solid resins as input materials, $\eta_a = 0.6$ and $\eta_m = 0.53$, the overall material efficiency (η_o) of the ISF is calculated to be 32%. If coating solvents are included in the input materials, the manufacturing efficiency (η_m) is 31% and the overall material efficiency is 19%.

4.1.4 Air Emissions

Air emissions evaluated over the life cycle are CO_2, CO, HC, NO_x, Particulates and SO_2. Figure 4-4 shows that 581 g of airborne CO_2 emissions are produced over the life cycle of the ISF. A majority (66%) of life cycle CO_2 emissions occur during the use phase, 61% of these result from the contribution of the ISF to the fuel consumption of the vehicle. The remaining 39% of CO_2 emissions in the use phase result from the generation of electricity used for washing. The manufacturing phase contributes approximately 10% of the life cycle CO_2 emissions. Most of the manufacturing emissions result from the oxidation of solvents in the thermal oxidizers during coating operations. Thermal oxidizers have a destruction efficiency of 98% for hydrocarbons.

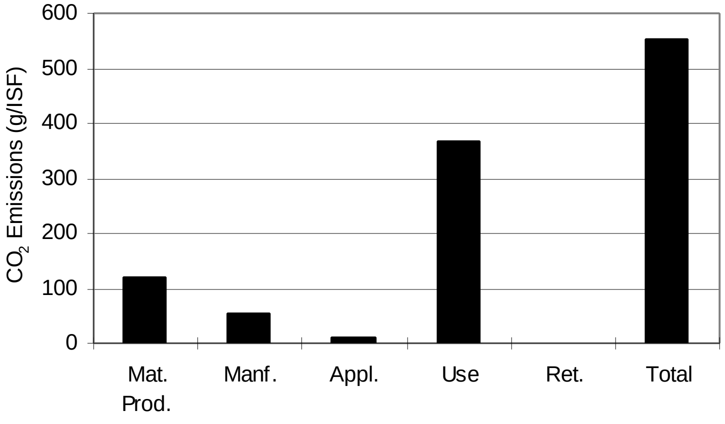

Figure 4-4. ISF life cycle CO_2 emissions by stage

Figure 4-5 illustrates the life cycle emissions of non CO_2 pollutants. Air emissions result from the material production, manufacturing, use and retirement stages. In the manufacturing stage, air emissions include emissions from thermal oxidizers and emissions from energy use. Use phase air emissions comprise both combustion and precombustion gasoline wastes and electricity production emissions related to car washing. Hydrocarbon emissions from the manufacturing phase (33% of which come from thermal oxidizer emissions) comprise 26% of the total life cycle hydrocarbon emissions. In comparison, the use phase contributes 59% of the total life cycle hydrocarbon emissions. In the retirement stage, only energy production emissions were evaluated.

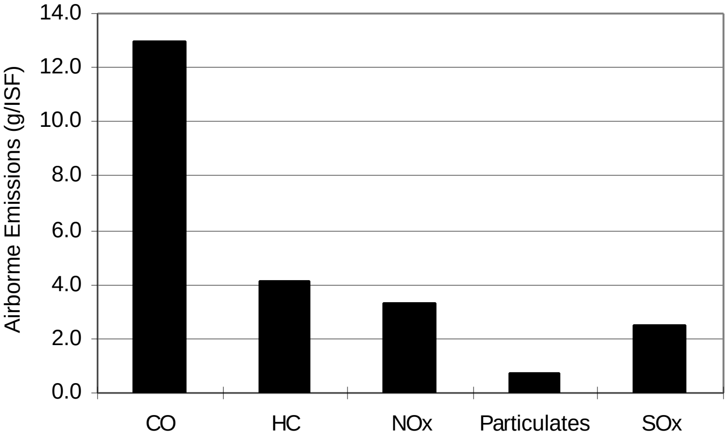

Figure 4-5. Airborne Emissions for the ISF total life cycle

4.1.5 Water Effluents

Life cycle water effluents of ISF are shown in Figure 4-6. Dissolved solids are the major (1.911 g/ISF) water effluents. The dominance of dissolved solids is due to the high levels released during petroleum processing (80.9 lb./1000 gal processed (Franklin Associates 1992)). Petroleum processing and other energy systems are the major source for all life cycle waterborne effluents.

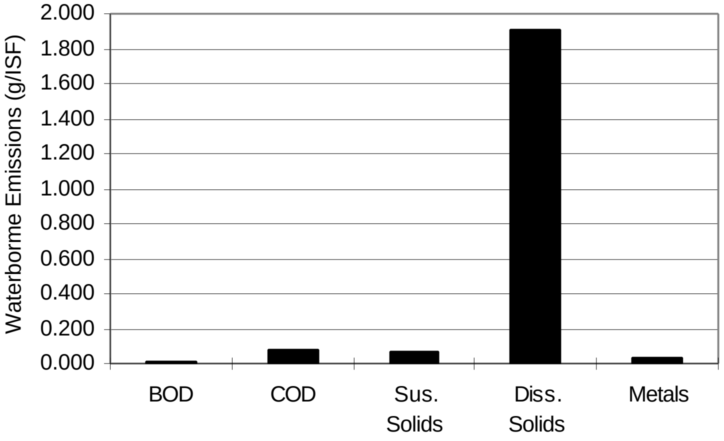

Figure 4-6. ISF total life cycle water effluents.

4.2 Cost Metrics

Figure 4-7 shows that the life cycle cost for ISF on one prototype BSM part is $1.68. This cost is distributed differently over the life cycle stages. Material costs were accounted for as part of the manufacturing costs and are not shown in Figure 4-7. Manufacturing cost, which comprises 82% of total life cycle cost, was estimated from 3M's internal source (3M 1996). Application cost per ISF is about 10 cents and the use cost per ISF is about 21 cents. The cost for ISF retirement was estimated to be less than one cent. This life cycle cost analysis did not address external costs not reflected in the market system or hidden costs not accurately allocated by 3M's internal accounting system. A total cost assessment (White, Becker, and Goldstein 1992) of the ISF was not conducted.

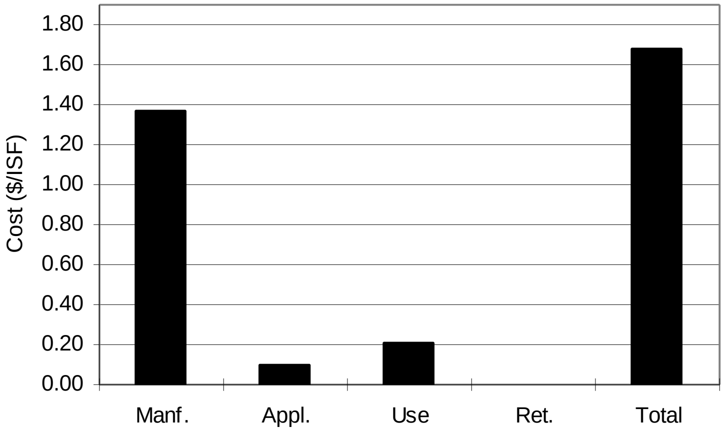

Figure 4-7. ISF Life Cycle Cost

5. Design Evaluation and Conclusions

The life cycle design framework was applied to in-mold surfacing film (ISF) applied on body side molded (BSM) parts. The methodology and results presented in Chapters 3 and 4 highlighted some key implications of ISF use. These are summarized in this chapter. These conclusions can be used for design evaluation and decision making related to the 3M ISF.

It is clear that a change from traditional painting methods to ISF results in a shift in environmental burdens. The major environmental burden for the ISF occurs during manufacturing, while environmental burdens for painting are concentrated in the application stage. In the case of BSM parts, this means that the film manufacturer (3M) is responsible for managing burdens previously generated by the tier one supplier.

The life cycle environmental burden of ISF may be overstated, because the TPO layer in the film is essentially integrated into the BSM part. A proportional reduction in the thickness of the BSM mold would result in a painted BSM part and an ISF coated BSM part having essentially the same weight and dimension. To optimize the system, different molds must be used for BSM parts that are to be painted and BSM parts that receive in-mold film. This will reduce the amount of BSM raw material required for a finished part, which would in turn reduce the burdens associated with ISF coated parts relative to painted parts

Drying ovens for clear, color and adhesive coating operations account for 94% of primary manufacturing energy. The heating of dilution air accounts for 91% of the total drying oven energy use. Increasing the efficiency of the drying process will reduce ISF life cycle energy use, but gains are limited because manufacturing accounts for only 14% of the total life cycle energy.

Disposal of the PET liner, during manufacturing, accounts for 10% of the total life cycle solid waste (35% of manufacturing solid waste) for ISF. Reusing the PET liner is one potential method of reducing the total life cycle solid waste of ISF. For example, if the PET liner were reused once, the ISF life cycle solid waste would be reduced by 5%; correspondingly, if the liner were reused twice, the total solid waste would be reduced by an additional 2%. This implies that the greatest proportional benefit is realized in the first reuse of the PET liner. Using the PET liner more than once presents a tradeoff in terms of solid waste reduction in manufacturing. The reason behind this is that frictional, tensile, and normal stresses during rolling operations, as well as tensile and compressive forces during wetting and drying operations degrade the surface properties of the PET liner with repeated reuses. Therefore, as the PET liner is reused more and more, the number of off-spec film parts is likely to increase, causing more material loss from rejected parts. Therefore, this research study indicates that the greatest reduction in solid waste is gained when the PET liner is reused once, unless its surface properties can be maintained with repeated reuses.

Die cutting, yield, and trimming losses combined account for 16% of the ISF life cycle solid waste. At the time of this study ISF was still in its infancy and production had not yet begun. It is believed that once in production experience will lead to increased manufacturing efficiency and a reduction in the total life cycle solid waste.

The overall material efficiency of the ISF (as calculated using equation 4.1), assuming only solid resins are considered input materials, is 32%. If both solids and coating solvents are included as input materials the overall material efficiency is 19%. In both cases the application material efficiency (equation 4.2) is 60%. It would be noteworthy to compare this data with transfer efficiency for paint. Transfer efficiency is defined as the ratio of the mass of solid coating deposited to the mass of solid coating used (Joseph 1993). Typical transfer efficiency for airless spray used in automotive painting is 40% (Joseph 1993). However, the transfer efficiency can vary from less than 20% for small parts to over 80% for very large parts. In the application stage, the film has higher transfer efficiency than paint. However, it is expected that manufacturing material efficiency for paint would be substantially higher than film because film manufacturing requires PET liner and die cut trimming waste. A holistic comparison of the material efficiencies of ISF and paint is not possible without more detailed study of the traditional paint life cycle.

The life cycle cost analysis indicated that manufacturing accounts for 82% of the ISF total life cycle cost. This leads to a relatively high product cost for ISF. The product cost of the film will probably be higher than that of paint, but application cost is expected to be lower. Thus to make a fair comparison, the total product and application cost must be taken into considerations for both film and paint. Film may not be competitive with paint when only the initial costs are considered, however, lower application costs could mean that total coated part costs for the two systems are comparable.

The most critical metric for paint film design is material efficiency in manufacturing and application. An increase in efficiency in these two stages will reduce life cycle energy, solid waste, air emissions, and water effluents. The most obvious way to increase material efficiency is to reuse the PET liner at least once. Additional gains can be achieved by optimizing die cut pieces to the mold dimensions.

Another potential method for reducing the life cycle burdens associated with ISF is the use of water based clear coat and color coat solutions. The current mineral spirit based system accounts for approximately 52% of the manufacturing energy use, most of which can be attributed to the embodied energy in the petroleum derived solvents. A water based coating system would require minimal energy for solvent production. However, water based clear coat and color coats may result in increased energy use by the drying ovens.

This study contributed to the project team's understanding of the total life cycle environmental burdens related to in-mold surfacing film. The sources of the major burdens were also identified and opportunities for environmental improvement were discussed. This project represents an initiative taken by an automotive supplier to improve vehicle design and performance through innovation in a single vehicle part. This effort will hopefully lead to the application of life cycle systems thinking to other parts and components, as well as higher level vehicle systems (e.g. vehicle body subsystem) in the future.

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Appendix A

Acronyms Table

APC	American Plastics Council
APME	Association of Plastics Manufacturers in Europe
ASR	Automotive Shredder Residue
BOD	Biological Oxygen Demand
BSM	Body Side Molded
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
EPDM	Ethylene Propylene Diene Monomer
HC	Hydrocarbon
HDPE	High Density Polyethylene
ISF	In-Mold Surfacing Film
LCD	Life Cycle Design
NO_X	Nitrogen Oxides
NSWMA	National Solid Waste Management Association
OEM	Original Equipment Manufacturer
PET	Polyethylene Terepthalate
PVDF	Poly (Vinylidene Fluoride)
TPO	Thermoplastic Polyolefin
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

Appendix B

ENVIRONMENTAL MATRIX

ENVIRONMENTAL MATRIX: PRODUCTION OF ISF MATERIAL

Mass of materials processed		**lb/TDCP**	**kg/ISF**		
	TPO resin	6.84E+03	0.0150		TDCP = Total number of die cut parts
	PVDF resin	4.37E+03	0.0096		=207254
	Acrylic resin	1.46E+03	0.0032		
	PET liner	2.94E+03	0.0064		
	Adhesive resin	3.34E+02	0.0007		
	Pigment	7.55E+02	0.0017		
	TOTAL resin		0.0349		• Material production energy
Energy					does not include pigment production
	(primary energy)	**MJ / kg**	**MJ/ISF**		energy and solvent production energy.
			3.57E+00		
Air emissions		**kg/kg**	**kg/ISF**		
	CO2		1.21E-01		
	CO		1.87E-04		
	NMHC		6.23E-04		
	CH4				
	Kerosene				
	NOx		6.01E-04		
	Particulates		1.72E-04		
	SO2		6.37E-04		
	Aldehydes				
	Ammonia				
	Lead				
	Other				
Solid waste	Solid waste		5.00E-04		
Water effluents					
	BOD		1.00E-05		
	COD		4.40E-05		
	Suspended solids		5.70E-05		
	Dissolved solids		2.60E-05		
	Metal ion		8.00E-06		
	Oil				
	Phenolic compounds				
	Sulfides				
	Acids				

ENVIRONMENTAL MATRIX : FILM MANUFACTURING

Energy					
Unit operation	**Type**	**MJ / kg**	**MJ / ISF**		**Data Source and Methodology**
- TPO film extrusion	1.1dE, electricity	6.57E-01	9.83E-03		**Proprietary data, 3M**
- mix / mill clear coat	1.1aE, electricity	2.00E-02	3.89E-04		• Energy in MJ / kg of film is calculated by
- clear coating	2.3E, gas oven	1.14E+01	2.97E-01		normalizing the energy of unit operations
- mix / mill color coat	1.1bE, electricity	2.35E-02	3.89E-04		by the total mass of ISF die cut film,
- color coating	3.3E, gas oven	8.47E+00	2.54E-01		i.e. 8856 lb or 4017 kg
- adhesive mixing	1.1cE, electricity	7.97E-02	3.89E-04		• Energy per ISF die cut film is obtained by
- adhesive coating	4.3E, gas oven	4.27E+00	1.01E-01		multiplying the energy density (MJ / kg) by the
- lamination	5.3E, electricity	6.20E-02	1.89E-03		mass of ISF die cut film
- strip / slit / inspect	6.5E, electricity	9.34E-02	2.70E-03		• The mass of ISF die cut film is obtained
	TOTAL energy, electricity		1.56E-02		by dividing the total mass of film (8856 lb)
	TOTAL energy, gas oven		6.52E-01		by the number of die cut parts (207254)
	Primary energy, electricity		4.87E-02		• The total mass of one die cut film is
	Primary energy, natl. gas		7.33E-01		0.04273 lb or 0.01938 kg
	Primary energy equivalent		7.82E-01		

Appendix B

Process waste					
Air emissions					
Unit operation	**Inlet oxidizer**	**kg / kg**	**kg / ISF**		
- clear coating	2.5P*, coating solvents	4.51E-01	1.17E-02		**Proprietary data, 3M**
- color coating	3.5P*, color coating	3.30E-01	9.91E-03		• Obtained using similar methodology as
- adhesive coating	4.5P*, coating solvents	1.75E-01	4.15E-03		explained above
	TOTAL air emissions	9.56E-01	2.57E-02		
	Outlet oxidizer				
	CO2		9.50E-04		
	HC		3.52E-04		
Film waste					
Unit operation	**Type**	**kg / kg**	**kg / ISF**		
- TPO film extrusion	1.4dPSW, TPO film	2.50E-01	3.74E-03		**Proprietary data, 3M**
- clear coating	2.6P*SW, PET liner				• kg of waste / kg of film is calculated by
	2.7PSW, clear coated PET	2.75E-02	7.11E-04		normalizing the waste of unit operations
- color coating	3.6PSW, clear coat film	8.82E-03	2.65E-04		by the total mass of ISF die cut film,
	3.7PSW, color / clear film	3.30E-02	9.91E-04		i.e. 8856 lb or 4017 kg
- adhesive coating	4.6PSW, color /clear film				
	4.7PSW, color / clear film w/ adhesive	1.65E-02	3.92E-04		• Waste per ISF die cut film is obtained by
- lamination	5.4PSW, TPO film				multiplying the kg of waste/kg of film
	5.5PSW, color /clear film w/adhesive				by the mass opf the film
	5.6PSW, laminated film	5.00E-02	1.52E-03		
- strip / slit / inspect	6.2P*SW, PET liner	1.83E-01	5.29E-03		
	6.3PSW, slitting/edge trim	3.10E-02	8.97E-04		
	6.4PSW, off-spec. film	4.08E-02	1.18E-03		
- die cutting	7.4PSW, cutting scrap	1.00E-01	2.15E-03		
	7.3PSW, yield loss				
	TOTAL film waste	7.41E-01	1.71E-02		
Water effluents					
Unit operation	**Type**	**kg / kg**	**kg / ISF**		
- mix / mill clear coat	1.5aP*LW, cleaning solvents	7.53E-03	1.47E-04		**Proprietary data, 3M**
- clear coating	2.8P*LW, cleaning solvents	1.10E-03	2.85E-05		• Obtained using similar methodology as
- mix / mill color coat	1.6bP*LW, cleaning solvents	8.88E-03	1.47E-04		explained above
- color coating	3.8P*LW, cleaning solvents	9.48E-04	2.85E-05		• 95% reclamation of cleaning solvents
- adhesive mixing	1.4cP*LW, cleaning solvents	3.01E-02	5.83E-04		were assumed.
- adhesive coating	4.8P*LW, cleaning solvents	1.20E-03	2.85E-05		
	TOTAL cleaning solvents	4.97E-02	9.61E-04		
	TOTAL water effluents	2.49E-03	4.81E-05		
Energy waste					
Unit operations	**Type**	**lb / 100 kWh**	**kg / ISF**		**Data Source and Methodology**
Air emissions	**Electricity**				
	CO2	1.53E+02	3.01E-03		• Obtained from [Franklin, 1992]
	CO	1.58E-01	3.09E-06		
	NMHC	1.41E-01	2.77E-06		
	CH4	9.00E-04	1.77E-08		
	Kerosene				
	NOx	6.99E-01	1.37E-05		
	Particulates	5.02E-01	9.86E-06		
	SO2	1.32E+00	2.59E-05		
	Aldehydes	1.00E-04	1.96E-09		
	Ammonia	1.00E-04	1.96E-09		
	Lead				
	Other	1.00E-04	1.96E-09		
Solid waste	Solid waste	1.84E+01	3.60E-04		

Appendix B

Water effluents					
	BOD	1.00E-04	1.96E-09		
	COD	3.00E-04	5.89E-09		
	Suspended solids	2.00E-04	3.93E-09		
	Dissolved solids	4.65E-02	9.13E-07		
	Metal ion	2.75E-02	5.40E-07		
	Oil	1.00E-04	1.96E-09		
	Phenolic compounds				
	Sulfides				
	Acids	1.10E-01	2.16E-06		
	Iron	8.24E-02	1.62E-06		
Air emissions	**Natural gas**	**kg / MJ**	**kg / ISF**		**Data Source and Methodology**
	CO2	5.27E-02	3.86E-02		
	CO	1.41E-04	1.03E-04		• Obtained from [Franklin, 1992]
	NMHC	6.33E-04	4.64E-04		
	CH4				
	Kerosene				
	NOx	8.19E-04	6.00E-04		
	Particulates	3.72E-06	2.73E-06		
	SO2	4.84E-06	3.55E-06		
	Aldehydes				
	Ammonia				
	Lead				
	Other				
Solid waste	Solid waste	5.58E-04	4.09E-04		
Water effluents					
	BOD				
	COD				
	Suspended solids				
	Dissolved solids	7.44E-04	5.45E-04		
	Metal ion				
	Oil				
	Phenolic compounds				
	Sulfides				
	Acids				
	Iron				
Mass of solvents	Solvents	kg / kg	kg / ISF		
	Mineral spirit		2.58E-02		
			l / ISF		
			0.0349		
Energy		MJ/l	MJ/ISF		Assume that 50% of energy from burning
		2.46E+01	8.57E-01		mineral spirits is recovered
Air emissions	**Gasoline**	**lb/1000 gal**	kg / ISF		Thus energy for mineral spirit includes
	Carbon dioxide	2.49E+03	1.04E-02		precombustion energy and 50% of the
	Carbon monoxide	1.13E+01	4.72E-05		combustion energy
	Hydrocarbon	5.43E+01	2.27E-04		
	Methane				
	Nitrogen oxide	3.47E+01	1.45E-04		
	Particulates	4.20E+00	1.75E-05		
	Sulfur dioxide	3.17E+01	1.32E-04		
	Aldehydes	4.00E-01	1.67E-06		
	Ammonia	4.00E-01	1.67E-06		
	Lead	3.00E-03	1.25E-08		
Solid waste	Solid waste	3.60E+01	1.50E-04		

Water effluents					
	BOD	4.00E-01	1.67E-06		
	COD	1.10E+00	4.60E-06		
	Suspeneded solids	6.00E-01	2.51E-06		
	Dissolved solids	8.09E+01	3.38E-04		
	Metal ion	1.00E-01	4.18E-07		
	Oil	2.00E-01	8.36E-07		
	Phenolic compounds	1.00E-01	4.18E-07		
	Sulfides	1.00E-01	4.18E-07		
	Acids	2.00E-01	8.36E-07		
TOTAL FILM INVENTORY: MANUFACTURING					
Energy			**MJ / ISF**		**Data source and methodology**
	Energy (primary)		1.64E+00		
Air emissions	Type		**kg / ISF**		• Obtained as the sum of process and
	CO2		5.30E-02		energy burden
	CO		1.54E-04		
	NMHC		1.05E-03		
	CH4		1.77E-08		
	Kerosene		0.00E+00		
	NOx		7.59E-04		
	Particulates		3.01E-05		
	SO2		1.62E-04		
	Aldehydes		1.67E-06		
	Ammonia		1.67E-06		
	Lead		1.25E-08		
	Other		1.96E-09		
Solid waste	Solid waste		1.81E-02		
Water effluents					
	BOD		1.67E-06		
	COD		4.60E-06		
	Suspended solids		2.51E-06		
	Dissolved solids		8.84E-04		
	Metal ion		9.58E-07		
	Oil		8.37E-07		
	Phenolic compounds		4.18E-07		
	Sulfides		4.18E-07		
	Acids		2.99E-06		
	Iron		1.62E-06		
	Cleaning solvents		4.81E-05		
ENVIRONMENTAL MATRIX : FILM APPLICATION					
Energy					
Unit operation	**Type**	**kW / kg**	**MJ / ISF**		**Data Source and Methodology**
		Neidermair	**3M**		
- molding, electricity	8.2E	7.50E+01	4.36E-02		• Energy value from [Neidermair,1993] is used
	Primary energy equivalent		1.36E-01		• Cycle time for 3M film = 30 sec
- transportation	diesel		4.38E-02		• 1000 mile distance manufacture->application
	primary energy equivalent		5.21E-02		• Energy consumption for diesel trucks
	TOTAL primary energy		1.88E-01		= 2.05 MJ/ton-mile
Process waste					
Solid waste					
Unit operation	**Type**	**kg / kg**	**kg / ISF**		
- molding	W25, edge trim	3.63E-01	7.03E-03		**Proprietary data, 3M**
	W26, yield loss	3.50E-02	6.78E-04		
	TOTAL solid waste		7.71E-03		

Appendix B

Energy waste					
Air emissions	Electricity				
	CO2	1.53E+02	8.43E-03		• Electricity waste are obtained
	CO	1.58E-01	8.65E-06		from [Franklin, 1994]
	NMHC	1.41E-01	7.74E-06		
	CH4	9.00E-04	4.94E-08		
	Kerosene				
	NOx	6.99E-01	3.84E-05		
	Particulates	5.02E-01	2.76E-05		
	SO2	1.32E+00	7.25E-05		
	Aldehydes	1.00E-04	5.49E-09		
	Ammonia	1.00E-04	5.49E-09		
	Lead				
	Other	1.00E-04	5.49E-09		
Solid waste	Solid waste	1.84E+01	1.01E-03		
Water effluents					
	BOD	1.00E-04	5.49E-09		
	COD	3.00E-04	1.65E-08		
	Suspended solids	2.00E-04	1.10E-08		
	Dissolved solids	4.65E-02	2.55E-06		
	Metal ion	2.75E-02	1.51E-06		
	Oil	1.00E-04	5.49E-09		
	Phenolic compounds				
	Sulfides				
	Acids	1.10E-01	6.04E-06		
	Iron	8.24E-02	4.53E-06		
Air emissions	**Diesel**	**kg / MJ**	**kg / ISF**		• Diesel wastes are obtained
	Carbon dioxide	6.62E-02	3.45E-03		from [Franklin, 1992]
	Carbon monoxide	5.75E-04	3.00E-05		
	Hydrocarbon	2.41E-04	1.26E-05		
	Nitrogen oxide	6.40E-04	3.34E-05		
	Particulates	8.89E-05	4.63E-06		
	Sulfur dioxide	1.78E-04	9.28E-06		
	Aldehydes	1.54E-05	8.03E-07		
	Ammonia	1.05E-06	5.47E-08		
	Lead	7.85E-09	4.09E-10		
	Other	3.05E-04	1.59E-05		
Solid waste	Solid waste	9.41E-05	4.91E-06		
Water effluents					
	BOD	1.05E-06	5.47E-08		
	COD	2.88E-06	1.50E-07		
	Suspeneded solids	1.57E-06	8.19E-08		
	Dissolved solids	2.12E-04	1.11E-05		
	Metal ion	2.62E-07	1.37E-08		
	Oil	5.23E-07	2.73E-08		
	Phenolic compounds	2.62E-07	1.37E-08		
	Sulfides	2.62E-07	1.37E-08		

Appendix B

TOTAL FILM INVENTORY: APPLICATION

Energy			**MJ / ISF**		**Data source and methodology**
	Energy (primary)		1.88E-01		
Air emissions	Type		**kg / ISF**		• Total waste is the sum of process and energy
	Carbon dioxide		1.19E-02		waste
	Carbon monoxide		3.86E-05		
	Hydrocarbon		2.03E-05		
	Methane		4.94E-08		
	Kerosene		0.00E+00		
	Nitrogen oxide		7.18E-05		
	Particulates		3.22E-05		
	Sulfur dioxide		8.18E-05		
	Aldehydes		8.08E-07		
	Ammonia		6.02E-08		
	Lead		4.09E-10		
	Other		1.59E-05		
Solid waste	Solid waste		8.72E-03		
Water effluents					
	BOD		6.02E-08		
	COD		1.67E-07		
	Suspeneded solids		9.28E-08		
	Dissolved solids		1.36E-05		
	Metal ion		1.52E-06		
	Oil		3.28E-08		
	Phenolic compounds		1.37E-08		
	Sulfides		1.37E-08		
	Acids		6.04E-06		
	Iron		4.53E-06		

ENVIRONMENTAL MATRIX : FILM USE

Mechanical washing					
Metrics	**Type**	**kWh / car**	**MJ / ISF**		**Data Source and Methodology**
Energy	Electricity	3.50	7.42E-01		• $35,000 electricity bill for 100,000 cars
					washed yearly
					• Thus, $0.35 electricity per car
	Primary energy equivalent		2.32		• Electricity rate $0.0995 / kWh
					• Thus, energy per car wash = 3.5 kWh
					• Energy/film=(energy/car)x(SA film/SA car)
					• SA car ~ 175 ft2
					• SA film = 61.8 in2
					[Light House washing, 1995]
Water used		**gallons / car**	**kg / film**		
	Soap water solution	75.00	283.91		• 75 gallons of soap water used per car
					[Light House washing, 1995]
Air emissions	Electricity				
	CO2	1.53E+02	1.43E-01		• Electricity wastes are obtained from
	CO	1.58E-01	1.47E-04		[Franklin, 1994]
	NMHC	1.41E-01	1.32E-04		
	CH4	9.00E-04	8.41E-07		
	Kerosene				
	NOx	6.99E-01	6.53E-04		
	Particulates	5.02E-01	4.69E-04		
	SO2	1.32E+00	1.23E-03		
	Aldehydes	1.00E-04	9.34E-08		
	Ammonia	1.00E-04	9.34E-08		
	Lead				
	Other	1.00E-04	9.34E-08		
Solid waste	Solid waste	1.84E+01	1.71E-02		

Appendix B

Water effluents					
	BOD	1.00E-04	9.34E-08		
	COD	3.00E-04	2.80E-07		
	Suspended solids	2.00E-04	1.87E-07		
	Dissolved solids	4.65E-02	4.34E-05		
	Metal ion	2.75E-02	2.57E-05		
	Oil	1.00E-04	9.34E-08		
	Phenolic compounds				
	Sulfides				
	Acids	1.10E-01	1.03E-04		
	Iron	8.24E-02	7.70E-05		
Driving: fuel consumption					
Metrics	**Type**	**volume/ISF**	**MJ / ISF**		**Data Source and Methodology**
Energy	Gasoline	**lit / ISF**			• Contribution of film to vehicle weight
	(primary energy)	0.10	4.09		• Assume average 1995 vehicle
		gal / ISF			• Test weight of vehicle = 3200 lb
		0.03			• Life of film on vehicle = 100,000 miles
					• Fuel economy = 21.6 mpg=10.89 l / 100 km
					• 10% weight reduction =
					6.6% fuel consumption reduction
Combustion waste			**kg / ISF**		• 1 l gasoline = 42.03 MJ (comb+precomb)
Air emissions	CO2		1.94E-01		• Combustion tail pipe emissions data:
	CO		1.23E-02		CO2 = 362.87 g / mile
	HC		1.65E-03		CO=23 g / mile
	NOx		8.54E-04		HC=3.1 g / mile
Precombustion waste					NOx=1.6 g / mile
Air emissions	**Gasoline**	**lb/1000 gal**	**kg / ISF**		[US EPA, 1995][AAMA, 1995]
	Carbon dioxide	2.49E+03	2.90E-02		• Emissions data are obtained from
	Carbon monoxide	1.13E+01	1.32E-04		following correlation: E, kg / ISF =
	Hydrocarbon	5.43E+01	6.32E-04		(E,lb/1000 gal)*(0.45359/1000)*gallons
	Methane				
	Nitrogen oxide	3.47E+01	4.04E-04		
	Particulates	4.20E+00	4.89E-05		
	Sulfur dioxide	3.17E+01	3.69E-04		
	Aldehydes	4.00E-01	4.66E-06		
	Ammonia	4.00E-01	4.66E-06		
	Lead	3.00E-03	3.49E-08		
Solid waste	Solid waste	3.60E+01	4.19E-04		
Water effluents					
	BOD	4.00E-01	4.66E-06		
	COD	1.10E+00	1.28E-05		
	Suspeneded solids	6.00E-01	6.99E-06		
	Dissolved solids	8.09E+01	9.42E-04		
	Metal ion	1.00E-01	1.16E-06		
	Oil	2.00E-01	2.33E-06		
	Phenolic compounds	1.00E-01	1.16E-06		
	Sulfides	1.00E-01	1.16E-06		
	Acids	2.00E-01	2.33E-06		

Appendix B

TOTAL FILM USE INVENTORY : USE PHASE

Energy			**MJ / ISF**		**Data source and methodology**
	Energy (primary)		**6.40**		
Air emissions			**kg / ISF**		• Total waste is the sum of process and
	Carbon dioxide		3.66E-01		energy waste
	Carbon monoxide		1.25E-02		
	Hydrocarbon		2.42E-03		
	Methane		8.41E-07		
	Nitrogen oxide		1.91E-03		
	Particulates		5.18E-04		
	Sulfur dioxide		1.60E-03		
	Aldehydes		4.75E-06		
	Ammonia		4.75E-06		
	Lead		3.49E-08		
Solid waste	Solid waste		1.76E-02		
Water effluents					
	BOD		4.75E-06		
	COD		1.31E-05		
	Suspeneded solids		7.18E-06		
	Dissolved solids		9.86E-04		
	Metal ion		2.69E-05		
	Oil		2.42E-06		
	Phenolic compounds		1.16E-06		
	Sulfides		1.16E-06		
	Acids		1.05E-04		

ENVIRONMENTAL MATRIX : FILM RETIREMENT

Energy					
Unit operation	**Type**	**MJ / kg**	**MJ / ISF**		**Data Source and Methodology**
Shredding	electricity	9.70E-02	1.18E-03		• Shredding energy = 0.097 MJ/kg
					[Texas Shredder, 1995]
TOTAL	electricity	9.70E-02	1.18E-03		
Primary energy, electricity			3.70E-03		
- Transportation	diesel	4.52E-01	5.51E-03		• Shredder to Separator = 100 miles
Primary energy, diesel			6.56E-03		• Separator to landfill = 100 miles
TOTAL primary energy	electricity+diesel		1.03E-02		• Total transportation distance = 200 miles
					[Franklin, 1992]
Air emissions	Electricity				
	CO2	1.53E+02	2.29E-04		• Electricity wastes are obtained from
	CO	1.58E-01	2.35E-07		[Franklin, 1992]
	NMHC	1.41E-01	2.10E-07		
	CH4	9.00E-04	1.34E-09		
	Kerosene				
	NOx	6.99E-01	1.04E-06		
	Particulates	5.02E-01	7.49E-07		
	SO2	1.32E+00	1.97E-06		
	Aldehydes	1.00E-04	1.49E-10		
	Ammonia	1.00E-04	1.49E-10		
	Lead				
	Other	1.00E-04	1.49E-10		
Solid waste	Solid waste	1.84E+01	2.74E-05		
Water effluents					
	BOD	1.00E-04	1.49E-10		
	COD	3.00E-04	4.47E-10		
	Suspended solids	2.00E-04	2.98E-10		
	Dissolved solids	4.65E-02	6.93E-08		
	Metal ion	2.75E-02	4.10E-08		
	Oil	1.00E-04	1.49E-10		
	Phenolic compounds				
	Sulfides				
	Acids	1.10E-01	1.64E-07		
	Iron	8.24E-02	1.23E-07		

Appendix B

ENVIRONMENTAL MATRIX : FILM RETIREMENT					
Air emissions	Diesel	**kg / MJ**	**kg / film**		
	Carbon dioxide	6.62E-02	4.35E-04		
	Carbon monoxide	5.75E-04	3.77E-06		• Diesel wastes are obtained from
	Hydrocarbon	2.41E-04	1.58E-06		[Franklin, 1992]
	Nitrogen oxide	6.40E-04	4.20E-06		
	Particulates	8.89E-05	5.84E-07		
	Sulfur dioxide	1.78E-04	1.17E-06		
	Aldehydes	1.54E-05	1.01E-07		
	Ammonia	1.05E-06	6.89E-09		
	Lead	7.85E-09	5.15E-11		
	Other	3.05E-04	2.00E-06		
Solid waste	Solid waste	9.41E-05	6.18E-07		
Water effluents					
	BOD	1.05E-06	6.89E-09		
	COD	2.88E-06	1.89E-08		
	Suspended solids	1.57E-06	1.03E-08		
	Dissolved solids	2.12E-04	1.39E-06		
	Metal ion	2.62E-07	1.72E-09		
	Oil	5.23E-07	3.43E-09		
	Phenolic compounds	2.62E-07	1.72E-09		
	Sulfides	2.62E-07	1.72E-09		

TOTAL FILM INVENTORY: RETIREMENT-LANDFILL DISPOSAL

Energy			**MJ/ISF**		**Data source and methodology**
	Energy (primary)		1.03E-02		
Air emissions	(electricity+diesel)		**kg/ISF**		• Total environmental burden is the
	Carbon dioxide		6.63E-04		sum of process and energy related burden
	Carbon monoxide		4.01E-06		
	Hydrocarbon		1.79E-06		
	Methane		1.34E-09		
	Kerosene		0.00E+00		
	Nitrogen oxide		5.24E-06		
	Particulates		1.33E-06		
	Sulfur dioxide		3.14E-06		
	Aldehydes		1.01E-07		
	Ammonia		7.04E-09		
	Lead		5.15E-11		
	Other		2.00E-06		
Solid waste	Solid waste		1.22E-02		
Water effluents					
	BOD		7.04E-09		
	COD		1.94E-08		
	Suspended solids		1.06E-08		
	Dissolved solids		1.46E-06		
	Metal ion		4.27E-08		
	Oil		3.58E-09		
	Phenolic compounds		1.72E-09		
	Sulfides		1.72E-09		

Appendix B

COST MATRIX

COST MATRIX : STAKEHOLDER TIER 1, Application

Process	Metric	Paint Film Data			Data Source and Methodology
	Cost	**$/film**	**$ /film**		Assumption:
					• Molding cost is proportional to cycle time
					• Cycle time = 10 sec
- Tooling Cost			0.07		
- Machine Cost			0.01		
- Labor Cost			0.02		• Total solid waste =
- credit for selling					Edge trimming waste + yield loss waste
TOTAL tier 1 cost			0.10		

COST MATRIX : STAKEHOLDER USER

Process	Metric	Paint Film Data			Data Source and Methodology
	Cost		$ /film		• 3 times per year -8 years at 3$ a wash
BSM washing cost			1.76E-01		• Yearly electricity $35000,100000 cars/year,
- Car washing	Electricity cost		2.63E+01		• Surface area of the car 175 ft^2
- Car washing	Water cost		2.25E+01		• Water cost 30cents/car
- Car washing	Soap cost		1.05E+01		• $14000 Soap/year
- Car washing	Labor cost		1.31E+01		• Wage $7 dollar/hour
Fuel cost for driving			3.00E-02		• Wash cycle1.5 minutes for160 feet tunnel
					Typical tunnel varies 100 to 160 feet
					• Data obtained from [Lighthouse car wash, 1995]
TOTAL use cost			2.06E-01		• Fuel cost = $1.17/gallon

COST MATRIX : END OF LIFE MANAGERS

Process	Metric	Paint Film Data			Data Source and Methodology
	Cost		**$ /film**		
- Transportation cost $0.12/ton-mile	Transportation		3.23E-04		• 200 mile transport
- Shredder processing cost $33.5/hulk	Shredding		2.87E-04		• Retirement costs are from [APC, 1994]
- Landfill cost $30.25/ton	Tipping Landfill		4.07E-04		[NSWMA, 1995] Natl. average cost
TOTAL retirment cost			1.02E-03		

CUMULATIVE LIFE CYCLE COST

Manufacturing	3M	$1.37			
Application	Tier 1	$0.10			
Use	User	$0.21			
Retirement	ELV manager	$0.00			
TOTAL		$1.67			

Appendix C

(8) UNIT OPERATION - MOLDING	
• Length of BSM part (in.)	43
• Assumption 1: 50,000 4-door vehicles	
• (9.1P) ISF molded parts	200,000
• Covered surface area of BSM (sq. in.)	61.8
• Assumption 2: Use widest dimension of BSM of 1.75" as basis for rectangular die cut parts	
• Assumption 3: Allow 0.25" per side and 0.5" per end excess material for molding of rectangular die cut part	
• Surface area (sq. in.) of die cut parts (2.25" x 44")	99
• Assumption 4: Molding yield (%) of die cut parts	96.5
• (8.1P) Number of ISF die cut parts	207,254
• (8.3P) Edge trim (sq. in.)	7,440,000
• (8.4P) Yield loss (sq. in.)	718,135
(7) UNIT OPERATION - DIE CUTTING	
• Assumption 5: Film weed (%) (nesting)	90
• (8.1P) ISF die cut parts (cu.in.)	201,078
• ISF, converted roll (cu.in.)	223,420
• (7.3PSW) Film weed (cu.in.)	22,342
• (7.4PSW) Yield loss	negligible
(6) UNIT OPERATION - STRIP/SLIT/INSPECT	
• (7.1P) ISF, converted roll (cu.in.)	223,420
- (7.1P) ISF, converted roll (sq. yds.)	17,591
- (7.1P) ISF, converted roll (lyds)	13,193 (x 48")
• Assumption 6: 95% process yield + edge trim	
- Input film width (in.)	50
- Output film width (in.)	48
• (6.1P) ISF, jumbo (cu.in.)	244,978
- (6.1P) ISF, jumbo (sq.yds.)	19,288
- (6.1P) ISF, jumbo (lyds)	13,888 (x 50")
• (6.2P*SW) PET casting liner (lyds)	13888 (x 50")
• (6.3PSW) Slitting/edge trim (cu.in.)	9,309
• (6.4PSW) Quality waste, 5% yield loss (cu.in.)	12,249
(5) UNIT OPERATION - LAMINATION	
• (6.1P) ISF, jumbo (lyds)	13,988 (x 50")
• Assumption 7: 95% process yield	
• (5.1P) TPO film (lyds)	14,619 (x 50")
• (5.2P) Color/clear film w/adhesive (lyds)	14,619 (x 50")
• (5.4PSW) TPO film	negligible
• (5.5PSW) Color/clear film w/adhesive	negligible
• (5.6PSW) Laminated film (lyds)	731 (x 50")
(1d) UNIT OPERATION - TPO FILM EXTRUSION	
• (5.1P) TPO film (cu.in.)	157,880
- (5.1P) TPO film (lyds)	14,619 (x 50")
• Assumption 8: 75% resin and film yield	
• (1.2dP) TPO resin (cu.in.)	210,507
• (1.4dPSW) TPO film (cu.in.)	52,627
(4) UNIT OPERATION - ADHESIVE COATING	
• (5.2P) Color/clear film w/adhesive (lyds)	14,619 (x 50")

Appendix C

• Assumption 9: 98% film and solution yield		
• (4.2P) Color/clear film (lyds)	14,917 (x 50")	
• (4.7PSW) Color/clear film w/adhesive (lyds)	298 (x 50")	
• (4.8P*LW) Cleaning solvents, MEK (gallons)	2	
- (4.8P*LW) Cleaning solvents, MEK (lbs)	13	
• (4.6PSW) Color/clear film	negligible	
• Assumption 10: Coating solution, 15% solids		
• Material required for solid adhesive layer (cu.in.)	8,055	
- Material required for solid adhesive layer (lbs)	334	
• (4.1P) Adhesive solution (lbs)	2,229	
• Mineral spirits required (lbs)	1,895	
(1c) UNIT OPERATION - ADHESIVE MIXING		
• (4.1P) Adhesive solution (lbs)	2,229	
• (1.2cP) Adhesive resin (lbs)	334	
• (1.3cP*) Solvent, mineral spirits (lbs)	1,895	
• (1.4cP*LW) Cleaning solvents, MEK (gallons)	10	
- (1.4cP*LW) Cleaning solvents, MEK (lbs)	67	
(3) UNIT OPERATION - COLOR COATING		
• (4.2P) Color/clear film (lyds)	14,917 (x 50")	
• Assumption 11: 95% film and solution yield		
• Assumption 12: Clear coat film is 51" wide, coated width of the color coat is 50"		
• (3.2P) Clear coat film (lyds)	15,702 (x 51")	
• (3.6PSW) Clear coat film	15,702 (x 1")	
• (3.7PSW) Color/clear film (lyds)	785	
• (3.8P*LW) Cleaning solvents, MEK (gallons)	2	
- (3.8P*LW) Cleaning solvents, MEK (lbs)	13	
• Assumption 13: Color solution 40% solids		
• Material required for solid color layer (lbs)	3,019	
• (3.1P) Color coat solution (lbs)	7,548	
• Mineral spirit required (lbs)	4,529	
(2) UNIT OPERATION - CLEAR COATING		
• Clear coat film (lyds)	15702 (x 51")	
• Assumption 14: 95% film and solution yield		
• (2.2P) PET casting liner (lyds)	16,528 (x 51")	
• (2.8P*LW) Cleaning solvents (gallons)	2	
- (2.8P*LW) cleaning solvents (lbs)	13	
• (2.7PSW) Clear coated PET (lyds)	826 (x 51")	
• (2.6P*SW) PET casting liner	negligible	
• Assumption 15: Clear solution 40% solids		
• Material required for solid clear layer (%)	3,560	
• (2.1P) Clear coat solution (lbs)	8,901	
• Mineral spirits required	5,341	
(1a) UNIT OPERATION - MIX/MILL CLEAR COAT		
• (2.1P) Clear coat solution (lbs)	8,901	
• (1.4aP*) Solvent (lbs)	5,341	
• (1.3aP) Acrylic resin (lbs)	890	
• (1.2aP) PVDF resin (lbs)	2,670	
• (1.5aP*LW) Cleaning solvents (gallons)	10	

- (1.5aP*LW) Cleaning solvents (lbs)	67	
(1b) UNIT OPERATION - MIX/MILL COLOR COAT		
• (3.1P) Color coat solution (lbs)	7,548	
• (1.4bP*) Solvent (lbs)	4,529	
• (1.5bP) Pigment (lbs)	755	
• (1.3bP) Acrylic resin (lbs)	566	
• (1.2bP) PVDF resin (lbs)	1,698	
• (1.6bP*LW) Cleaning solvents (gallons)	10	
- (1.6bP*LW) Cleaning solvents (lbs)	67	

Appendix D. Life Cycle Design Framework

Primary elements of the life cycle design framework are (Keoleian, Koch, and Menerey 1995):

- Product life cycle system
- Goals
- Principles
- Life cycle management
- Development process

Product Life Cycle System

Life cycle design and management requires an accurate definition of the product system, including both spatial and temporal boundaries. The product system can be organized by life cycle stages and product system components. Life cycle stages include materials production, manufacturing and assembly, use and service, and end-of-life management as shown in Figure D-1.

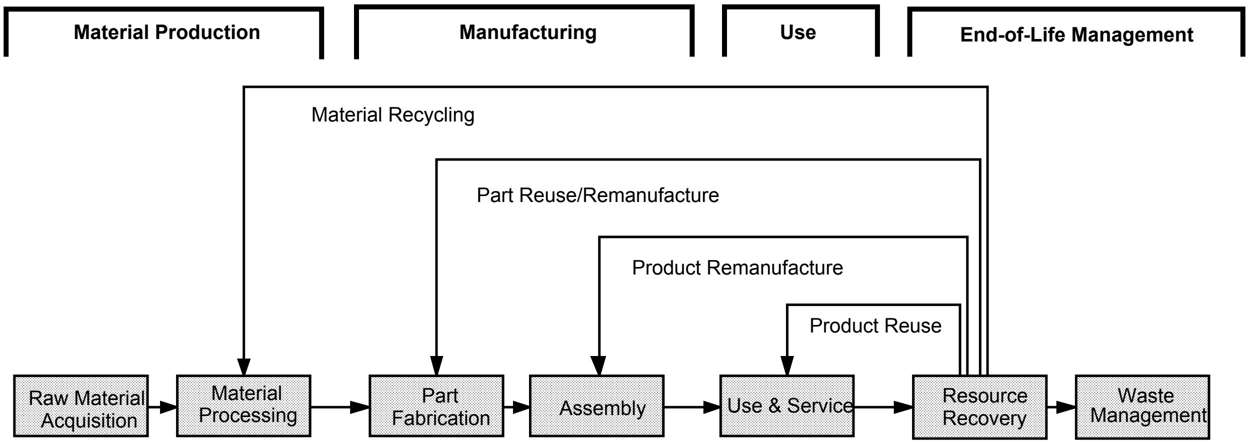

Figure D-1. Product Life Cycle System

Product, process and distribution components further characterize the product system for each life cycle stage as shown in Figures D-2 and D-3. This organization in contrast to LCA convention can better accommodate product and process design functions. The time frame for a design project ranges between a short term horizon that may emphasize incremental improvements in the product system or a long range view that explores next generation designs.

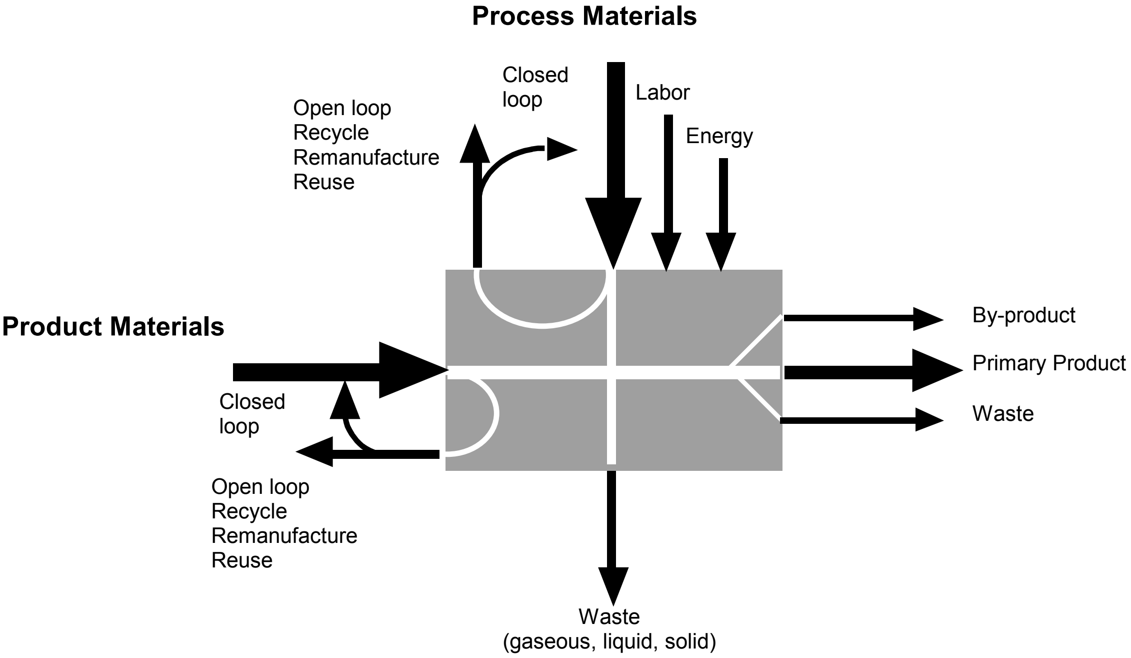

Figure D-2. Flow Diagram Template for Life Cycle Subsystem

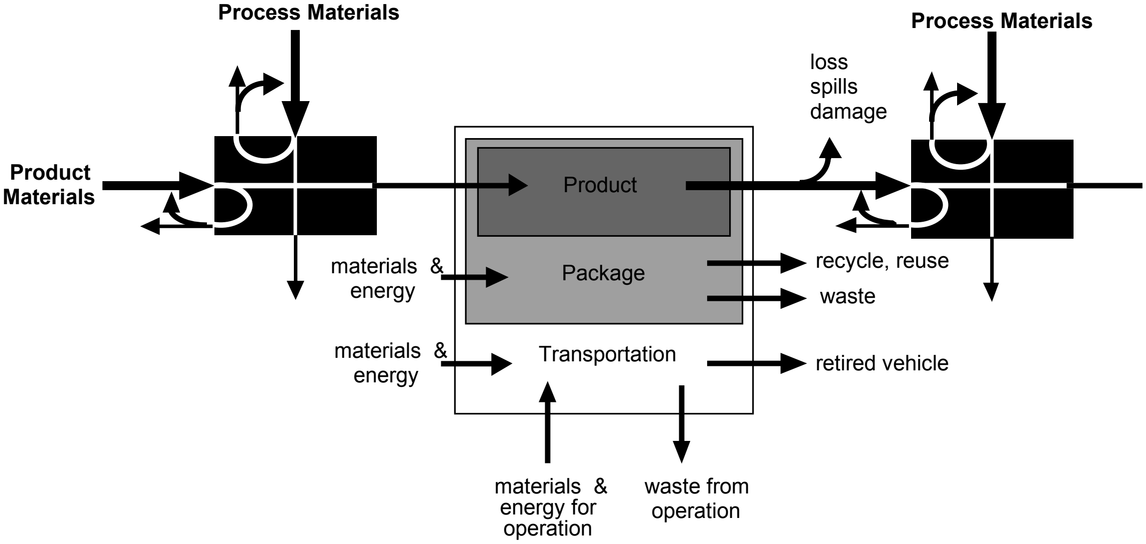

Figure D-3. Distribution Component Flow Diagram

Goals

The broad goal of life cycle design is to design and management products that are ecologically and economically sustainable. Necessary conditions for sustainability include: sustainable resource use (conserve resources, minimize depletion of non-renewable resources, use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. All of these conditions are interrelated and highly complementary. Economic sustainability requires that the product system meet basic cost, performance, legal and cultural criteria.

The specific environmental goal of life cycle design is to minimize the aggregate life cycle environmental burdens and impacts associated with a product system. Environmental burden include resource inputs and waste outputs which can be classified into impact categories according to life cycle impact assessment methods. (Guinée et al. 1993; SETAC 1993a; Weitz and Warren 1993) General impact categories include resource depletion and ecological and human health effects. No universally accepted method for aggregating impacts is available.

Principles

There are three main themes for guiding environmental improvement of product systems in life cycle design: *systems analysis* of the product life cycle; *multicriteria analysis* of environmental, performance, cost, and legal requirements and issues (see specification of requirements section); and *multistakeholder participation and cross-functional teamwork* throughout the design process. The following principles relating to each of these themes have been derived from our empirical research. Many of these principles of life cycle design are already considered best design practice.

Systems Analysis

Systems analysis focuses on understanding the behavior of individual components of a system and the relationships between the collection of components that constitute the entire system. In addition the relationships between the system under study and higher order/larger scale systems should be analyzed. Both time and space dimensions must be addressed.

1. The product life cycle is a logical system for product management and design because it encompasses the total physical flow of product materials through the economy.
2. Successful design initiatives should establish clear system boundaries for analysis. The scope of a design activity can be restricted to smaller system boundaries such as individual life cycle stages or process steps, but this will inherently limit the opportunities for improvement.
3. Studying the relationship between product materials and related process/distribution components - systems that transform/transport the product material along the life cycle - is critical towards improving the product system design.
4. The breadth of system boundaries depends on the vision of the organization; less responsible firms do not address environmental issues much beyond the manufacturing domain whereas more ecologically responsible corporations will address the full product life cycle. The broader perspective may not yield immediate economic benefits but should lead to long term success.

Multiobjective Analysis

A successful design will satisfy multiple objectives including performance, cost, legal and environmental requirements. Many design requirements will overlap and reinforce each other while others conflict and limit design possibilities.

1. Specifying design requirements for both guiding improvement and evaluating alternatives is a critical to efficient product design and management. Clearly defined requirements that are both internal and external to an organization reduce uncertainty in decision making.
2. Understanding the interactions and conflicts between performance, cost, legal, and environmental requirements serves to highlight opportunities as well as vulnerabilities. In some cases, environmentally preferable designs may not be adopted because they do not show a direct cost advantage to the manufacturer, are not supported by regulations, or do not demonstrate performance advantages.
3. Unless more specific guidance can be offered through well-established corporate environmental policies and goals or national environmental policies or goals design teams must rely on. their personal knowledge and experience to make complex tradeoffs. Tradeoffs often exist among environmental criteria, such as minimizing waste, energy and emissions as well as between environmental, cost, performance and legal criteria. Judgment is ultimately required to weight and rank criteria.

Multistakeholder Participation

The stakeholders that control the life cycle of a product can be considered part of a virtual organization. Some stakeholders share a common goal for enhancing the overall economic success of the product, while maximizing their own individual profit. Minimizing life cycle burdens, however, may not be a priority. Identifying the actors that control the life cycle of a product and their interests is a first step in achieving better life cycle management of a product.

1. Harmonizing the often diverse interests of stakeholders (suppliers, manufacturers, customers, waste managers, regulators, investors) into a product design that is technically, economically, socially and ecologically feasible/optimal is a fundamental challenge of design.
2. Partnerships are helpful in implementing changes that affect more than one stage or activity in the life cycle.
3. Initiatives to reduce life cycle environmental burdens will be limited in their effectiveness by the degree to which stakeholders recognize this a common goal for product design and management.

Life Cycle Management

Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system. Key stakeholders are users and the public, policy makers/regulators, material and waste processors, suppliers, manufacturers, investors/shareholders, the service industry, and insurers. The design and management decisions made by the manufacturer of the end-use product may have the greatest influence over the life cycle environmental profile of a product system. It is useful to distinguish between environmental management by internal and external stakeholders. A major challenge for product manufacturers is responding to the diverse interests of external stakeholder groups.

The environmental management system (EMS) within a corporation is the organizations structure of responsibilities, policies, practices, and resources for addressing environmental issues. Several voluntary EMS standards and guidelines have been developed (BS7750, ISO 14,001, GEMI). Although EMS activities have emphasized proactive measures in addition to regulatory compliance, traditionally these systems have only addressed the manufacturing domain of the corporation (Marguglio 1991) and did not cover end-of-life management or material acquisition processing stages.

Life Cycle Development Process

The product development process varies widely depending on the type of product and company and the design management organization within a company. In general, however, most development processes incorporate the key activities shown in Figure D-4. For life cycle design this process takes place within the context of sustainable development and life cycle management.

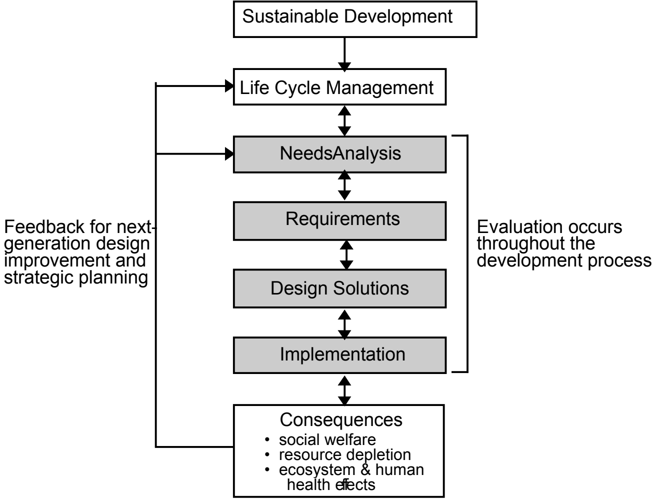

Figure D-4. Life Cycle Development Process

The life cycle design framework emphasizes three important design activities: specifying requirements to guide design improvements, selecting strategies for reducing environmental burden, and evaluating design alternatives.

The specification of requirements to guide design and management decisions is a fundamental activity for any design initiative (Gause and Weinberg 1989). Techniques for assisting development teams in establishing environmental design criteria have not been widely implemented. A multilayer requirements matrix has been developed as a tool to identify, organize, and evaluate environmental, cost, performance, legal and cultural design criteria (Keoleian and Menerey 1993; Keoleian and Menerey 1994; Keoleian, Koch, and Menerey 1995). DFX or Design for X strategies (Gatenby and Foo 1990) such as design for recyclability, disassembly, and remanufacturability have been more widely promoted. Life cycle assessment tools for evaluating product systems (Vigon et al. 1993; Heijungs et al. 1992; Guinée, de Haes, and Huppes 1993; SETAC 1993b; SETAC 1991) have probably received the most attention in the last two decades. The practical application of LCA tools by product development engineers, however, is limited (Keoleian and Menerey 1994; White and Shapiro 1993). It is the refinement and application of these three types of design and analysis tools that will lead to the most effective implementation of life cycle design and DFE.

Specification of Requirements

Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives into successful designs. Environmental requirements should focus on minimizing natural resource consumption, energy consumption, waste generation, and human health risks as well as promoting the sustainability of ecosystems. A primary tool of life cycle design is the multicriteria matrices for specifying requirements shown in Figure D-5. Other tools for guiding designers include design checklists and guidelines.

The matrices shown in Figure D-5 allow product development teams to study the interactions and tradeoffs between environmental, cost, performance and legal requirements. Each matrix is organized by life cycle stages and product system components. Elements can then be described and tracked in as much detail as necessary. Requirements can include qualitative criteria as well as quantitative metrics.

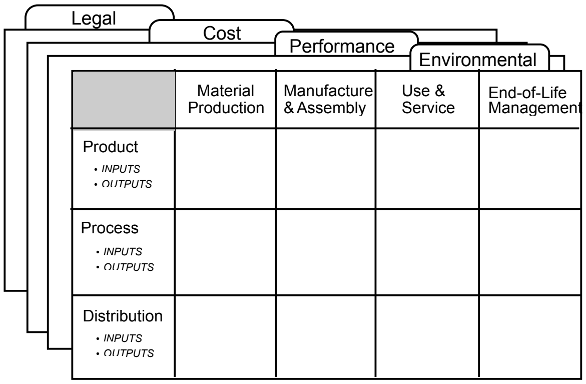

Figure D-5. Multicriteria Requirements Matrix

Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements is a major challenge of life cycle design and management. General strategies for fulfilling environmental requirements are product oriented (product life extension, remanufacturability, adaptability, serviceability, and reusability); material oriented (recycling, substitution, dematerialization); process oriented; and distribution oriented (optimize transportation and packaging). An explanation of each strategy is provided in the *Life Cycle Design Guidance Manual* (Keoleian and Menerey 1993).

Design Evaluation

Analysis and evaluation are required throughout the product development process as well as during strategic planning by management. Approaches for design evaluation range from comprehensive analysis tools such as life cycle assessment (LCA) to the use of single environmental metrics. LCA tools can be broadly classified as SETAC related methodologies (Vigon et al. 1993; Heijungs et al. 1992; SETAC 1993b), semi-quantitative matrix evaluation tools (Graedel, Allenby, and Comrie 1995; Allenby 1991), and other techniques such as the Environmental Priority Strategies (EPS) system (FSI 1993). If environmental requirements for the product system are well specified, design alternatives can be checked directly against these requirements. Several tools for environmental accounting and cost analysis are also emerging (US EPA 1989) (White, Becker, and Goldstein 1992) (US EPA 1995) (SNL 1993). Cost analysis for product development is often the most influential tool guiding decision making. Key issues of environmental accounting are: measuring environmental costs, allocating environmental costs to specific cost centers, and internalizing environmental costs.

In principle, LCA represents the most accurate tool for design evaluation in life cycle design and DFE. Many methodological problems, however, currently limit LCA's applicability to design (Keoleian 1994). Costs to conduct a LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles (Sullivan and Ehrenfeld 1992) (White and Shapiro 1993). Although significant progress has been made towards standardizing life cycle inventory analysis, (SETAC 1991) (Heijungs et al. 1992) (Vigon et al. 1993) (SETAC 1993b) results can still vary significantly (Svensson 1992) (Curran 1993). Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and data availability and quality issues.

Incommensurable data presents another major challenge to LCA and other environmental analysis tools. A large complex set of inventory data can be overwhelming to designers and managers who often lack environmental training and expertise. The problem of evaluating environmental data remains inherently complicated when impacts are expressed in different measuring units (e.g., kilojoules, cancer risks, or kilograms of solid waste). Furthermore, impact assessment models vary widely in complexity and uncertainty.

Even if much better assessment tools existed, LCA has inherent limitations in design and management, because the complete set of environmental effects associated with a product system can not be evaluated until a design has been specified in detail (Keoleian 1994). This limitation indicates the importance for requirements matrices, checklists and design guidelines which can be implemented during conceptual design phases.

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Appendix E

Life Cycle Design Reports

The following list provides reference information for other LCD reports available from the National Technical Information Service (**NTIS:** www.ntis.gov or 800-553-6847) or the **EPA**'s National Service Center for Environmental Publications (www.epa.gov/ncepi or 800-490-9198).

Report Title		Report Number	Available From
Life Cycle Design Guidance Manual: Environmental Requirements and the Product System			
	full report		
		EPA/600/R-92/226	EPA
	summary report	PB 93-164507AS	NTIS
		EPA/600/SR-92/226	EPA
Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal			
	full report		
		EPA/600/R-95/107	EPA
Life Cycle Design of Amorphous Silicon Photovoltaic Modules			
	full report	PB 97-193106	NTIS
	summary report	EPA 600/SR-97/081	EPA
Life Cycle Design of Milk and Juice Packaging Systems			
	full report		
	summary report	PB 98-100423	NTIS
		EPA 600/SR-97/082	EPA
Life Cycle Design of a Fuel Tank			
	full report	PB 98-447856INZ	NTIS
	summary report	EPA 600/SR-97/118	EPA
Life Cycle Design of Air Intake Manifolds: Phase I: 2.0 L Ford Contour Air Intake Manifold	full report	EPA 600/R-99/023	EPA
Life Cycle Design of Air Intake Manifolds: Phase II:.Lower Plenum of the 5.4 L F-250 Air Intake Manifold, Including Recycling Scenarios	full report	EPA 600/R-01/059	EPA

Additional Information

Additional information on life cycle design publications and research can be found on our website (http://css.snre.umich.edu) under the heading *Research*.