EPA/600/R-99/023
February 1999

Life Cycle Design of Air Intake Manifolds

Gregory A. Keoleian and Krishnendu Kar

Gregory A. Keoleian, Project Director

Center for Sustainable Systems
School of Natural Resources and Environment
University of Michigan
Dana Bldg. 430 E. University
Ann Arbor, MI 48109-1115

Phase I: 2.0 L Ford Contour Air Intake Manifold

Project Leaders
Wayne Koppe, Powertrain Environmental Engineering
Phillip Lawerence, Environmental Quality Office
John Sullivan, Scientific Research Laboratory
Mia Costic, Scientific Research Laboratory

Ford Motor Company
Dearborn, Michigan

Assistance Agreement # CR 822998-01-0

Project Officer
Kenneth Stone

National Risk Management Research Laboratory
Office of Research and Development
US Environmental Protection Agency
Cincinnati, OH 45268

1. Notice

This publication was developed under Cooperative Agreement No. 822998-01-0 awarded by the U.S. Environmental Protection Agency. EPA made comments and suggestions on the document intended to improve the scientific analysis and technical accuracy of the document. However, the views expressed in this document are those of the University of Michigan and EPA does not endorse any products or commercial services mentioned in this publication.

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)”.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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, a cross functional team at Ford, and the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency. The project team applied the life cycle design methodology to the design analysis of three alternative air intake manifolds: a sand cast aluminum, brazed aluminum tubular, and nylon composite. The design analysis included a life cycle inventory analysis, environmental regulatory/policy analysis, life cycle cost analysis and a product/process performance analysis. These analyses highlighted significant tradeoffs among alternatives.

The life cycle inventory indicated that the sand cast aluminum manifold consumed the most life cycle energy (1798 MJ) compared to the tubular brazed aluminum (1131 MJ) and nylon composite (928 MJ) manifolds. The manifold contribution to the vehicle fuel consumption dominated the total life cycle energy consumption. The cast aluminum manifold generated the least life cycle solid waste of 218 kg per manifold, whereas the brazed aluminum tubular and nylon composite manifolds generated comparable quantities of 418 kg and 391 kg, respectively. Red mud generated during alumina production accounted for 70% of the total life cycle solid waste for the brazed tubular manifold while the nylon component of auto shredder residue was responsible for 53% of the total waste for the nylon composite manifold.

The life cycle cost analysis estimated Ford manufacturing costs, customer gasoline costs, and end-of-life management costs. The nylon composite manifold had the highest estimated manufacturing costs which were about $10 greater than the two aluminum manifold designs. The use phase gasoline costs to the customer over the lifetime of the vehicle, however, for the composite and the aluminum brazed tubular manifolds were about $6 and $5 cheaper, respectively, compared to the cast aluminum manifold. End-of-life management credits of $4.10 for the cast aluminum manifold and $2.30 for the brazed aluminum tubular manifold would accrue to Ford under automobile take back legislation. In addition, 20 performance requirements were used to evaluate each design alternative.

This report was 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 1, 1994 to May 31, 1997 and work was completed June 1, 1997.

IV. Contents

IV. Contents (continued)

V. Acknowledgment

We wish to thank Ford Project Team for collaborating with us on this project. The cross functional team included members from Powertrain Engineering, Scientific Research Laboratory, Materials Engineering, Casting Operations,and Environmental and Safety Engineering. Wayne Koppe, Powertrain Engineering, was a key champion and team leader of this project. Other members of his staff including Fred Heiby, Cymel Clavon, David Florkey, and Mitch Baghdoian played an important role data collection for this project. John Sullivan and Mia Costic from the Scientific Research Lab provided valuable technical support throughout the project. Mia Costic played a major role in the data collection phase of the life cycle inventory analysis. Gerald Czadzeck, intake manifold design engineer, provided performance and cost information and knowlegde of the product development process. Philip Lawrence from the Environmental Quality Office provided key corporate environmental policy information and was instrumental in initiating this project. Bernd Gottselig contributed information regarding recycling and other end-of life issues as well European data. George Good was helpful in gathering data on aluminum casting operations. Mike Johnson assisted in providing the corelation between mass reduction and fuel consumption.

In addition we wish to thank Ken Martchek from Alcoa and William Haaf and David Doyen from DuPont for providing material production and manfuacturing inventory data, and for reviewing sections of this report.

Robb Beal and David Spitzley from the National Pollution Prevention Center assisted in the data analysis phase of this project.

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 U.S .Environmental Protection Agency collaborated with the University of Michigan to develop the life cycle design framework [1][2][3]. This framework is documented in two publications: *Life Cycle Design Guidance* Manual [1] and the *Life Cycle Design Framework and Demonstration Projects* [3].

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 [4] and AlliedSignal investigated heavy duty truck oil filters [5]. 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 Ford Motor Company project that investigated the design of air intake manifolds. An overview of the life cycle design framework is provided in Appendix B of this document. A list of Project Reports from other life cycle design demonstration projects is also provided in Appendix C.

1.2 Project Description

This pilot project with Ford Motor Company applied the life cycle design (LCD) framework and tools to the design of powertrain parts. The project began November 1, 1995. A cross-functional core team from Ford Motor Company, shown in the following list, participated with University of Michigan project team members.

Division	**Team Member**
Powertrain Operations (engine)	Wayne Koppe
Powertrain Operations (engine)	Gerald Czadzeck
Powertrain Operations (engine)	David Florkey
Powertrain Operations (engine)	Fred Heiby
Powertrain Operations (engine)	Cymel Clavon
Powertrain Operations (engine)	Mitch Baghdoian
Environmental Quality Office	Phil Lawrence
Scientific Research Laboratory	John Sullivan
Scientific Research Laboratory	Mia Costic
Materials Engineering	Norm Adamowicz
Casting Operations	George Good
Advanced Vehicle Technology	Steve Church
Advanced Vehicle Technology	Mike Johnson
Environmental & Safety Engineering	Susan Day
Environmental & Safety Engineering	Bruce Hoover
Environmental & Safety Engineering	Bernd Gottselig

Besides the Ford core team, Ken Martchek from Alcoa and David Doyen and Bill Haaf from DuPont participated as external stakeholders by providing valuable data and comments.

1.3 Product Selection

This project is a comparative assessment of the following three types of intake manifolds for a 2.0 l, 1995 Contour engine: composite, sand-cast aluminum and multi-tube brazed aluminum . Existing and prototype manifolds were selected for this project based on the availability of data and relative comparability of engine size. At present, 1995 Contours/Mystiques are equipped with a nylon composite intake manifold. Aluminum manifolds, which can be manufactured by several different processes including sand casting, permanent mold casting, die casting, lost foam process and multi-tube brazing, were considered as alternatives.

Recently, Ford of Europe along with Stuttgart University in Germany performed a life cycle inventory analysis of sand-cast aluminum and composite intake manifolds [6]. The project team used this study as an initial source for inventory data. Sand casting was selected by Ford’s manifold design group as an alternative process for manufacturing a prototype aluminum manifold as a backup for the composite manifold. The multi-tube brazed manifold is currently used in a low volume production for the 1.9 l Ford Escort. This manifold was not considered as an alternative for the composite manifold by Ford’s manifold design group because of its manufacturing complexity and higher manufacturing cost compared to the sand-cast manifold.

1.4 Goal and Significance

The goal of this project is to develop simplified life cycle environmental and cost metrics that can be used by Ford’s design engineer for product design. Such a simplified tool will help Ford’s management to develop guidelines for integrating environmental requirements into product design, that incorporates corporate environmental policies, specifications and guidelines. The results of this project will be used by Ford’s DFE training program as a case study to demonstrate the applicability of life cycle design tools to product design engineers.

1.5 Objectives

The automobile sector in recent years has seen a significant increase in the demand for glass reinforced polyamide 66 as a result of OEMs switching to nylon air intake manifold from the traditional aluminum manifold.

The objective of this project is to integrate the life cycle design framework and tools with existing product design tools for alternative intake manifolds.

Specific objectives of this project include:

- Compare nylon and aluminum intake manifolds based on multicriteria matrices
- Evaluate key criteria and metrics for material selection
- Facilitate cross-functional team interaction and networking to (effectively) use the internal resources within Ford
- Demonstrate the value of LCD as an engineering design method to management and note barriers associated with its use

2. Systems Analysis

2.1 Scope

This study considers the entire life cycle of an air intake manifold from materials production through end-of-life management. Comparisons are made between the 2.74 kg composite manifold currently used in 2.0 l 1995 Ford Contours, a 6.5 kg sand-cast backup (used as a prototype for the composite manifold) and a 3.43 kg multi-tube brazed manifold currently used in the 1.9 l Escort engine. For uniform baseline comparison, the 1.9 l Escort manifold (3.43 kg) is converted to a 2.0 l equivalent by multiplying the weight ratio of the two engines (1.05). The converted 2.0 l multi-tube brazed manifold weighs 3.62 kg.

2.2 Product Composition

The composite manifold consists of 33% glass reinforced nylon (PA6.6 GF33), brass (UNS C36000) inserts and stainless steel (304 steel) EGR tube. UNS C36000 brass, which is more commonly known as 360 brass, consists of 77% copper, 20% zinc and 3% lead. 360 brass has a high scrap content and is usually made at the extruder's facility. In this analysis, 360 brass is assumed to be composed of 99 % scrap [7]. 304 stainless steel is made from, 100% scrap [8].

The sand-cast aluminum manifold consists of 100% secondary aluminum. The multi-tube brazed aluminum manifold consists of 4 bent, extruded tubes and an extruded air collection chamber screwed to the motor block through a sand-cast flange. The sand-cast flange section comprises 65% of the manifold weight; the extruded sections account for the remaining 35%. Material for the sand-cast flange section consists of 100% secondary aluminum, whereas the extruded sections are assumed to be made of 70% primary and 30% secondary aluminum [9] which is a representative mix of extruded parts. Thus, overall the multi-tube brazed manifold consists of 24.5% primary aluminum and 75.5% secondary aluminum. Product composition by mass for each manifold is shown in Figure 2-1.

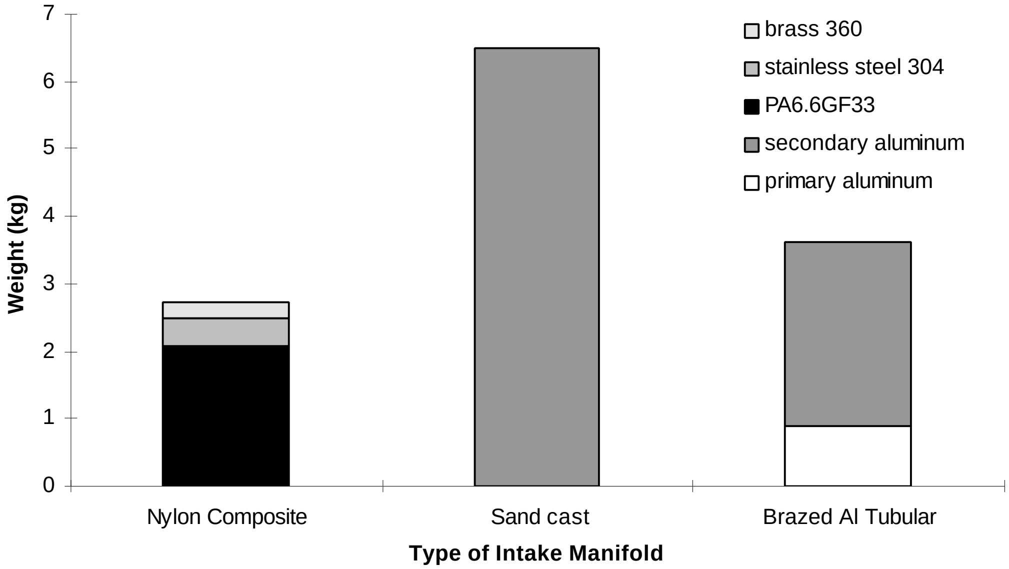

Figure 2-1. Product Composition of Intake Manifolds

2.3 Boundaries and Assumptions

Table 2.1. Boundaries and Assumptions for LCD of Intake Manifolds

LC Stage	Composite	Sand-Cast Aluminum	Multi-Tube Brazed Aluminum
Material production	• Mass of product materials calculated by material balance for nylon, brass and stainless steel shown in Figures 2-2 through 2-4. • Assumed nylon resin from virgin & in-house scrap; primary copper, zinc and lead; and stainless steel from scrap. • Tin-bismuth alloy production is not included.	• Mass of product materials is calculated by a material balance model for secondary aluminum as shown in Figure 2-5. • Secondary aluminum production involves conversion of separated scrap into ingot. • Production of sand and salt are not included.	• Mass of product materials is calculated by a material balance model for primary and secondary aluminum, shown in Figure 2-6. • Primary and secondary aluminum production are included. • Production of sand, salt and aluminum-silica filler material are not included.
Manufacturing	• Lost core process includes inductive melting of the 30 kg tin-bismuth core and average energy for injection molding of 2.13 kg of PA6.6 GF33 resin for the 2.07 kg manifold. • 0.1% scrap rate is assumed as testing loss for each manifold; start-up scrap is calculated to be 2.67% for the nylon resin. • 15% scrap rate for extrusion and stamping is assumed. • Stainless steel EGR tube production includes billet from electric arc furnace, rolling, extrusion and stamping. Scale loss during rolling excluded. • Brass fittings production includes melting/mixing scrap with virgin materials to produce billet, extrusion and cutting. • 95% recycling efficiency is assumed for all in-house scrap. • The average efficiency factor for natural gas is 0.89. Electricity production efficiency is 0.32 [10].	• Energy for the production of a sand-cast aluminum manifold is obtained from for 7.557 kg of molten aluminum. • The overall scrap includes production scrap (5.67%) and machining scrap (10%). • The crucible furnaces for sand casting are assumed to be gas fired. The average efficiency factor for natural gas is 0.89. • Process wastes for sand casting are filter dust, sand and salt slag. Mass of filter dust, salt slag and sand per kg of manifold is about 0.046 kg, 0.45 kg and 1.85 kg. • 95% recycling efficiency is assumed for in-house scrap.	• Energy for the production of the sand-cast flange is obtained from 2.731 kg of molten aluminum. • Production energy for the extruded part is obtained from for 1.537 kg of billet consisting of 70% primary and 30% secondary aluminum. • Overall scrap includes machining scrap (10%), extrusion scrap (15%) and production scrap (5.67%). • Process waste and emissions for sand casting are evaluated, while process waste for extrusion is neglected. • 95% closed-loop recycling efficiency is assumed for all in-house scrap. • The average efficiency factor for natural gas is 0.89. Electricity production efficiency is 0.32 [10].
Use	• The contribution of manifold weight to use phase energy consumption for a 1995 Contour over an assumed 150,000 mile life was calculated by assuming that weight is linearly proportional to fuel consumption without considering secondary weight. • Contour tail pipe emissions data obtained from EPA emission testing laboratory. • Manifold contribution to vehicle emissions is obtained by assuming that emissions are proportional to vehicle mass; the allocation rule is accurate for CO_2 but for other gases the relationship is non-linear.		
Retirement	• During the dismantling stage, it is assumed that no manifolds are recovered and sold for reuse • Mass balances for materials in the retirement stage are shown in Figures 2-2 through 2-6.. • An overall 5% loss in recovering all metals (aluminum, brass and stainless steel) is assumed in the shredding and separation stage; breakdown of the loss between shredding and separation is unknown. • The base case scenario assumes 100% nylon disposed to landfill.		

2.4 Product System for Composite Manifolds

The product system for the composite manifold consists of the following life cycle stages:

Material production

Nylon
- Production of polyamide 6.6 (PA6.6)
- Production of glass fibers
- Compounding of PA6.6 with 33% glass fiber to produce PA6.6 GF 33 pellet

Brass
- Production of primary copper, zinc and lead
- Mixing of 1% primary metals with 99% brass scrap to produce 360 brass billet

Stainless steel
- Production of stainless steel slab in an electric arc furnace from 100% scrap

Manufacturing

- Lost core process of manufacturing the nylon manifold
- Extrusion and machining to manufacture the brass inserts
- Rolling, stamping, extrusion and brazing to manufacture the stainless steel EGR tube
- Assembly of the manifold

Use

- Use of the manifold

Retirement

- Recycling of metal parts
- Disposal of nylon and unrecoverable shredded metal parts

The life cycle material balance of nylon, brass and stainless steel are shown in Figures 2-2, 2-3 and 2-4 respectively. The material balance model is based on the assumptions indicated in Table 2-1. For the nylon manifold, 95% of in-house scrap resulting from start-up loss and testing is crushed and melted along with virgin nylon 6.6 during injection molding. Figure 2-2 shows that the mass of scrap recycled is 5.6 g, whereas the mass of virgin resin processed is 2.073 kg.

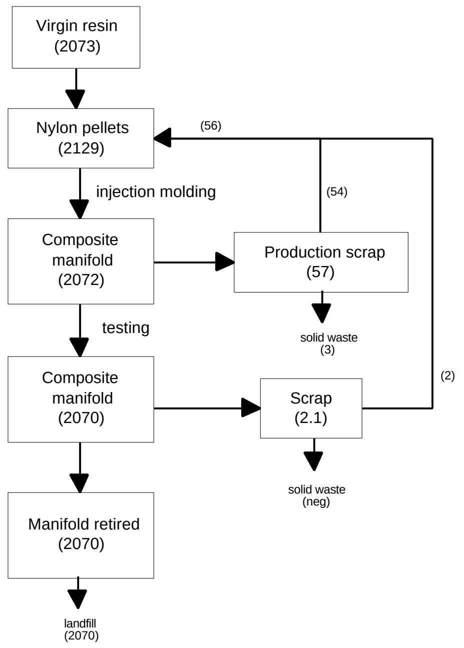

Figure 2-2. Life cycle of the composite manifold

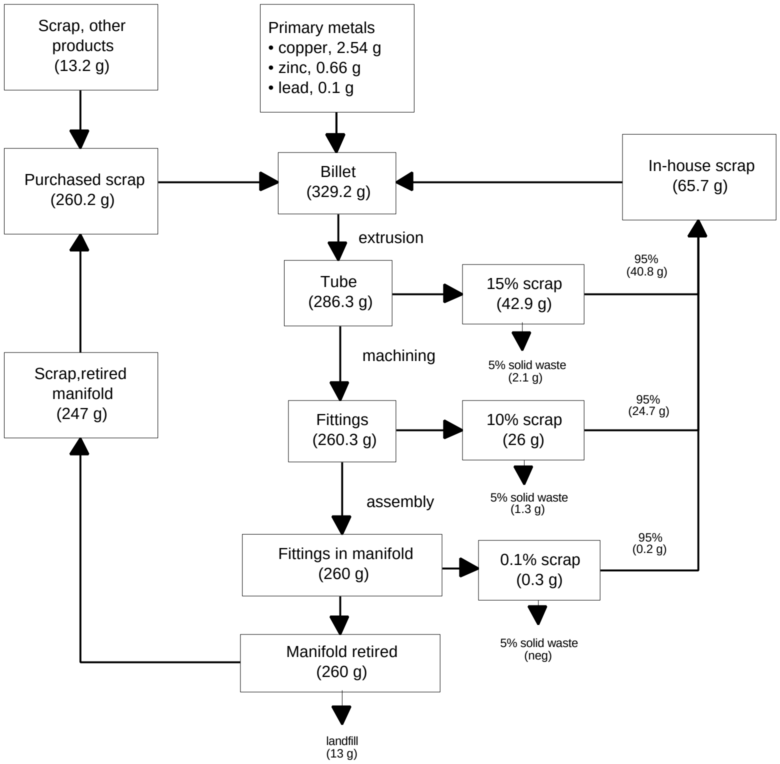

Figure 2-3. Life Cycle of Brass Inserts

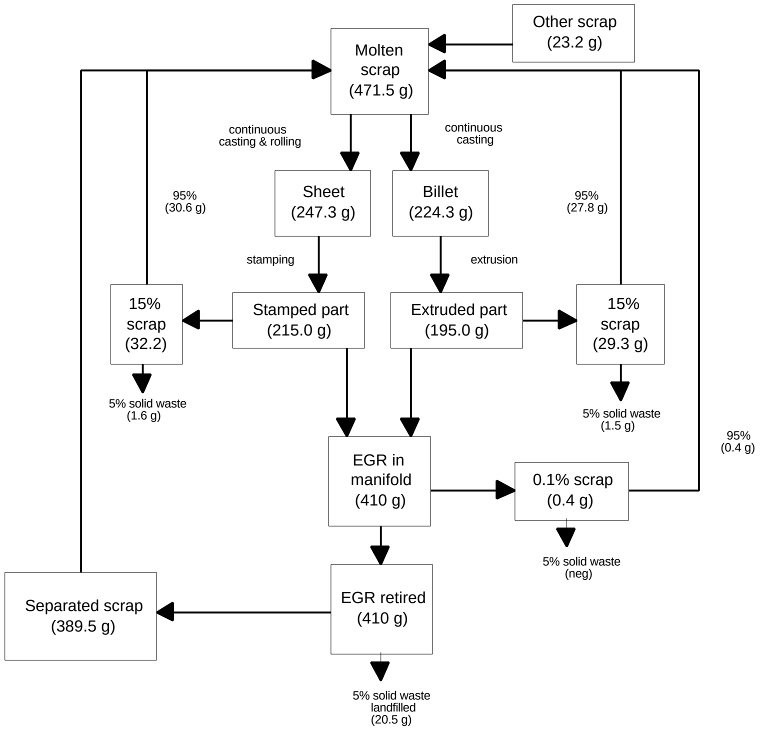

Figure 2-4. Life Cycle of the Stainless Steel EGR Tube

The tin-bismuth core for the lost core process of manufacturing the composite manifold is recycled almost completely within the plant [11] [6]. However, a certain quantity of virgin tin-bismuth alloy is added to offset melting and handling losses. The environmental burden for the production of virgin tin-bismuth alloy is not considered in this analysis. The environmental burdens for equipment such as the mold, injection tool, furnace, extruders, stamping and cutting machines are also not included.

Figure 2-3 shows that the billet for extruding brass tubes consists of 260.2 g of purchased scrap, 65.7 g of in-house scrap, 2.54 g of primary copper, 0.66 g of primary zinc and 0.1 g of primary lead. We assume that 95% of purchased scrap consists of brass recovered from retired manifolds; thus 247 g of purchased scrap comes from previous manifolds while the remaining 13.2 g is recovered from other products.

Figure 2-4 shows that the 0.41 kg stainless steel EGR tube consist of a 195 g extruded part and a 215 g stamped part. Assuming 15% scrap for extruding and stamping [12], the mass of billet required for extrusion is 224.3 g and the mass of sheet required for stamping is 247.3 g. The billet can be directly cast into the desired shape from an electric arc furnace, whereas the sheet is produced from a billet in a rolling mill. Thus, the mass of stainless steel processed is 471.5 g. It is assumed that scrap generated from extrusion and stamping is transported to steel plants and recycled with 95% efficiency. The mass of recycled scrap converted into new products is therefore 58.8 g. This scrap is clean compared to scrap steel generated from the manifold's end-of-life. Shredded stainless steel has to be separated from other nonferrous materials at a nonferrous separator's facility. Assuming 95% efficiency in shredding and separating, the mass of stainless steel scrap recycled back to the manifold is 389.5 g. The mass of scrap from other products is 23.2 g.

2.5 Product System for Sand-Cast Aluminum Manifolds

The product system for the sand-cast aluminum manifold consists of the following life cycle stages:

Material production	• Pretreatment of separated scrap • Smelting, refining and casting to produce secondary ingot
Manufacturing	• Sand casting • Assembly into the engine block
Use	• Use of the manifold
Retirement	• Shredding, separation of aluminum scrap and disposal of unrecoverable scrap

The life cycle material balance for the sand-cast aluminum manifold is shown in Figure 2-5. The sand-cast manifold consists of 100% secondary aluminum. Scrap from the manifold includes production and testing scrap of 0.37 kg (5.67%) and machining scrap of 0.687 kg (10%). 95% of the scrap (1.005 kg) is assumed to be recycled within the plant. This scrap is put directly into the melting furnace along with 6.552 kg of secondary aluminum ingot. In this model, it is assumed that 95% of aluminum from retired manifolds is recycled back into additional manifolds as secondary aluminum ingot. The 6.552 kg secondary aluminum ingot consists of 6.175 kg aluminum from the recycled manifold and 0.377 kg of secondary aluminum from other products.

The material production stage involves pretreatment of separated scrap and smelting and refining. Pretreatment typically involves sorting and processing step to remove contaminants and cleaning processes. Smelting and refining operations involve charging, melting, fluxing, demagging, degassing, alloying, skimming and pouring stages. The sand casting process involves preparation of green sand and pattern, melting and mixing of ingot with in-house scrap, and holding and pouring the molten metal into the pattern. The environmental burden for green sand and salt production, and sand and salt slag recycling is outside the boundary of this analysis.

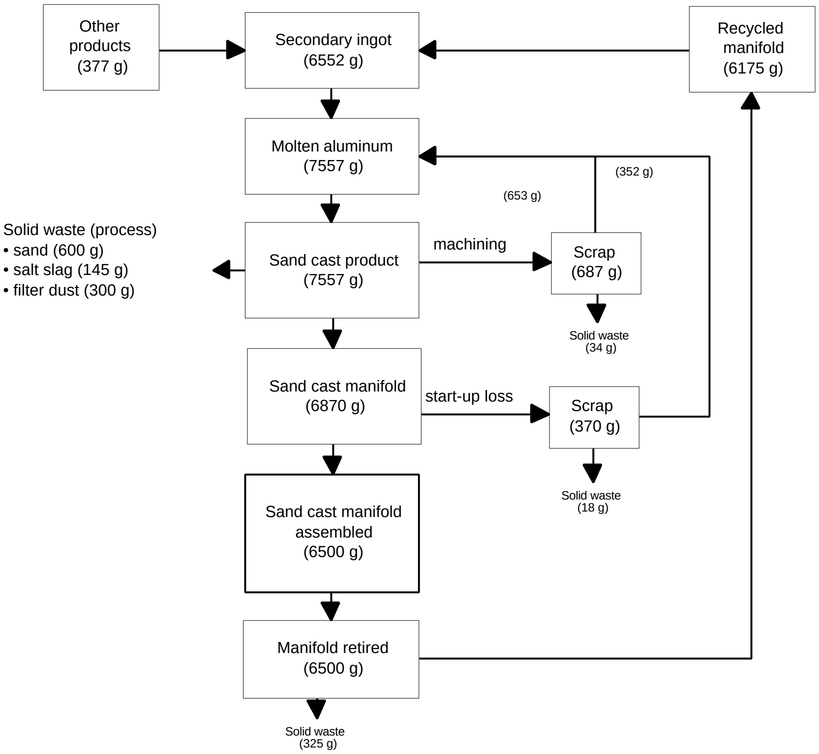

Figure 2-5. Life Cycle of the Sand-cast Aluminum Manifold

2.6 Product System for Multi-Tube Brazed Aluminum Manifolds

The product system for the multi-tube brazed aluminum manifold consists of the following life cycle stages :

Material production	Primary aluminum • Bauxite mining, refining • Alumina production • Electrolysis • Melt cleaning and casting to produce primary ingot Secondary aluminum • Pretreatment of separated scrap • Smelting and refining to produce secondary ingot
Manufacturing	• Sand casting to produce the flange section • Extrusion to produce the tube and air collection chamber • Bending of tubes and brazing of components • Assembly into the engine block
Use	• Use of the manifold
Retirement	• Shredding, separation of aluminum scrap and disposal of unrecoverable scrap

Figure 2-6 illustrates the life cycle material balance for a multi-tube brazed manifold consisting of a sand-cast flange, extruded tubes and an extruded air collection chamber. Overall scrap from the manufacturing process includes production / testing scrap of 0.2 kg (5.67%) from the entire manifold, machining scrap of 0.248 kg (10%) from the flange section and extrusion scrap of 0.2 kg (15%) from extruded sections.

In this model, it is assumed that all machining scrap from sand casting is remelted and fed back into the flange with 95% efficiency. Production and extrusion scrap are assumed to be recycled into extruded products with 95% efficiency. Aluminum extruders use all in-house scrap to produce billets and purchase only primary ingot and scrap. It is assumed that the manifold manufacturer receives the sand-cast flange from another supplier, then extrudes tubes and air collection chambers and brazes different sections to produce the multi-tube brazed manifold. The assembly and extrusion scrap are assumed to be recycled internally within the plant. The mass of scrap recycled internally for extruded parts is 0.38 kg. The mass of scrap from retired manifolds used for extruded parts is 0.081 kg. The mass of primary ingot used for extruded parts, assuming 70% primary and 30% secondary aluminum in the billet, is 1.076 kg. The mass of secondary ingot used for the sand-cast flange section is 2.496 kg. The mass balance shows 3.439 kg (95%) of aluminum recycled from the manifold and 0.862 kg of manifold material leaving the system for application in another product system. No credit was given to the system for this 0.862 kg of post-consumer aluminum.

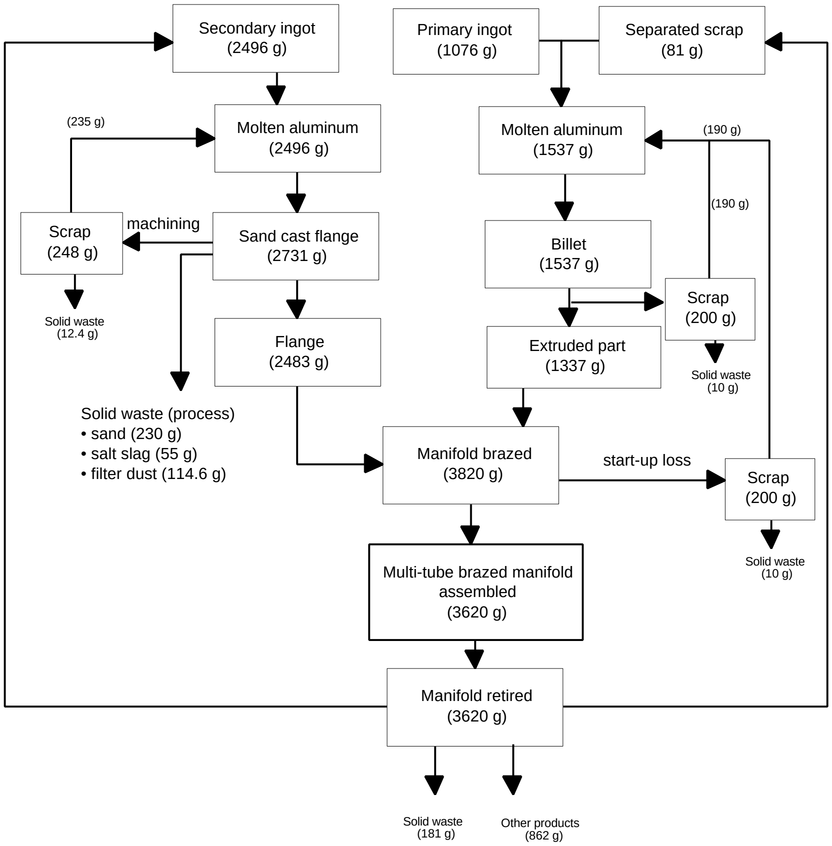

Figure 2-6. Life Cycle of the Multi-tube Brazed Aluminum Manifold

3. Data Collection and Analysis

3.1 Methodology

This chapter describes environmental, cost and performance analyses for three intake manifold designs. A life cycle inventory analysis was conducted following EPA and SETAC guidelines. The inventory analysis of each manifold was reviewed by material suppliers and Ford team members. A life cycle cost analysis was performed according to conventional practices [13]. Manufacturing and warranty costs to Ford, use phase (gasoline) costs to customers, and end-of-life costs and salvage material credits to auto recyclers were evaluated. This analysis did not address externality costs not reflected in the market system. A total cost assessment [14] of manifold manufacturing was not conducted. Specifically, hidden costs not accurately allocated by Ford's internal accounting system, probabilistic (with the exception of warranty) costs, and less tangible costs (e.g., potential increased productivity and revenues associated with environmentally preferable products) were not evaluated.

Environmental and cost data in each life cycle stage were obtained for the mass of materials as indicated in Table 3-1.

Environmental data evaluated are material, energy and waste. Environmental data in the material production stage were obtained from suppliers (DuPont and Alcoa)[15][9][16] and other published sources [6][17][18][19][20]. Environmental data in the manufacturing stage were obtained from published sources [12][21][22][23][24][25][11][6][26][27] and engineering models for different manufacturing processes. Environmental data in the use phase were obtained from fuel economy and emissions data for the 1995 Contour [28]. In the retirement phase, environmental data evaluated are shredding energy, nonferrous separation energy and transportation energy [29][APC, 1994a]. Emissions and wastes for different life cycle stages were obtained as the sum of process and fuel-related wastes. A major objective of the investigation was to demonstrate the life cycle design approach to Ford participants. The timeline for this project precluded primary inventory data collection in several cases. This study insures data transparency. A complete documentation of the inventory analysis is provided in Appendix A.

Cost data evaluated were material cost, manufacturing cost, use cost and retirement cost. The material costs were evaluated from unit cost ($/kg) data obtained from *American Metal Market* [30] in 1995, whereas the manufacturing costs were estimated by Ford's manifold design group. The use costs were obtained as the price of gasoline consumed [31]. The retirement costs were estimated from the retirement spreadsheet model of APC [32] and data obtained from several other sources [33][29].

Performance data evaluated were manufacturability, cycle time and warranty. Manufacturability was estimated from manufacturing unit processes of different manifolds [11][6] and cycle time data provided by Ford's manifold design group.

The details of the calculation process and data for the three manifold systems are included in Appendix A.

Table 3-1. Mass of Materials at Different Life Cycle Stages for the Three Manifold Systems

		Input, Product Material		Output, Product Material	
Manifold	LC Stage	Type	(kg/IM)	Type	(kg/ IM)
Sand-cast manifold	Material production	• Secondary aluminum ingot	6.552	• Molten aluminum	7.557
	Manufacturing	• Molten aluminum	7.557	• Sand-cast manifold	6.500
	Use	• Sand-cast manifold	6.500	• Sand-cast manifold	6.500
	Retirement	• Sand-cast manifold	6.500	• Secondary aluminum ingot	6.175
Multi-tube brazed manifold	Material production	• Secondary aluminum ingot	2.496	• Molten aluminum	2.731
		• Primary aluminum ingot	1.076	• Billet (70% primary + 30% secondary)	1.537
	Manufacturing	• Molten secondary aluminum	2.731	• Sand-cast flange	2.353
		• Billet	1.537	• Extruded parts	1.267
	Use	• Multi-tube brazed manifold	3.620	• Multi-tube brazed manifold	3.620
	Retirement	• Multi-tube brazed manifold	3.620	• Secondary aluminum ingot	2.496
				• Scrap aluminum	0.081
Composite manifold	Material production	• Primary lead ingot	9.87×10^{-5}	• Brass billet	0.329
		• Primary copper ingot	2.53×10^{-3}		
		• Primary zinc ingot	6.58×10^{-4}		
		• Scrap stainless steel	0.471	• Stainless steel billet	0.224
				• Stainless steel strip	0.247
		• Virgin nylon resin	2.073	• Molded nylon resin	2.129
	Manufacturing	• Brass billet	0.329	• Brass fittings	0.260
		• Stainless steel billet	0.224	• Stainless steel EGR tube	0.410
		• Stainless steel strip	0.247		
		• Molded resin	2.129	• Lost core manifold	2.070
	Use	• Composite manifold	2.740	• Composite manifold	2.740
	Retirement	• Composite manifold	2.740	• Brass scrap	0.247
				• Stainless steel scrap	0.389

3.2 Life Cycle Inventory Analysis

The complete Life Cycle Inventory for each manifold system is shown in Appendix A.

3.2.1 Material Production

Composite Manifold

The composite manifold consists of 33% glass reinforced nylon, brass and stainless steel materials. Environmental data for the production of these materials are based on analysis of the following processes.

Nylon

Environmental data for the material production of nylon, glass fiber and primary brass were obtained from [15]. Table 3-2 shows a short list of cumulative material production data for nylon, brass and stainless steel. Nylon production data represent average data at a DuPont facility. Environmental data, from drilling to the refinery, for natural gas and petroleum were provided by Chem Systems. DuPont provided data on the production of adipic acid, hexamethylenediamine, A-H salt and PA6.6.

Table 3-2. Environmental Data for Materials Production of the Composite Manifold

Primary Energy (MJ / IM)		297
Waste (g / IM)		
Air emissions		
	Carbon dioxide	8530.0
	Particulates	16.1
	Nitrogen oxide	36.0
	Sulfur dioxide	62.0
	Carbon monoxide	23.0
	Hydrocarbon	6.0
	Methane	82.0
	Fluorine	1.0
	Hydrochloric acid	0.5
	Heavy metals	4×10^{-4}
	Halogenated hydrocarbon	3.1×10^{-3}
Solid waste		956.0
Water effluents		
	Dissolved solids	701.0
	BOD	3.0
	COD	25.0
	Suspended solids	116.0
	Acids	4.0
	Heavy metals	0.6
	Oils	1.5
	Nitrates	1.6×10^{-2}
	Chlorides	51.0
	water (l)	20200.0
	Halogenated hydrocarbon	6.8×10^{-2}

IM = intake manifold source: [15][34]

Nylon processing begins after petroleum and natural gas are transported to refineries where benzene, ethylene, propylene and butadiene are produced by desulfurisation and steam cracking [6]. Acrylonitrile is produced from propylene. Benzene is used to produce cyclohexane and adipic acid, whereas adiponitrile, an intermediate compound is produced from butadiene, adipic acid, ammonia and acrylonitrile. Adiponitrile is used to produce hexamethylenediamine, which along with adipic acid are the source material for the production of A-H salt. An aqueous A-H salt solution of 40-60% is heated 200-300° C at 8-25 bars for 1- 30 hours to produce PA6.6 resin. Glass fibers are produced from colemanite, limestone, kaolin and silica by melting, refining, homogenizing and temperature setting between 1200 - 1650°C.

Brass

360 brass alloy consists of 77% copper, 20% zinc and 3% lead; it is composed of 99% scrap and 1% virgin metals [7][35]. Brass extruders use in-house scrap and purchase scrap from scrap

dealers. The purchased scrap may be either 260 or 360 brass. The ratio of copper, zinc and lead are then varied to obtain the desired specifications of the 360 brass [7][35]. In this analysis, it was assumed that purchased scrap consists of 100% 360 brass. Therefore, the fraction of copper, zinc and lead added is 0.77, 0.20 and 0.03 respectively. Because the mass of virgin metals added is 3.292 g, environmental burden in the material production stage was evaluated for 2.535 g of copper, 0.658 g of zinc and 0.099 g of lead.

Stainless steel

Stainless steel 304 is produced from 100% scrap through remelting, mixing and alloying in an electric arc furnace. The environmental burden for stainless steel production was obtained from Franklin Associates [34].

Sand-Cast Manifold

The sand-cast manifold consists of 100% secondary aluminum. Secondary aluminum production involves two general operations- scrap pretreatment and smelting/ refining. Pretreatment includes sorting, carbonizing and briquetting [36]. The smelting/refining operation includes melting down, melting in salt bath furnace, dross processing, melt cleaning and casting (alloying). As shown in Table 3-3, environmental data for secondary aluminum production were obtained from several sources and representative data were used for this analysis. For example, primary energy for secondary aluminum production was obtained from five different sources [6][17][18][19][20]; the average energy was calculated to be 17.9 MJ /kg ± 10.0 (99% confidence interval). This variation resulted from different assumptions such as the inclusion of energy to transport scrap, shredding and decoating, type of furnace used and power source efficiency. Waste and emissions data were obtained from [6], except CO_2 which was obtained from [17].

Multi-Tube Brazed Manifold

Production of the multi-tube brazed aluminum manifold requires processing 1.067 kg primary aluminum and 2.496 kg of secondary aluminum. Primary aluminum production is a two-step process that refines bauxite into alumina by the Bayer process and reduces alumina to aluminum metal by electrolytic reduction in the Hall-Herault process [37]. The molten aluminum is subsequently cleaned and cast into ingot. Table 3-3 shows the environmental burden from primary aluminum production. These data were obtained from several sources; representative data were used in this analysis. For example, primary energy for primary aluminum production was obtained from five different sources [6][17][18][19][20] and average energy was calculated to be 177.9 MJ /kg ± 28.3 (99% confidence interval).

Primary aluminum production has been identified as a major source of fluorocarbon emissions (CF_4 and C_2F_6) which has a very high global warming potential. The global warming potentials (GWPs) on a mass basis and a time horizon of 100 years are reported to be 6300 for CF_4 and 12,500 for C_2F_6 [38]. Average emissions of CF_4 and C_2F_6 are based on a world mix of 20% Modern Prebake, 40% Prebake, 29% VS Soderberg, and 11% HS Soderberg potlines [38]. If one assumes 0.08 kg / mt for Modern-Prebake, 0.4 kg/mt for Prebake, 0.7 kg/mt for VS Soderberg, and 0.9 kg/mt for HS Soderberg one obtains a crude estimate of specific CF_4 emissions to be about 0.5 kg/mt for this global mix [38]. This same study reported 20:1 as the ratio of mass concentration of CF_4 to C_2F_6. Using this study, the mass concentrations of CF_4 and C_2F_6 were calculated to be 0.5 kg/mt and 0.025 kg/mt respectively.

Solid waste from alumina production is digested in a caustic solution to dissolve the available alumina. After recovery, 60% of the caustic solution by mass (consisting mostly of iron oxide and silica) is disposed to landfills. This residue is commonly known as red mud; it comprises most of the solid waste from primary aluminum production. Since red mud remains alkaline, it causes itching upon exposure to humans. Research is currently going on to recover the red mud and use it for soil amendment, but currently about 99% of red mud is disposed to landfill [9]

Estimates for red mud waste varied from 2 kg/kg (Europe) to 3 kg/kg (Western Australia) of aluminum depending on the bauxite content in the ore. For example, Alcoa's Western Australia facility processes a lower bauxite content ore compared to the Jamaican facility and therefore generates more red mud than the Jamaican facility [9]. In this analysis, an average value for red mud of 2.63 kg / kg.

Emissions for primary aluminum production were calculated as the sum of emissions from alumina production, anode production, electrolysis and energy contribution. For SO_2 and NO_x, alumina production data were obtained from Alcoa [9]; the remaining data were obtained from Eyerer et al [6]. CO_2 emissions were not available for individual processes and were obtained as an aggregate value for primary and secondary aluminum production [17].

Primary aluminum processing has a considerably higher environmental burden in terms of energy use (9.9 times), solid waste (49 times), CO_2 (15 times) and water consumption (7 times) than secondary aluminum processing.

Table 3-3. Environmental Data for Primary and Secondary Aluminum Production

Metrics	Primary Al	Secondary Al	Data Source
Energy (MJ / kg)			
	163.73	16.76	[6]; German condition
	188.40	13.25	[17]; Alcoa Worldwide operations
	171.20	15.60	[18]; Swiss study
	170.00	18.00	[19]; European study
	196.3	26.00	[20]; US condition
Solid waste (kg / kg)			
alumina production 1	2.0		[9]; estimate Europe
alumina production 2	3.0		[9]; estimate Western Australia
alumina production 3	2.9		[6]; German condition
average alumina production (red mud)	2.63		average of alumina 1, 2, 3 production
electrolysis	3.57 x 10^{-2}		[6]; German condition
cleaning/casting	2.0 x 10^{-2}		[6]; German condition
energy	0.27		[6]; German condition
smelting		4.3 x 10^{-2}	[6]; German condition
energy supply		1.87 x 10^{-2}	[6]; German condition
Total	**2.96**	**0.062**	
Air emissions (kg / kg)			Reasonable average condition
CO_2	13	0.86	[17]; Alcoa worldwide operations
CO	1.65 x 10^{-2}	2.21 x 10^{-4}	[6]; Europe condition
SO_2	9.19 x 10^{-2} *	1.33 x 10^{-3} **	*[9], **[6] Europe condition
NO_x	2.85 x 10^{-2} *	3.58 x 10^{-3} **	*[9], **[6] Europe condition
Particulates	1.96 x 10^{-2} *	3.57 x 10^{-4} **	*[9], **[6] Europe condition
HC	3.77 x 10^{-3}	2.61 x 10^{-3}	[6]; German condition
FC	5.25 x 10^{-4}		[38]; estimated global average
HCl		1.3 x 10^{-3}	[6]; German condition
H_2		7.5 x 10^{-4}	[6]; German condition
Others	1.0 x 10^{-3}	5.0 x 10^{-5}	[6]; German condition
Water use (m^3 / kg)	11.44 *	1.6 **	*[9]; estimate Western Australia **[6]; German condition
Water effluents (kg/kg)			[6]; German condition
Dissolved solids	2.55		
Suspended solids	0.013		
BOD	1.27		
COD	31.47		
Acids	3.60	1.1 x 10^{-4}	
Metal ions	0.97	3.0 x 10^{-5}	
Lead	0.003		
Tar	0.002		
Fluorides	0.001		
Others	5.77	1.0 x 10^{-4}	

3.2.2 Manufacturing

Composite Manifold

Manufacturing composite manifolds involves producing nylon manifolds, brass inserts and stainless steel EGR tubes, and assembling the different components into finished products. Environmental data for different aspects manufacturing are discussed below.

Nylon Manifold

Nylon manifolds are manufactured by the lost core process. The lost core process consists of the following unit processes:

- **Casting melt cores of tin-bismuth alloy**

  A core-casting machine molds two 30 kg tin-bismuth cores per cycle. The weight of a core for this manifold could not be obtained directly from Montaplast or CMI, who are the direct suppliers of the manifold in Europe and the US. However, for a European 2.0 l Ford Sierra with a 2.068 kg composite manifold, Montaplast was reported to use two 30 kg cores [6]. The lost core process used by Siemens Automotive to manufacture a 1.63 kg composite intake manifold for a Chrysler Neon uses two 35 kg tin-bismuth cores per cycle [11]. In this analysis, two 30 kg cores were assumed for the 2.07 kg composite manifold. The cycle time for casting two cores was obtained from the Ford core team as 3 minutes [39], which implies a cycle time of 1.5 minutes per core. The environmental burden for core casting was not considered in this analysis.

  The cores are cast at 340° F (171° C) and the centers are still molten when the parts are placed on the conveyor [11]. The conveyor transports 30 parts through a core cooling area, where the temperature of the cores are dropped to 80° F (27° C), to the injection molding machine. The environmental burden for transportation via conveyor was not considered in this analysis.

- **Injection molding the cores with nylon 6.6**

  The cores are overmolded with nylon in an injection molding machine to produce manifolds with a hollow interior. The outer surface of the manifold is obtained by pressing the molten resin against several molds. The edge of the mold gives the partition line on the manifold. For these manifolds, an estimated 800-ton injection molding machine is used [39]. The cycle time for injection molding the composite manifold is 1.5 minutes.

  The average energy for a 500-ton injection molding machine is reported to be 65.92 kW [40]. Assuming that injection molding energy is proportional to machine tonnage, the average energy for an 800-ton machine is 105.47 kW. Therefore, the energy for a cycle time of 1.5 minutes was estimated to be 9.5 MJ. For a 2.073 kg injection-molded manifold , this results in an energy density of 4.58 MJ / kg. The energy density for injection molding was compared with data from other sources. For example, Eyerer et al [6] used the Boustead database for calculating injection molding energy, which states an electricity consumption of 1.16 kWh for 1.03 kg nylon. This results in an energy density of 4.05 MJ/kg. The Franklin database [34] reported an electricity consumption of 800 kWh for 1000 lb of plastic, which results in an energy density of 6.35 MJ/kg. The Ford core team reported a primary energy consumption of electricity of 4300 BTU/lb [20] which results in 3.2 MJ / kg of resin. The average energy density for injection molding was calculated to be 4.54 MJ / kg. The total electrical energy consumed for 2.129 kg resin injection molded (as shown in Figure 2-2) was evaluated to be 9.66 MJ / IM.

A portable robot loads the cores into the mold, cuts the spurs and unloads finished parts. Molded manifolds with cores travel on a vertical conveyor into the melt-out tank [11].

- **Inductive melting of the core**

  The cores are placed in an inductive melting furnace for a 45-minute melt-out stage. Since it takes 1.5 minutes to overmold a core with nylon resin, the total number of cores that pass through the 45-minute melt-out stage is 30. The melting furnace is heated above the melting point of the tin-bismuth alloy, 320° F (160° C), which is well below the 491° F (255° C) melting point of nylon. The molten alloy sinks to the bottom of the tank and is gravity fed to a heated storage tank.

  Because the energy for inductive melting could not be directly obtained from suppliers (Montaplast or CMI) of the manifold, it was indirectly estimated from pilot experiments on inductive melting of tin-bismuth alloy for the lost core process for one intake manifold [41]. In this experiment, a 250 kW furnace was used to melt the core of one manifold in a 1 minute cycle time. The furnace was 80% efficient in converting electricity to heat, but only 80% of this heat was actually used to melt the tin-bismuth alloy because of its complex geometry. The furnace used for manufacturing the Contour composite manifold melts 30 cores in a 45-minute cycle time. Heat loss per core in a large furnace holding 30 cores is expected to be smaller than the heat loss from a furnace that holds a single core because of efficiencies of scale. So the maximum electric energy needed for inductive melting of one core was estimated to be 250 kW. Electric energy for a 1.5-minute cycle time was therefore 22.5 MJ / IM.

- **Washing/rinsing**

  Another robot transfers the empty manifolds into a four-stage hot water washer to rinse off all traces of glycol. The rinse water is subsequently vacuum distilled so that the glycol (which costs about $6 / gal) can be recycled [11]. The energy for washing/rinsing operations was not considered in this analysis.

- **Post molding assembly**

  A conveyor takes the clean parts to a series of manual finishing stations where operators install brass inserts, ultrasonically weld a plastic cap over a hole in the plenum (used to locate the cores securely in the injection mold), and leak-test the part [11][6]. The energy for post molding assembly was not considered in this analysis.

Thus, the electrical energy consumed per intake manifold was calculated to be 32.16 MJ / IM. Taking into account the energy required to extract and process fuels and the losses in combustion and distribution, this corresponds to a primary energy of 100.5 MJ / IM. A primary energy density of 47.2 MJ / kg was evaluated for 2.129 kg of nylon resin processed to produce 2.07 kg manifold.

Brass inserts

Manufacturing of brass inserts can be divided into the following unit processes:

- **Billet production**

  Manufacturing of brass inserts begins with the production of billet at a brass extruder's facility. Brass 360 billets for extrusion are produced by mixing and melting 99% scrap with 1% primary metals consisting of 77% copper, 20% zinc and 3% lead. The melting is done in a inductive furnace. Typical energy densities for melting 360 brass are reported by Ajax Magnetothermic Corporation to vary from 6.5-7.0 lb / kWh [42]. An average energy density of 6.75 lb / kWh (1.176 MJ / kg) was used in this study. These data were obtained by experimental test, rate test and theoretical analysis of furnace design. The mass of billet produced was 329.2 g.

- **Tube production**

  Tube is produced by extruding hot billet. In this analysis, it was assumed that billet production and tube making is a continuous operation. This avoids reheating cold billet and saves energy in the extruder's facility. The extrusion energy density (E_{ex}) is obtained from [12] as:

  $$E_{ex} = \left(\frac{K}{r \cdot h_e} \right) \times \ln r \qquad (3.1)$$

  where, for brass [12][43]

  K = extrusion constant = 35,000 psi = 241.3 MPa,
  r = density = 8400 kg / m^3 ,
  C_p = specific heat = 0.38 kJ / kg-K and
  h_e = efficiency accounting for nonuniform deformation and friction = 0.6

  The extrusion ratio r is the ratio of the cross-sectional area of the hollow tube to the cross-sectional area of the billet. The diameter of the billet was assumed to be 9" (0.2286 m) and the hollow tube was 5 cm in diameter and 3 mm thick. Therefore, the extrusion ratio was calculated to be 740. The electrical energy for extrusion was evaluated from EQ(3.1) as 0.32 MJ/kg. The mass of tubes extruded was 329.2 g.

- **Machining**

  Machining for brass inserts involves cutting, inside and outside threading, and tapering. The cutting energy density for copper alloy (brass) was obtained from Kalpakjian [12] as 1.4-3.3 J / mm^3. An average cutting energy of 2.35 J / mm^3 was assumed for brass. Volume of material removed was obtained by multiplying the area of the tube machined by an average cutting length of 1 mm. Machining is normally done in a lathe, which is electrically operated. Overall machining energy (electrical) was estimated to be 8745 J for 0.329 kg of brass tube in the manifold

The total electrical energy for manufacturing brass inserts was evaluated to be 0.58 MJ / IM; primary energy density for 0.329 kg brass tube manufactured was calculated to be 5.51 MJ / kg.

Stainless Steel EGR Tube

The stainless steel EGR tube consists of brackets, tubes, fasteners, nuts and screws. The mass of each component was estimated by multiplying the volume of a geometrically equivalent shape with a density of 7900 kg / m^3 for stainless steel. Results are listed in Table 3-3.

Table 3-3. Weight of the Stainless Steel EGR Tube

Manufacturing Process	Part	Mass (g/IM)
Rolling and stamping	Bracket (a) attached to the shank portion (horizontal & vertical)	25.4
	Rhombus shaped bracket attached to the fuel delivery section	169.6
	TOTAL stamped part	*195.0*
Extrusion	Tube	185.1
	Nuts and screws attached to bracket (a)	21.4
	Hollow conical fastener attached to the tube	8.5
	TOTAL extruded part	*215.0*
Brazing and assembly	*TOTAL EGR tube*	*410.0*

The following unit processes are used to manufacture the stainless steel EGR tube:

- **Rolling**

  The energy for rolling was estimated by evaluating the energy for preheating the slab in a reheat furnace and the deformation energy required for hot rolling the workpiece.

  Preheating energy

  Slabs are heated in a reheat furnace to remove surface defects, soften the steel for rolling, maintain the austenitic temperature region during rolling and dissolving carbides and nitrides that are to be precipitated at a later stage of processing [44]. The heating is done in a batch type soaking pit or continuous furnace. Most existing furnaces combust fuel, oil, natural gas or coke oven gas [44]. Furnace energy depends on the length of the furnace and the slab charging temperature. Both hot and cold slabs can be charged in a furnace. The amount of fuel saved increases with an increase in the slab charging temperature. The energy balance for a 5 zone pusher-type slab reheating furnace with insulated skids is 1.91 MJ / kg [44]. 40% of this energy, which amounts to 0.76 MJ / kg, is reported to be used for steel making; this is in agreement with other slab heating data of 0.74 MJ / kg [45] . 20% of the energy is dissipated as radiation loss from surfaces, 32% is lost from stacks and 8%

is lost to the skid-pipe cooling water [44]. In this analysis, it was assumed that the furnace is heated by natural gas.

Deformation energy

Deformation energy was obtained from the specific power curve for stainless steel, which is 60 hp-hr / ton (or 0.177 MJ / kg) [46][44]. The rollers are electrically operated.

- **Stamping**

  Stamping involves cutting sheet metal by subjecting it to shear stresses, usually between a punch and a die. The major variables in stamping are the punch force, speed of the punch, lubrication, surface condition of the punch and die materials, their corner radii and the clearance between the punch and die. Primary energy for stamping was taken from [19] as 1019 MJ for a 280 kg raw body in white stainless steel part. This results in a primary energy density of 3.64 MJ / kg. Thus, the site electricity consumption for stamping was estimated to be 1.16 MJ / kg.

- **Extrusion**

  Extruding stainless steel involves reheating billet to approximately 1000° C and forcing the hot billet through a die opening (hot extrusion). The specific heating energy is evaluated from thermodynamics as:

$$E_h = \frac{C_p \cdot \Delta T}{h_f} \tag{3.2}$$

  where the specific heat for stainless steel C_p is 0.51 kJ/kg-K and η_f is the efficiency of the furnace in transferring heat to the stainless steel billet = 0.4. Therefore, reheating energy is 1.27 MJ / kg. Reheating is done in a natural gas furnace. The energy for hot extruding stainless steel billet was obtained from EQ(3.1). For stainless steel, K = 400 MPa. The billet diameter was assumed to be 9" and the tube was 1.8 cm in diameter and 3 mm thick. Therefore, the extrusion ratio was calculated to be 528. The extrusion energy (electricity) for stainless steel was therefore 0.53 MJ / kg.

Thus, the overall electricity energy for producing the stainless steel EGR tube was calculated to be 0.45 MJ / IM. The total natural gas energy for EGR tube production was evaluated to be 0.76 MJ / IM.

Sand-Cast Manifold

Manufacturing energy for sand-cast aluminum manifolds includes transportation, machining and sand casting in a foundry. Sand casting energy consists of melting, holding and distributing molten metal. The site energy for sand casting is obtained from site energy for gravity die casting, which is about 39.36 MJ/kg [21]. For every 6.5 kg sand-cast manifold there is a 0.687 kg casting/machining loss and a 0.37 kg scrap loss. Because of this waste, 7.557 kg of aluminum must be processed to manufacture a 6.5 kg sand-cast manifold. Therefore, the total energy for manufacturing a sand-cast manifold was estimated to be 297.44 MJ.

Most common furnaces in aluminum foundries are crucible type, which are either gas-fired, electric arc or induction furnaces [21][12]. The exact mix of gas-fired and electric-powered (electric arc or induction) furnaces in a foundry is difficult to predict. However, the Ford core team reported that most furnaces for sand casting in Ford facilities are gas fired. Thus, the primary energy required for manufacturing a sand-cast manifold was calculated to be 334.21 MJ.

Process wastes for sand casting were obtained from Scott et al [24] and McKinley et al [25] as quantities of chemicals released in the green sand process for sand casting in an iron foundry as indicated by EQ(3.3). The results are shown in Table 3-4.

$$\left|m_e\right|_{sc} = \frac{\left|C_e\right|_{sc} \times Q \times T_s}{M_m} \tag{3.3}$$

where,

$\left|m_e\right|_{sc}$ = emission factor in kg of air emissions per kg of metal poured

$\left|C_e\right|_{sc}$ = concentration of air emissions in mg per m^3

Q = flow rate through the stack = 1000 l / min

T_s = sampling time = 30 min

M_m = mass of metal poured = 40 kg

Table 3-4. Emission Factors for Sand Casting

Air Emissions	Concentration $\left\|C_e\right\|_{sc}$, (mg / m^3)	Emission Factor $\left\|m_e\right\|_{sc}$, (kg / kg)
Sulfur dioxide	12.0	9 .0 x 10^{-6}
Hydrogen sulfide	39.5	29.6 x 10^{-6}
Hydrogen cyanide	5.6	4.2 x 10^{-6}
Ammonia	3.1	2.3 x 10^{-6}
Nitrous oxide	26.7	20.0 x 10^{-6}
Formaldehyde	0.2	1.5 x 10^{-7}
Acrolein	0.1	7.5 x 10^{-8}
Total aldehyde	3.0	2.2 x 10^{-6}
Total aromatic amines	1.0	7.5 x 10^{-7}
Benzene	29.0	21.7 x 10^{-6}
Toluene	3.0	2.2 x 10^{-6}
m-xylene	<1.0	7.5 x 10^{-7}
o-xylene	<1.0	7.5 x 10^{-7}
Napthelene	<1.0	7.5 x 10^{-7}
Phenol	6.2	4.6 x 10^{-6}

source: [24][25]

It was assumed that bonding green sand in iron and aluminum foundries has the same property; therefore, process emissions become a function of the mass of metal poured. Process wastes for extrusion and brazing were neglected. The waste and emissions associated with electricity and natural gas use were obtained from Franklin Associates [10].

Multi-Tube Brazed Manifold

Manufacturing energy for a multi-tube brazed aluminum manifold involves sand casting the flange portion, extrusion and brazing.

The extrusion process generates 15% scrap [12], which results in a scrap loss of 0.20 kg for each manifold. In addition, a machining loss of 0.248 kg is estimated to be associated with the sand cast portion of the manifold. The mass of molten aluminum sand cast was 2.731 kg for the 2.483 kg flange section and the mass of billet extruded was 1.537 kg for the 1.337 kg of the extruded section. A further 0.2 kg is lost in production, resulting in a final multi-tube brazed manifold weight of 3.62 kg.

- **Sand casting**

  The energy for the sand-cast flange, assuming a 39.36 MJ/kg energy density [21], was calculated to be 107.49 MJ.

- **Extrusion**

  The average energy for extrusion was obtained from averaging extrusion data from three different plants in Europe [22] and the average data for extrusion in a U.S. extrusion mill [23]. The extrusion data include remelting primary aluminum ingot and mixing it with scrap to produce a billet, reheating the billet and forcing the billet through a die opening [12][22][23]. The average primary energy for extrusion was calculated to be 16.76 MJ / kg.

- **Brazing**

  The four bent, extruded tubes (5 cm diameter and 3 mm thickness) are brazed to an air collection chamber and a cast flange. There are a total of eight brazed joints divided equally between the cast flange and the air collection chamber. Typical brazing length for aluminum tubes was assumed to be 0.15 mm [12][26][27]. The commercial filler material for brazing aluminum contains 91% aluminum and 7% silica and has an average density of 2601 kg / m^3. The total mass of filler material to be brazed was calculated to be about 1.6 grams. The specific heat of fusion for aluminum is 0.356 MJ / kg and the mean specific heat for the filler material is 0.92 KJ / kg-K. The temperature difference for the furnace and room temperature for furnace brazing applications was about 900 K. Therefore, the minimum energy supplied for brazing was calculated from thermodynamics as 1.9 KJ.

The primary energy for casting, extruding, and brazing was calculated to be 120.77 MJ, 25.76 MJ, and 0.006 MJ respectively. Therefore, the total primary energy for the multi-tube brazed manifold was 146.54 MJ.

3.2.3 Use

Use phase energy and wastes were calculated for an assumed manifold life of 150,000 miles (241,350 km) in a 1995 Contour with the weight and fuel economy data indicated in Table 3-5.

Table 3-5. Weight and Fuel Economy Data for a 1995 Contour

Parameter	Metrics
Test weight	1471 kg or 3250 lb
Fuel economy	7.46 l / 100 km or 31.5 mpg
Weight to fuel economy correlation	10% weight reduction ≡ 4% fuel consumption reduction

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

$$F_{(l)} = M_{IM} \times L \times \left[\frac{FE_{(l)}}{M_v}\right] \times \frac{\Delta f}{\Delta M} \tag{3.4}$$

where,

$F_{(l)}$ = fuel (liters) used over the life of intake manifold (L)

M_{IM} = mass of the intake manifold

M_v = test weight (mass) of vehicle = 1471 kg

$\frac{\Delta f}{\Delta M}$ = fuel consumption correlation with mass. For a 1995 Contour the correlation was obtained from the Ford core team as: 10% weight reduction is equivalent to 4% fuel consumption reduction. Therefore,

$$\frac{\Delta f}{\Delta M} = 0.4$$

$FE(l)$ = fuel consumption in liters/km. For a 1995 Contour 7.46 l/100 km. Therefore, FE = 0.0746

L = life of intake manifold = 241,350 km

The lifetime fuel consumption and energy for the three manifolds are indicated in Table 3-6.

Table 3-6. Fuel Consumption and Use Phase Energy Contribution of Intake Manifolds

Manifold Type	Weight (kg)	Fuel Consumption		Energy (MJ)
		$F_{(l)}$, (liter)	$F_{(gal)}$, (gallons)	
Composite manifold	2.74	13.41	3.54	563.76
Sand-cast manifold	6.50	31.82	8.40	1337.39
Multi-tube brazed manifold	3.62	17.72	4.86	744.77

Air emissions and waste were evaluated as the sum of combustion and precombustion emissions and waste.

Combustion Emissions

Air emissions evaluated from EPA test results are carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxides (NO_x). CO_2 emission are based upon stoichiometric combustion, assuming that gasoline has a mean chemical formula of $CH_{1.9}$ and a density of 0.74 kg / l. This resulted in 3.16 kg of CO_2 emission per kg of gasoline combusted. Table 3-7 shows the tailpipe emissions data for a 1995 Contour.

Table 3-7. Certified Emission Data for the 1995 Contour

Description	1995 Contour
EPA test #	94-28-48
Engine family name	SFM2.0VJGFEA
Vehicle ID #	5NB1-2.0-H-238
Air emissions ($m_{e'}$, kg / mile)	
CO_2	0.281 *
CO	1.11×10^{-3}
Cold CO	4.56×10^{-3}
Hydrocarbon	1.0×10^{-4}
Nonmethane Hydrocarbon	8.5×10^{-6}
NO_x	1.2×10^{-5}
Evaporative	7.2×10^{-5}

Emission data include deterioration factors [28]

* CO2 emissions reported is not certified and is obtained using stoichiometry

The mass of air emissions over the life of an intake manifold was obtained from the mass of air emissions per vehicle miles traveled using EQ (3.5).

$$m_e = m_{e'} \times FE_{(gal)} \times F_{(gal)} \tag{3.5}$$

where,

m_e = mass (kg) of air emissions allocated to the manifold
$m_{e'}$ = mass of vehicle air emissions per mile (kg/mile)
$FE_{(gal)}$ = vehicle fuel economy (miles per gallon)
$F_{(gal)}$ = lifetime fuel (gallons) consumption allocated to manifold

Precombustion Waste

Precombustion wastes (air emissions, waterborne waste and solid waste) per 1000 gallons of gasoline consumed were obtained from the Franklin database [10]. The Franklin waste data were multiplied by gasoline used in gallons per manifold to obtain wastes in kg per manifold.

Total use phase wastes were obtained by summing precombustion and combustion waste. The use phase energy and waste were calculated by neglecting the secondary weight effect. This means that the intake manifold is replaced in the vehicle without altering any other parts.

3.2.4 Retirement

Retirement of the manifold is characterized by the following steps:

- Transportation from the dismantler as part of the whole vehicle to the shredder (100 miles).
- Shredding.
- Transportation from the shredder to the non-ferrous separators (200 miles).
- Separation of aluminum, brass and stainless steel from automotive shredder residue (ASR) and other nonferrous metals.
- Disposal of nonrecovered metal (5%) and nylon to landfills (200 miles).
- For the composite manifold, 0.247 kg of brass and 0.3895 kg of stainless steel is recycled back into the manifold.
- For the sand-cast manifold, 6.175 kg of shredded aluminum is separated and recycled back into the manifold.
- For the multi-tube brazed manifold, 3.439 of shredded aluminum is recycled. 2.577 kg of the shredded aluminum is recycled back into the manifold and the remaining 0.862 kg leaves the system for another application. 2.496 kg of recycled aluminum is used as ingot for sand casting the flange section and 0.081 kg of recycled aluminum is used as scrap for extruding four tubes and an air collection chamber.

The energy data for these steps are:

- Shredding energy = 0.097 MJ / kg (42 BTU / lb); shredding energy was obtained from Texas shredder (1995).
- Separation energy for aluminum = 0.1 MJ / kg; separation energy was obtained from Huron Valley Steel (1995).
- Transportation energy = 2.05 MJ / ton-mile [10]. Shredders and separators are run by electric motors. Transportation trucks are diesel operated. Total waste in the retirement stage from electricity and diesel fuel use was obtained from Franklin [10].

3.3 Cost Analysis

A life cycle cost analysis was performed which accounted for explicit costs to manufacturers, customers, and end-of-life managers. The life cycle cost analysis traces the conventional costs accrued to manufacturers, customers, and end-of-life vehicle managers associated with the air intake manifold. Hidden or indirect costs, probabilistic costs (with the exception of warranty), and less tangible costs (e.g., potential increased productivity and revenues associated with environmentally preferable products), however, were not investigated. For example, special permitting, reporting , tracking and other hidden environmental costs that may be associated with the use of hazardous materials in the manufacturing phase were not analyzed. While a more detailed accounting of these costs would provide more accurate data for decision making, such a total cost assessment was outside of the scope of this life cycle design project.

Since the Contour is marketed and used in Europe, the cost analysis includes a European (German) scenario as well as a US scenario. The objective of this scenario analysis was to explore differences in market conditions that affect the use phase and end-of-life stages of the air intake manifold. The German scenario accounts only for differences in gasoline and landfill disposal costs; no attempt was made to estimate the differences in material costs and manufacturing costs in Germany.

3.3.1 Material Production

Material costs were evaluated using EQ(3.6). The material costs were evaluated only to show their relative contribution to the total manufacturing cost of each manifold system.

$$C_{matl} = \sum_{i=1}^{n} C_i \times M_i \tag{3.6}$$

where,

C_i = cost of i^{th} material purchased
M_i = mass of i^{th} material purchased
n = total number of different material in the manifold

Composite Manifold

The composite manifold consists of three materials (n=3): nylon resin, brass and stainless steel. Thus, EQ(3.6) reduces to:

$$\left|C_{matl}\right|_{com} = C_n \times M_n + C_b \times M_b + C_s \times M_s \tag{3.7}$$

where,

$\left|C_{matl}\right|_{com}$ = material cost of the composite manifold
C_n = material cost of the nylon resin = \$2.53 / kg
C_b = material cost of the 360 brass = \$1.54 / kg
C_s = material cost of the 304 stainless steel = \$0.77 / kg
M_n = mass of the nylon resin purchased = 2.0729 kg
M_b = mass of 360 brass purchased = 0.2635 kg
M_s = mass of 304 stainless steel purchased = 0.4715 kg

Thus, $\left|C_{matl}\right|_{com}$ = \$6.013

Sand-Cast Manifold

The sand-cast manifold consists of 100% secondary aluminum (n=1). Thus, EQ(3.6) reduces to:

$$\left|C_{matl}\right|_{sc} = C_{sa} \times M_{sa} \tag{3.8}$$

where,

$\left|C_{matl}\right|_{sc}$ = material cost of the sand-cast manifold
C_{sa} = material cost of secondary aluminum ingot = \$1.89 / kg
M_{sa} = mass of secondary aluminum purchased = 6.552 kg

Thus, $\left|C_{matl}\right|_{sc}$ = \$12.38

Multi-Tube Brazed Manifold

The multi-tube brazed manifold consists of primary and secondary aluminum (n=2). Thus, EQ(3.6) reduces to:

$$\left|C_{matl}\right|_{mtb} = C_{pa} \times M_{pa} + C_{sa} \times M_{sa} \tag{3.9}$$

where,

$\left|C_{matl}\right|_{mtb}$ = material cost of the multi-tube brazed manifold
C_{pa} = material cost of the primary aluminum ingot = \$2.12 / kg
C_{sa} = material cost of secondary aluminum ingot and scrap = \$1.89 / kg
M_{pa} = mass of primary aluminum purchased = 1.076 kg
M_{sa} = mass of secondary aluminum purchased = 2.577 kg

Thus, $\left|C_{matl}\right|_{mtb}$ = \$7.15

For the German scenario analysis, material costs were considered to be equivalent to US costs.

3.3.2 Manufacturing

Manufacturing costs consists of two main components: fixed costs, which include production and prototype tooling and development costs, and variable costs.

- Because manufacturing costs were proprietary, indirect cost estimates were used. The variable manufacturing cost of the manifold is estimated as one sixth of the part cost of the dealer. Thus,

$$C_{\text{var. mfg}} = \frac{C_{\text{dealer}}}{6} \tag{3.10}$$

- The differential cost of the composite manifold without the EGR tube and the sand-cast manifold is \$3.00. The cost of the EGR tube was estimated by Ford's manifold design group as \$8.50. Therefore,

$$\left|C_{\text{var. mfg}}\right|_{\text{comp}} - \left|C_{\text{var. mfg}}\right|_{\text{sc}} = \$11.50 \tag{3.11}$$

- As of August, 1995, the dealer part cost for the composite intake manifold for the 1995 Ford Contour is \$300.95 and the dealer cost for the multi-tube brazed manifold for the 1995 Ford Escort is \$244.78 . Thus,

$$\left|C_{\text{dealer}}\right|_{\text{comp}} = \$300.95$$

$$\left|C_{\text{dealer}}\right|_{\text{mtb}} = \$244.78$$

These costs were obtained from Ford dealers in Ann Arbor, MI [47][48]. There is a price revision every three months.

- Thus, variable manufacturing costs were computed as:

$$\left|C_{\text{var. manf}}\right|_{\text{comp}} = \$50.16$$

$$\left|C_{\text{var. manf}}\right|_{\text{mtb}} = \$40.80$$

$$\left|C_{\text{var. manf}}\right|_{\text{sc}} = \$38.66$$

- Estimates of the fixed manufacturing costs, which include production and prototype tooling and development costs, were provided by the Ford project team.

$$\left|C_{\text{fixed manf}}\right|_{\text{comp}} = \$3.90$$

$$\left|C_{\text{fixed manf}}\right|_{\text{mtb}} = \$2.90$$

$$\left|C_{\text{fixed manf}}\right|_{\text{sc}} = \$2.70$$

- Thus, the total manufacturing costs for different manifolds were obtained as:

$$\left|C_{\text{mfg}}\right|_{\text{comp}} = \$54.06$$

$$\left|C_{\text{mfg}}\right|_{\text{mtb}} = \$43.70$$

$$\left|C_{\text{mfg}}\right|_{\text{sc}} = \$41.36$$

For the German scenario analysis, manufacturing costs are based on the U.S. costs.

3.3.3 Use

In the use phase gasoline costs to the users and warranty costs to Ford were evaluated. It was assumed that the manifolds perform without maintenance costs to the owner over 150,000 miles. The US average cost (C_f) for gasoline was estimated as US $1.24 / gallon [49]. The German average cost (C_f) for gasoline was estimated as US $3.34 / gallon [49]. Lifetime use phase fuel cost (C_{use}) of the manifold was obtained from the life time fuel consumption ($F_{(gal)}$) as:

$$C_{use} = C_f \times F_{(gal)} \tag{3.12}$$

Lifetime fuel consumption ($F_{(gal)}$) was obtained from Table 3-6. The lifetime fuel costs for both the US and Germany are presented in Table 3-8.

Table 3-8. Lifetime Use Phase Fuel Costs for US and Germany

	Fuel Costs (US $)		
	Cast Aluminum	Brazed Aluminum Tubular	Nylon Composite
US	10.42	5.80	4.39
Germany	28.06	15.62	11.82

Warranty costs which are based on repair rates and service part costs were estimated by Ford to be $0.10, $0.04, and $0.08 for the cast aluminum, brazed aluminum tubular and nylon composite manifolds respectively.

3.3.4 Retirement

A cost analysis for each stage of the retirement process was conducted. The value of a used 1991 Escort multi-tube brazed manifold was found to be $50.00 [50]. The 1991 Escort manifold, however, weighs more than the 1995 Escort manifold. Although some aluminum manifolds are recovered during the dismantling stage, no data are available to estimate the fraction sold for used parts. Therefore, this credit was not incorporated in the life cycle cost analysis.

Intake manifolds are transported from dismantlers to the shredders as part of the retired vehicle. Transportation cost from dismantlers to shredders, assuming a 100-mile average distance [10] are: flattened hulks - $0.12 / ton-mile, unflattened hulks - $0.18 / ton-mile. Assuming a 50% split between flattened and unflattened hulks, total transportation cost is $0.15 / ton-mile. This value was used for this analysis.

Total costs and credits to shredder operators were obtained from the APC retirement spreadsheet model [32] as $116.64 / hulk and $125.21 / hulk respectively. Shredding cost (C_{sh}) includes hulk sale value (C_h), transportation cost (C_t), disposal cost (C_d)and the processing cost (C_{pr}) as shown in EQ (3.13).

$$C_{sh} = C_h + C_t + C_d + C_{pr} \tag{3.13}$$

Because the actual processing cost was not available, it was estimated using EQ(3.13) assuming a 1992 average automobile. The average weight of a 1992 vehicle was 1425.22 kg [51]. The material composition of this automobile includes 953.41 kg of ferrous material, 136.82 kg of non ferrous metals, 254.54 kg of nonmetals and 80.45 kg of fluids [51]. Assuming the dismantler drains all fluids and transports the remaining materials to the shredder, the weight of each hulk sold to the shredder is 1344.77 kg. The APC study assumed a hulk sales value (C_h) to the shredder to be $30.00 and a transportation cost of $0.12 / ton-mile [32]. In this model, the metal portion (1090.23 kg) of the hulk was assumed to be transported from shredders to metal recyclers an average distance of 200 miles and the nonmetal portion (254.54 kg) was assumed to be transported from shredders to landfills an average distance of 100 miles. Thus the total cost for transportation (C_t) was calculated to be $32.14. The APC study assumed a disposal fee for nonhazardous waste of $75.00 / ton. Because automotive shredder residue (ASR) in the US is classified as nonhazardous, the total cost for disposing (C_d) 254.54 kg of nonmetal ASR was calculated to be $21.00. The processing cost (C_{pr}) for the hulk was estimated from EQ (3.13) to be $33.50.

Table 3-9 itemizes costs for an intake manifold's end-of-life management.

Table 3-9. Itemized Cost Description for Different ELV Managers per Manifold

ELV Managers	Cost Descriptors	Composite manifold, 2.74 kg	Sand-Cast manifold, 6.5 kg	Multi-Tube Brazed manifold, 3.62 kg
Dismantler	• transportation (a)	$0.045	$0.110	$0.060
Shredder	• transportation to metal recycler (b)	$0.017	$0.160	$0.090
	• transportation to landfill (c)	$0.028	$0.004	$0.002
	• disposal (d)	$0.070	$0.011	$0.006
	• processing (e)	$0.068	$0.160	$0.090
Non-Fe Processor	• processing (f)	$0.190	$1.360	$0.750
	• scrap value (g)	$0.680	$5.930	$3.300
Total cost	sum: (a) through (f)	$0.420	$1.81	$1.00
Total value	(g)	$0.680	$5.93	$3.30

The processing (separation) cost for aluminum, stainless steel and brass were estimated by Huron Valley Steel to be $0.22 / kg, $0.27 / kg and $0.34 / kg respectively [29]. The scrap value for aluminum, brass and stainless steel were obtained from *American Metal Market* to be $0.96 / kg, $1.54 / kg and $0.77 / kg respectively.

Retirement cost information for end-of-life vehicle (ELV) managers as described above was converted to cost per manifold as shown in Table 3-8. The US disposal cost was calculated using a national average tipping fee of $30.25 / ton [33]. The European average tipping fee was estimated as US $275 / ton [52]. Because of cost data availability limitations, other European end-of-life costs were considered to be equivalent to US costs.

US total retirement costs for the composite, sand cast and multi-tube brazed manifold are $0.42, $1.81 and $1.00 respectively. European total retirement costs are $0.63, $1.84 and $1.02 respectively. The scrap value of the composite, sand cast and multi-tube brazed manifolds is $0.68, $5.93 and $3.30 respectively.

3.4 Performance Analysis

3.4.1 Manufacturing Phase

Manufacturing unit processes for the three manifold systems are shown in Table 3-10.

Table 3-10. Manufacturing Unit Processes for the Three Manifold Systems

Manifold	Component	Manufacturing Unit Process
Composite	Nylon manifold	• casting tin-bismuth melt cores • injection molding - mold and core insertion - overmolding • inductive melting tin-bismuth core • washing • post manifold assembly
	Brass fittings	• extrusion • machining
	Stainless steel EGR tube	• stamping • extrusion • brazing
Sand cast	Aluminum manifold	• green sand preparation • mold and core insertion • gating and riser preparation • melting and pouring • post casting machining
Multi-tube brazed	Sand-cast aluminum flange	• green sand preparation • mold and core insertion • gating and riser preparation • melting and pouring • post casting machining
	Extruded tubes and air collection chamber	• extrusion • bending of tubes • arrangement • brazing

Composite Manifold

It can be seen from Table 3-10 that the composite manifold involves three different materials and requires eleven unit processes for manufacturing. The lost core process consists of five different unit processes. The cycle time for injection molding is 1.5 minutes, the cycle time for core casting is 3 minutes and the cycle time for core melt out is 45 minutes.

In the lost core process, maintaining an appropriate core casting temperature and controlling core dimensional change during injection molding presents significant challenges to manufacturers. Getting the time-temperature cycle right on the core casting tool is critical [11]. If cores are cooled too fast they crystallize and become brittle, but if cores are cooled too slowly portions can still remain molten when the core is overmolded by nylon resin. The most critical part of the lost core process is accounting for melt loss of cores during injection molding. Since the tin-bismuth core alloy has a lower melting temperature (320° F - 160° C) than nylon resin (491° F - 255° C), some core metal may get melted when it is overmolded with molten nylon resin. Nylon resin loses its heat while melting part of the core layer and also undergoes stress relief and shrinkage during the melt-out stage. Therefore, in lost core process design, these dimensional changes are built into the tool design [11].

Because the core material has to be melted every time, lost core molding is a very energy intensive process. In addition, the stainless steel EGR tube increases overall complexity because it requires three different manufacturing processes.

Sand-Cast Manifold

The sand-cast manifold was the only one-piece manifold studied. As indicated in Table 3-10, sand casting involves five different unit processes. A typical cycle time for manufacturing a sand-cast manifold is 14 minutes. This includes 1 minute for core fabrication, 2 minutes for casting, 5 minutes for cooling, 0.5 minute for premachining pressure testing, 0.5 minute for machining and 2 minutes for washing, assembly, testing and packaging. The tool life for a typical aluminum manifold is about 250,000 cycles. The die life is about 1 x 10^5 to 2 x 10^5 mold parts before reconditioning.

Multi-Tube Brazed Manifold

The multi-tube brazed Escort manifold is comprised of a cast aluminum flange, four bent aluminum tubes and an air collection chamber joined together by brazing. The aluminum tubes and the collection chamber are manufactured by extrusion. After extrusion, aluminum tubes are bent into desired shapes by a movable mandrel. The casting is placed into a die and pressurized hydraulic fluid turns out the four openings from inside [6]. Table 3-10 indicates that the multi-tube brazed manifold involves nine different manufacturing unit processes that include five processes for sand casting. The cycle time for a multi-tube brazed manifold was not available, but it is expected to be higher than that of a sand-cast manifold because of extrusion and brazing.

3.4.2 Use

The smoother wall of the multi-tube brazed manifold is expected to lead to less frictional loss compared to the rough-walled, sand-cast manifold. This theoretically translates into higher volumetric efficiency and higher power output at the same throttle opening. However, Ford test engineers reported no significant difference in power between engines equipped with rough-walled, sand-cast manifolds and smooth-walled, composite manifolds at part throttle. At full throttle a 2% increase in power for the composite manifold was obtained. Similar conclusion can be inferred about smoother-walled, multi-tube brazed manifolds.

Ford’s manifold design group reported that composite manifolds deform to the shape of the engine where they are used and therefore cannot be remounted on another vehicle after retirement. Ford’s manifold engineers could not confirm reports of defects due to heat deformation for the 1995 Contour manifold. The stainless steel EGR tube is expected to transfer most of the heat away from the manifold.

Seven warranty claims related to composite manifolds were filed for a 7-month period during which 55,000 1995 Contours were sold. This is a defect rate of 0.13 per 1000 vehicles. Because the sand-cast manifold was not used in actual vehicle production, warranty data for this manifold are not available. For the multi-tube brazed Escort manifold, 262 warranty claims were filed in the last five years during which 1,438,593 vehicles were sold . This is a defect rate of 0.18 per 1000 vehicles. These warranty data include manufacturing flaws, assembly errors, mis-bins (wrong parts serviced) and accident repairs.

4. Results and Discussion

In this chapter, the methodology described in Chapter 3 is used to evaluate environmental burdens and cost metrics for sand-cast aluminum, multi-tube brazed aluminum and composite intake manifolds. All results are expressed per one intake manifold (IM).

Environmental burdens evaluated are energy, solid waste, air emissions and water effluents, based on the mass of manifold materials shown in Figure 2-1.

4.1 Environmental Burdens

4.1.1 Energy

Figure 4-1 shows life cycle primary energy requirements for the three manifolds. It can be seen that a sand-cast manifold has the highest life cycle energy, followed by a multi-tube brazed manifold and a composite manifold. Overall life cycle energy requirements for a sand-cast manifold is about 1.9 times higher than that of a composite manifold. A multi-tube brazed manifold requires 1.2 times the life cycle energy of a composite manifold. Most of these differences occur during use and are directly attributable to manifold weight.

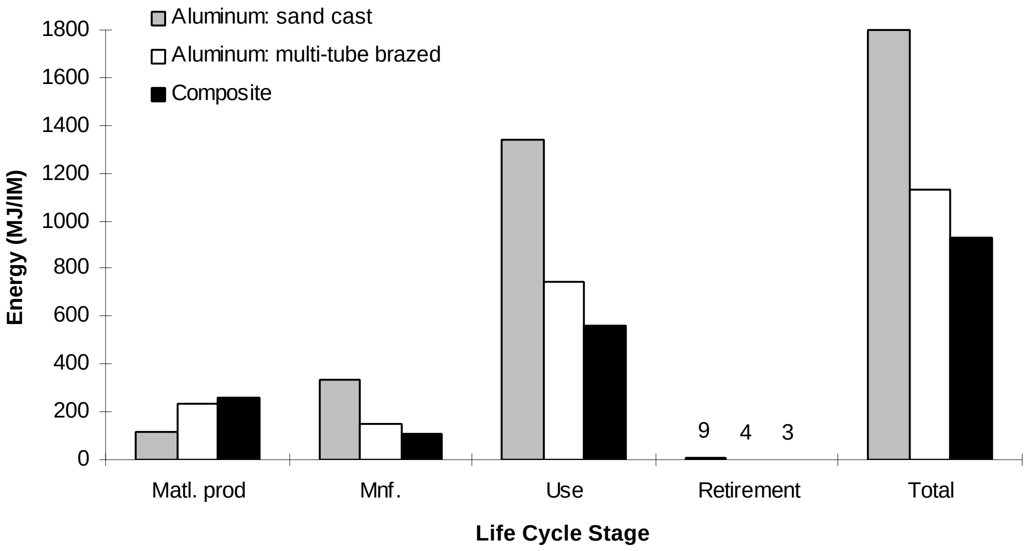

Figure 4-1. Life Cycle Energy of Intake Manifolds

A composite manifold requires the most material production energy as a result of producing virgin resin from petroleum and natural gas. Stainless steel and brass are mostly composed of secondary materials and contribute a small amount to the overall composite manifold energy profile. Production of a multi-tube brazed manifold requires 1.076 kg of primary ingot and 2.496 kg of secondary ingot. Primary aluminum production is about 10 times as energy intensive as secondary aluminum production. This results in about double the material production energy for a multi-tube brazed manifold compared to a sand-cast manifold, although the sand-cast manifold weighs 1.8 times more. For sand-cast, multi-tube brazed and composite manifolds, material production accounts for about 7%, 21% and 27% of total life cycle energy respectively.

Sand-cast manifolds are the most energy intensive to manufacture compared to other manifolds. The higher energy for manufacturing sand-cast manifolds is due partly to their higher mass and the higher energy density for sand casting. Primary energies for different manufacturing processes are shown in Table 4-1. The details of the methodology used to evaluate these data was presented in Chapter 3. Table 4-1 shows that sand casting is the most energy intensive manufacturing process for aluminum and extrusion is the most energy intensive process for stainless steel. Stamping energy for stainless steel is relatively small. Lost core process for manufacturing nylon manifold is the most energy intensive process among all manufacturing process studied. Melting of the tin-bismuth core accounts for 70% of the total manufacturing energy for lost core process. The rest 30% can be attributed to injection molding.

For a sand-cast manifold, manufacturing represents about 19% of life cycle energy; for a multi-tube brazed manifold, manufacturing accounts for about 13% of the life cycle energy; and for a composite manifold, manufacturing represents about 11% of life cycle energy.

Table 4-1. Primary Energy for Different Manufacturing Processes

Material	Manufacturing process	Primary Energy MJ / kg	Source and Representativeness
Aluminum	Sand casting	44.22	Sand casting data representative of Europe [21]
	Extrusion	16.76	Extrusion data representative of average European and US plant data [22] [23]
	Brazing	3.72	Brazing data obtained using engineering model
Nylon	Lost core process	47.21	• Injection molding data average of US and European • Plant specific data for inductive melting is used
Brass	Extrusion	5.51	• Brass extrusion data typical US plant [42] [7] • Energy for hot extrusion is obtained using engineering model [12]
Stainless steel	Rolling	2.70	• All steel data typical US [44][45]
	Stamping	0.20	• Extrusion and stamping data are obtained using engineering model [12]
	Extrusion	3.08	

As Figure 4-1 shows, the use phase dominates in terms of energy consumption. Use phase energy is directly proportional to manifold weight. For a sand-cast manifold, the use phase represents about 74% of life cycle energy; for a multi-tube brazed manifold, the use phase represents about 66% of the life cycle energy; and for a composite manifold, the use phase represents about 61% of life cycle energy.

Retirement represents on average only 0.4% of life cycle energy for these manifold systems and can be neglected to streamline analysis.

4.1.2 Solid Waste

Figure 4-2 shows that the multi-tube brazed manifold and the nylon composite generate the greatest amount of life cycle solid waste. Material production of primary and secondary aluminum for a multi-tube brazed manifold results in 76% of its overall life cycle solid waste. As shown in Table 3-3, red mud generated during alumina production accounts for 87% of solid waste for primary aluminum processing. The major components of solid waste from a composite manifold in the material production stage include mine tailings, combustion ash, mineral waste, sludge and polymer solids. On average, about 0.93 kg per kg of solid waste is generated from the production of materials for the composite manifold.

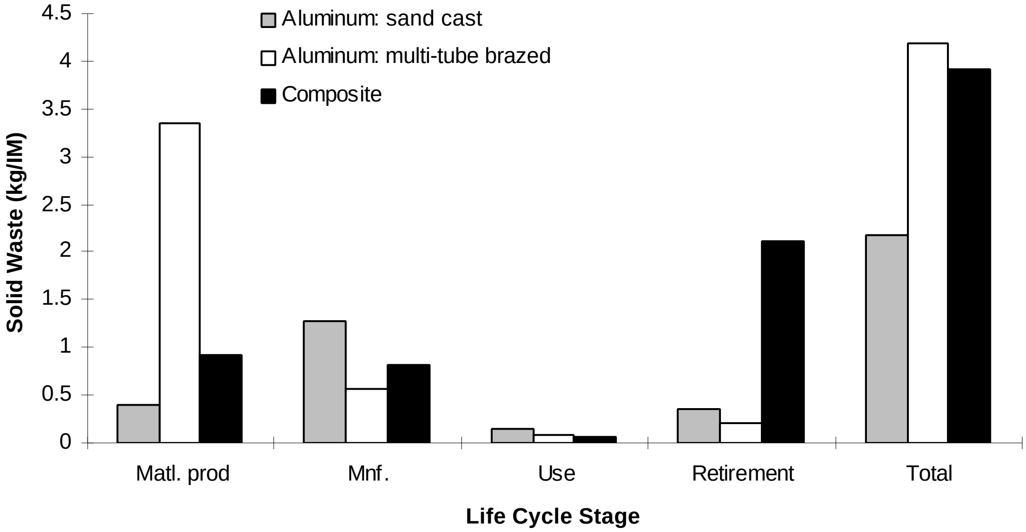

Figure 4-2. Life Cycle Solid Waste of Intake Manifolds

Solid waste in the manufacturing stage is comprised of process waste from sand casting, product waste and energy waste. Sand casting waste consists of fume dust and a 5% loss in recycling sand and salt slag. Product waste consists of a 5% loss in recycling scrap generated from manifold production. The process and product waste for a sand-cast manifold are 1.045 kg and 0.052 kg respectively. For a multi-tube brazed manifold, the process and product waste are 0.4 kg and 0.255 kg respectively. Process waste for a composite manifold in the manufacturing stage is primarily due to electricity generation and amounts to about 0.79 kg per intake manifold; product waste is 9.52 g per intake manifold.

Solid waste during use primarily results from waste generated in the production of gasoline.

Retirement solid waste includes a 5% loss in recycling metals at the end-of-life of the vehicle. For the composite manifold, in addition to 5% metals waste, all the nylon (2.07 kg) ends up as solid waste.

4.1.3 Air Emissions

Figure 4-3 shows life cycle pollutant emissions for the three manifold systems. The majority of pollutant emissions are in the form of nonmethane hydrocarbons (NMHC), NO_x, CO and SO_2. CO, NO_x and NMHC releases are highest for a sand-cast manifold, followed by a multi-tube brazed manifold and a composite manifold. However, the trend is different for CH_4, SO_2 and PM-10.

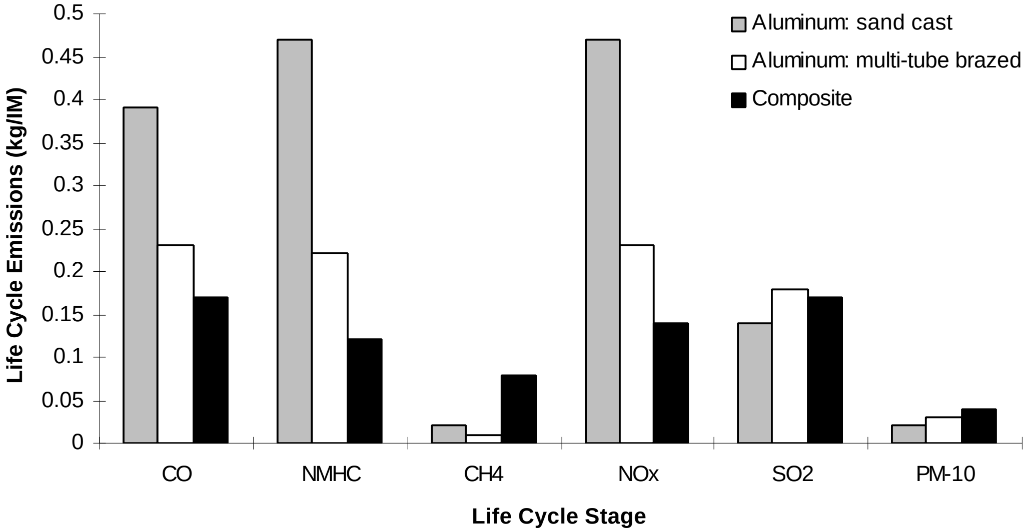

Figure 4-3. Life Cycle Pollutant Emissions of Intake Manifolds

The contribution of the intake manifold to the total vehicle use phase emissions was estimated assuming that these emissions are proportional to gasoline consumption. Although this relationship is valid for carbon dioxide, this allocation is probably not accurate for the other pollutants that are controlled by the catalytic converter.

The air emissions data for material production reported is expected to be highly uncertain and a comparison between the three systems is not recommended. A comparison of material production inventory data from two different sources showed a much greater variation in results for air and water emissions than was found for energy and solid waste [53].

Figure 4-4 shows that total greenhouse gas emissions for composite and multi-tube brazed manifolds are essentially similar. A sand-cast manifold is associated with about 1.5 times more greenhouse gas emissions compared to a composite manifold. This differential is primarily due to the heavier weight of a sand-cast manifold, which results in significantly greater greenhouse emissions during use.

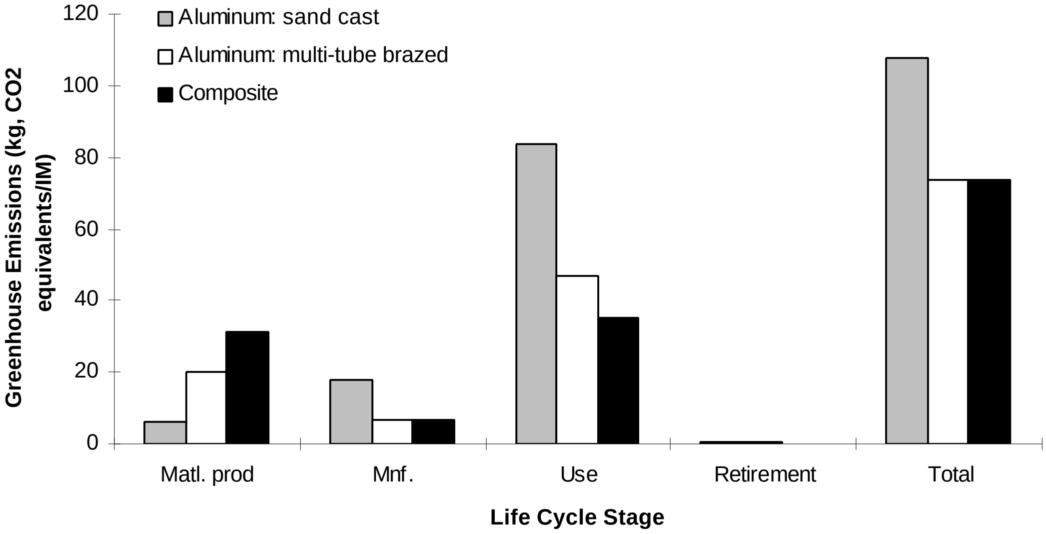

Figure 4-4. Life Cycle Greenhouse Gas Emissions for Intake Manifolds in CO_2 Equivalents

Figure 4-4 also illustrates that most greenhouse gases are released during the use phase for sand-cast and multi-tube brazed manifolds. For a sand-cast manifold, use phase greenhouse gas emissions represent about 76% of the life cycle total, while the use phase accounts for about 61% of total greenhouse gas emissions for a multi-tube brazed manifold. This difference is attributable to releases of CF_4 and C_2F_6 during primary aluminum production. Although only 0.56 g of these fluorocarbons are released in the production of primary aluminum for a multi-tube brazed manifold, their global warming potential is so much higher than $C0_2$ (6300 for CF_4 and 12500 for C_2F_6 where $CO_2 = 1$) that greenhouse gas emission in CO_2 equivalents for producing multi-tube manifolds is 19.9 kg compared to just 5.9 kg for sand-cast manifolds. This, coupled with much lower use phase emissions (46.7 kg vs. 83.8 kg for sand cast) due to the lighter weight of a multi-tube manifold, results in a significantly lower percentage of total greenhouse gas emissions occurring during the use phase.

For similar reasons, the use phase accounts for only about 48% of total life cycle greenhouse gas emissions for a composite manifold; materials production accounts for 43% . Nitrous oxide (N_2O, GWP = 270) releases during nylon production result in the highest greenhouse gas emissions of all the manifolds during this phase. N_2O constitutes 71% of greenhouse emissions in nylon material production, CO_2 for most of the remainder. In addition, the lighter weight of a nylon manifold results in the lowest CO_2 emissions during use. Thus, greenhouse emissions are nearly evenly distributed between material production and use for a composite manifold rather than being concentrated in the use phase.

It is apparent from this discussion that greenhouse gas emissions do not exactly parallel life cycle energy requirements for these manifolds. Use phase energy for sand-cast, multi-tube brazed and composite manifolds accounts for 74%, 66% and 61% of life cycle energy respectively; greenhouse gas emissions for these manifolds, 76%, 61% and 48%. These differences result from the high global warming potential of halogenated carbons released during material production.

Figure 4-5 shows how much of the greenhouse gas emissions associated with each manifold are actually CO_2. Use and manufacturing emissions are all in the form of CO_2 and are thus the same in Tables 4-4 and 4-5. As this table illustrates, greenhouse gas emissions associated with sand-cast manifolds are essentially all in the form of CO_2 while CO_2 emissions make up a smaller percentage of overall greenhouse emissions for the other manifolds.

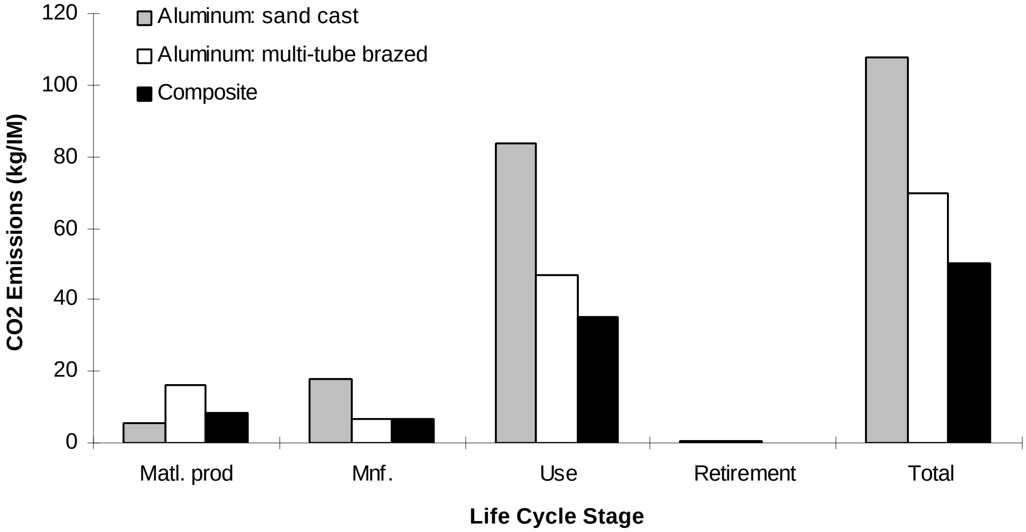

Figure 4-5. Life Cycle CO_2 Emissions of Intake Manifolds

4.1.4 Water Effluents

Figure 4-6 shows that the majority of water effluents on a mass basis are in the form of dissolved solids, the highest of which are associated with a composite manifold, the lowest with a multi-tube brazed.

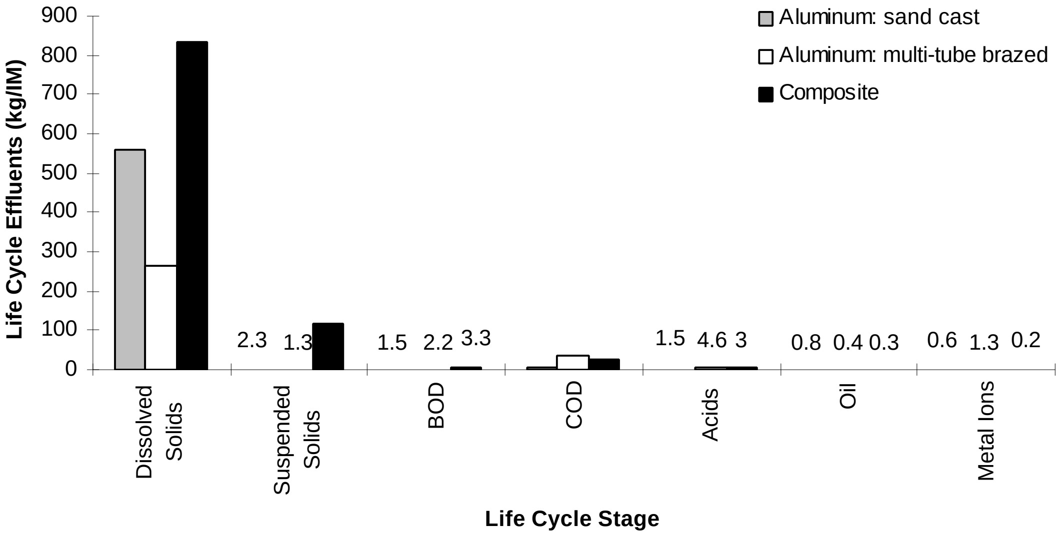

Figure 4-6. Cumulative Life Cycle Water Effluents of Intake Manifolds

4.2 Cost

4.2.1 U.S. Scenario

Table 4-2 shows that the life cycle costs of the two aluminum manifolds are similar. That of the composite manifold is approximately $10.76 more than that of the aluminum manifolds. The material cost of a sand-cast manifold is about $5.23 higher than that of multi-tube brazed and $6.87 higher than composite manifold. The higher material cost of a sand cast manifold is due to its higher weight compared to a multi-tube brazed manifold.

Table 4-2. Life Cycle Costs of Intake Manifolds (in U.S. dollars)

	Composite		Sand-cast		Multi-tube brazed	
	U.S.	German	U.S.	German	U.S.	German
Material cost	$6.01	$6.01	$12.38	$12.38	$7.15	$7.15
Manufacturing costs*						
fixed	$3.90	$3.90	$2.70	$2.70	$2.90	$2.90
variable	$50.16	$50.16	$38.66	$38.66	$40.80	$40.80
Use phase costs**	$4.47	$11.90	$10.52	$28.16	$5.84	$15.66
End of life costs***	$0.42	$0.42	$1.81	$1.81	$1.00	$1.00
Salvage value	$0.68	$0.68	$5.93	$5.93	$3.30	$3.30
Life cycle cost	$58.27	$65.70	$47.76	$65.40	$47.24	$57.06

* Manufacturing costs were estimated from data provided by Ford, for the German scenario analysis manufacturing costs were based on U.S. conditions.

** Use phase costs include both fuel and warranty costs.

*** End of life costs include transportation (dismantler, shredder, and landfill), disposal, and processing.

The sum of the manufacturing and warranty cost for a multi-tube brazed manifold was estimated to be about \$2.28 higher than a sand-cast manifold because of increased manufacturing complexity. The estimated manufacturing and warranty costs of a composite manifold is about \$12.67 more than that of a sand-cast manifold. Manufacturing accounts for the majority of life cycle costs for sand cast (87%), multi-tube brazed (93%) and composite (93%) manifolds. Ford’s manifold costs include both material purchase, manufacture, and warranty. Ford’s cost is estimated \$37.34 for a sand-cast manifold, \$41.44 for a multi-tube brazed manifold and \$53.87 for a composite manifold.

Gasoline cost to the user of a sand-cast manifold over a useful life of 150,000 miles is about \$4.62 more than that of a multi-tube brazed manifold and \$6.03 more than that of a composite manifold. These differences reflect the effect of weight on gas mileage.

In the retirement stage, a sand-cast manifold requires more to process, but has an aluminum scrap value that is results in a net cost \$1.82 lower than the multi-tube brazed manifold. A composite manifold requires the lowest processing cost in the retirement stage, because its major constituents are disposed to landfills rather than recovered.

4.2.2 German Scenario

In contrast to the US scenario, the life cycle costs of the two aluminum manifolds, shown in Table 4-2, diverge greatly due to the higher cost of gasoline in Germany. This results in the heavier cast aluminum manifold having a life cycle cost \$8.35 greater than the multi-tube brazed manifold and only a marginally lower cost than the composite manifold.

4.3. Design Analysis and Integration

4.3.1 Decision-Making

The life cycle inventory analysis, life cycle cost analysis, and performance analysis presented in the previous chapter reveal significant tradeoffs among each of the three intake manifold designs. The selection of the preferred manifold design using a complex and diverse set of criteria and data can be aided by a structured decision analysis process. A formalized process was applied in this project to highlight some of the challenges in evaluating environmental performance and integrating environmental performance with other criteria. Inherent in the decision making process are tradeoffs, judgments required for weighting criteria, and uncertain and incomplete data.

4.3.2 Scope

It is useful to recognize the difference between the planning process and the detailed design process. The planning process at Ford begins between 36 and 48 months before a vehicle is launched into production. During this process various elements of the design may be selected such as materials and manufacturing processes. A preferred design may be proposed but an alternative design may also be developed as a prototype which can be substituted in the event that unanticipated problems occur which no longer favor or prohibit the original preferred design.

The intake manifold must accommodate vehicle system, powertrain subsystem, and engine specific requirements. Consequently, the manifold design should be evaluated in the context of these larger system boundaries. This decision analysis presented here however will be limited primarily to the manifold system.

The life cycle inventory and cost analyses were based on U.S. conditions where possible. Since the Contour is marketed globally the product development team should consider factors that are unique to Europe and other markets. For example, the life cycle cost analysis is very sensitive to the price of gasoline. The use phase cost would triple or quadruple if the German gasoline price was substituted for the U.S. price.

The decision making process is also influenced by the time horizon considered. Strategic planning can be an important element of the design process and lead to more ecologically sustainable design solutions. Decision makers may weigh greenhouse emissions more heavily when taking a long range perspective compared to a short term development cycle.

4.3.3 Identification of Key Drivers

A wide range of factors influence the selection of alternative manifold designs. Design requirements and guidelines serve to guide the decision making process. The multi-criteria requirements matrices are a tool for identifying and organizing key requirements.[3][5][53] Ford guidelines, corporate directives and policies as well as external requirements such as government regulations were identified. The set of internal and external environmental "requirements" examined are presented in Table 4-3**.** These environmental “requirements” can be used to interpret results from the life cycle inventory and cost analyses. Design decision making occurs in the context of the business and external forces impacting the business and its products.

Table 4-3. Internal and External Environmental Requirements

Internal	External
Energy	
– Corporate citizenship – Minimize facility energy (Manufacturing Environmental Leadership) – Meet platform fuel economy targets	– CAFE – Voluntary pledge of German auto industry to reduce CO_2 emissions
Materials	
– Ford targets for recycled content of plastic resin (D109, A120, Manufacturing Environmental Leadership) – Substance use restrictions (WSS-M99P9999 also known as HEX9) – Reduce part/vehicle weight	– Reduce materials used, increase materials recycled, and reduce waste
Waste	
– Protect health and environment (Policy Letter 17) – Recyclability targets (Directive F-111) – Reduce manufacturing waste (A-120)	– European guidelines for reducing waste going to landfill: maximum 15% by weight—2002 maximum 5% by weight—2015 – Voluntary initiatives to reduce greenhouse emissions

4.3.4 Decision Analysis

A framework for decision analysis is necessary to integrate "requirements" and the results from life cycle inventory and cost analyses to select among the alternative intake manifolds. Two basic approaches can be taken for analyzing life cycle results. The full set of results can be evaluated together or environmental, performance, and cost data can be evaluated separately. The latter approach enables the decision maker to determine which design is most preferred environmentally, which is beneficial in understanding and comparing the environmental profile of each design.

The original matrix that Ford used to evaluate alternative manifold designs prior to this project is shown in Table 4-4**.** The rankings for each criteria are also shown. The individual weighting factors are not provided here for reasons of confidentiality, and therefore, the overall scores (weighting factor x ranking) could not be computed.

Table 4-4. Original Ford Requirements Matrix

Requirements	**Ranking**		
	Cast Aluminum	Brazed Aluminum Tubular	Nylon Composite
120k Durability	10	8	8
First Time Quality Capable	6	4	10
Airflow/Performance	6	8	8
Weight	4	6	10
Fastener Compatibility	10	6	2
Joint Sealing	8	8	6
Material Dimensional Stability	10	6	4
Flammability Resistance	10	10	2
High Temperature Performance	10	8	2
Low Temperature Performance	10	10	2
Positive Pressure Capability	10	8	4
NVH-Structural	10	6	4
NVH-Acoustical	8	4	2
Prototype Lead Times	8	6	4
Prototype Tooling Cost	8	6	2
Production Lead Times	8	6	4
Variable Cost	8	8	6
Production Tooling Cost	8	4	2
Appearance	6	6	8
Established Supply Base	10	4	6
Manufacturing Flexibility	6	4	2
Component Integration Opportunity	4	2	8
Design Flexibility	8	6	6

This project offers a more comprehensive assessment of each manifold by incorporating additional environmental and cost data. The decision analysis structure proposed for this project is shown in Figure 4-7**.**

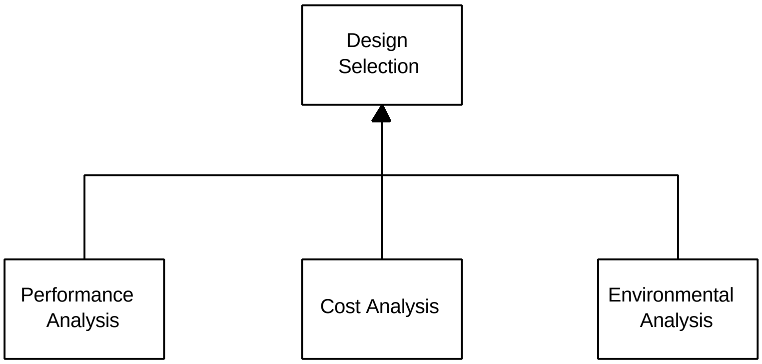

Figure 4-7. Decision Analysis Structure

4.3.5 Performance Analysis

Each manifold alternative must meet basic performance criteria to become a viable candidate for a particular design application. Weighting factors for the performance criteria are dependent on specific vehicle platform objectives. For example, the NVH-Acoustical (noise, vibration, and harshness) criterion would be weighted higher for a luxury car relative to an economy car. The cast aluminum manifold generally had higher rankings compared with the nylon composite or the brazed aluminum tubular manifolds. The nylon composite manifold, however, was preferred for several important criteria, including, first time quality capability, weight, and component integration opportunity. The three manifolds investigated in this project meet these criteria. As Table 4-4 shows, most of the requirements in the original Ford matrix were performance criteria. The components of the performance analysis are shown in Figure 4-8.

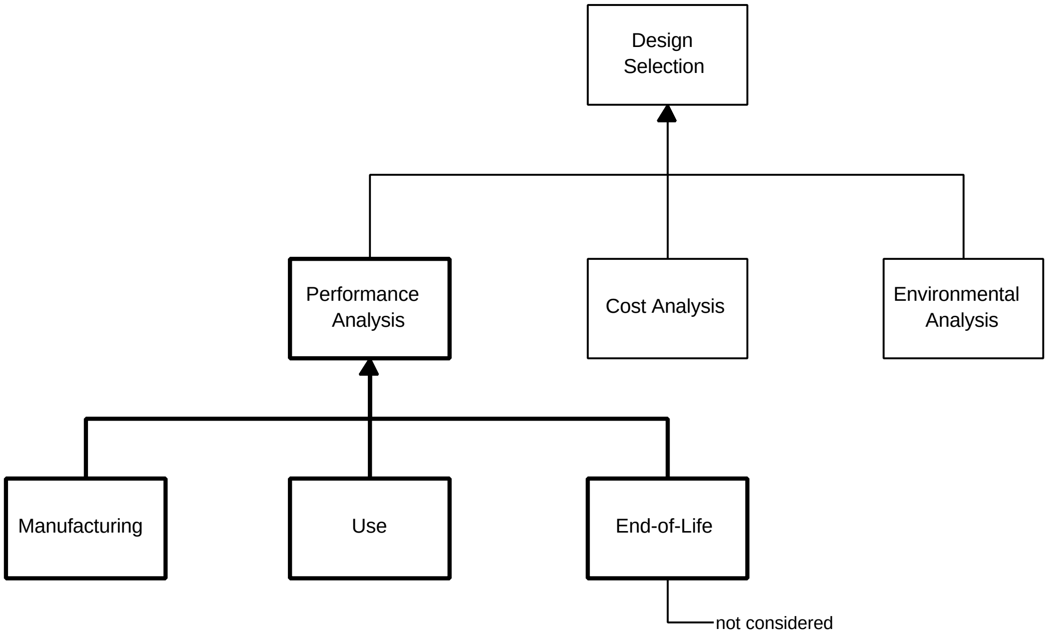

Figure 4-8. Components of the Performance Analysis

4.3.6 Cost Analysis

The cost analysis has three major components as shown in Figure 4-9.

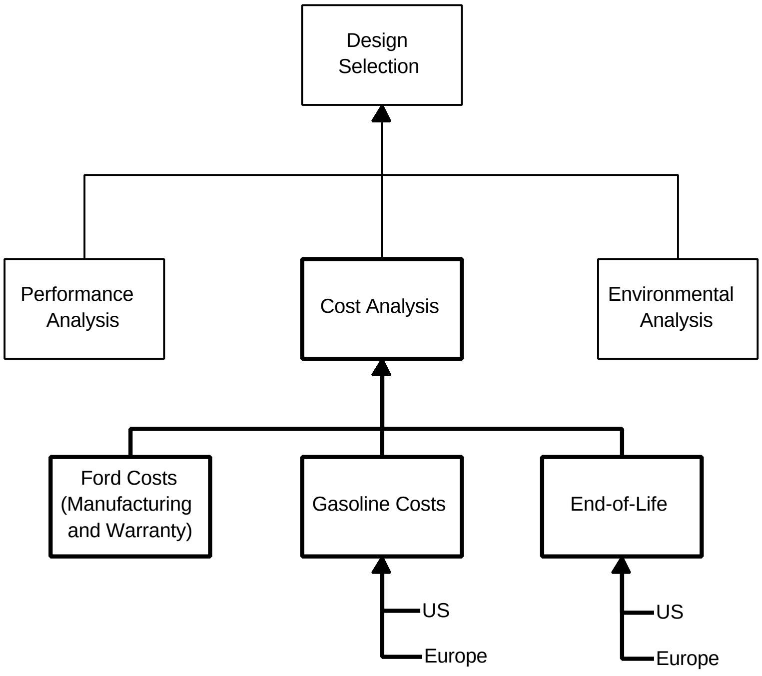

Figure 4-9. Components of the Cost Analysis

Life cycle costs can be grouped according to those direct costs incurred by Ford and those costs occurring outside Ford's cost domain. Ford manufacturing costs are a primary criteria for making a business decision. In addition, warranty costs are direct costs borne by Ford due to product defects or improper assembly of the manifold on the engine. The life cycle costs incurred outside of Ford's domain during the use and retirement phases represent costs to the customers and vehicle recyclers. Gasoline costs in Germany are much more significant than in the U.S. and therefore this criterion was evaluated for both U.S. and German conditions. In Germany, gasoline costs are an important factor in vehicle purchasing decisions for a greater fraction of customers than in the US. Consequently, as shown in Figure 4-10, the cast aluminum manifold may be cheaper to produce, but the effect of higher gasoline costs on vehicle sales must also be considered. The CAFE standard in the U.S. can also be an important factor in weighing alternative designs. This factor depends on how well specific vehicle platform weight targets are being met and how close the company is to violating CAFE standards. The cost of end-of-life vehicle management may become an important criteria since legislation is being discussed in Europe requiring OEM take back of automobiles at no cost. In this scenario, retirement costs would become part of the total Ford manifold cost as indicated in Figure 4-11. Figure 4-10 indicates that, the aluminum cast and the brazed aluminum tubular manifolds would provide a greater end-of-life credit compared to the nylon composite manifold.

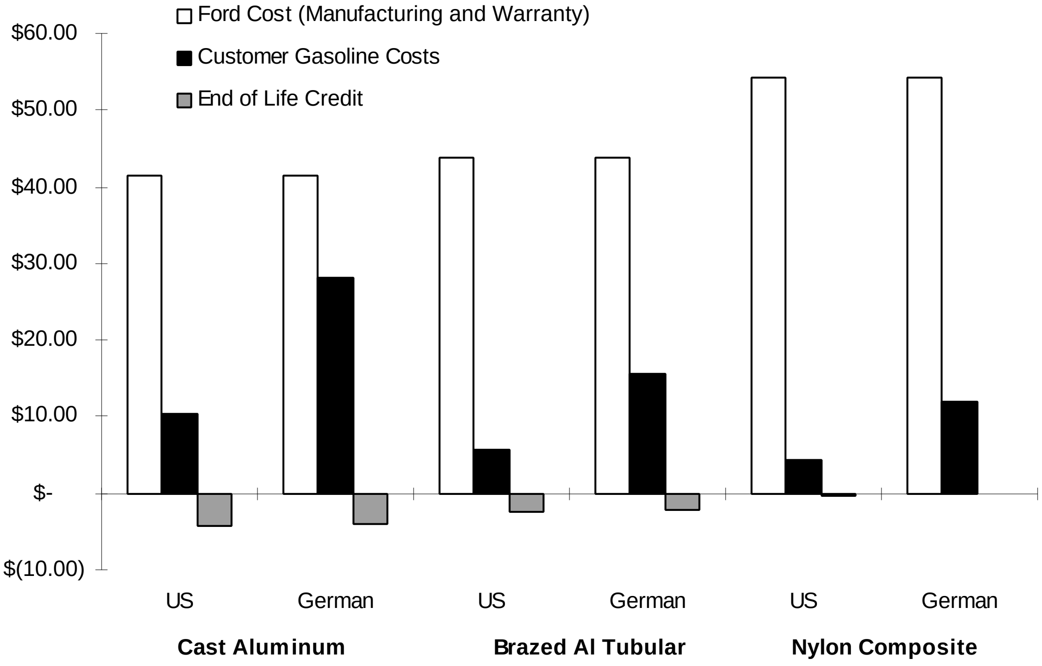

Figure 4-10. Life Cycle Costs for Intake Manifolds for US and Germany

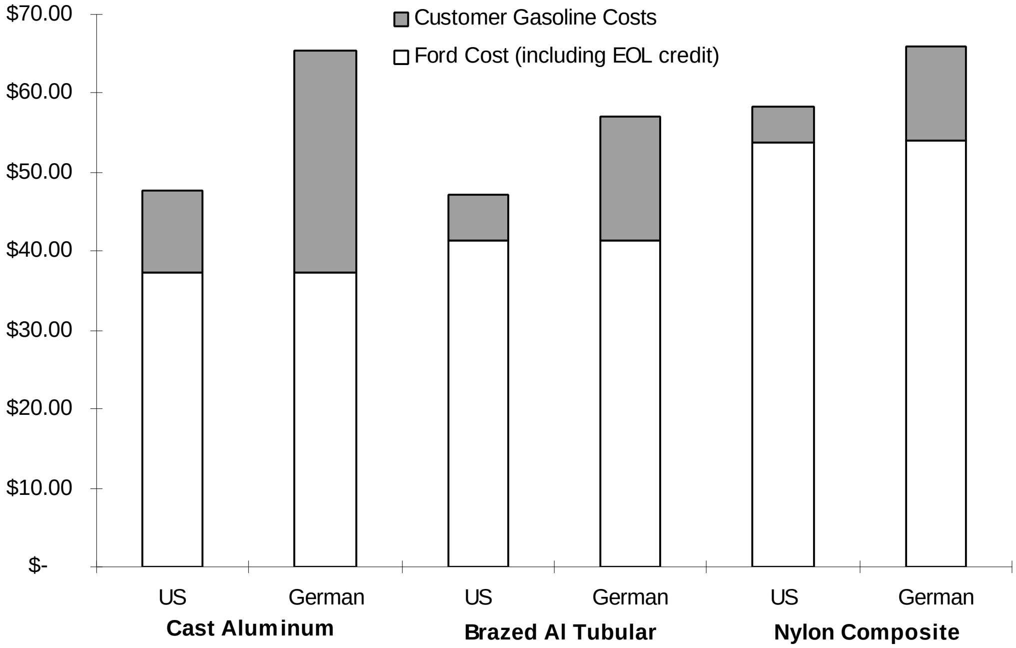

Figure 4-11. Life Cycle Costs under Take Back for Intake Manifolds for US and Germany

4.3.7 Environmental Analysis

The environmental analysis includes both the LCI analysis and a regulatory/policy analysis as shown in Figure 4-12.

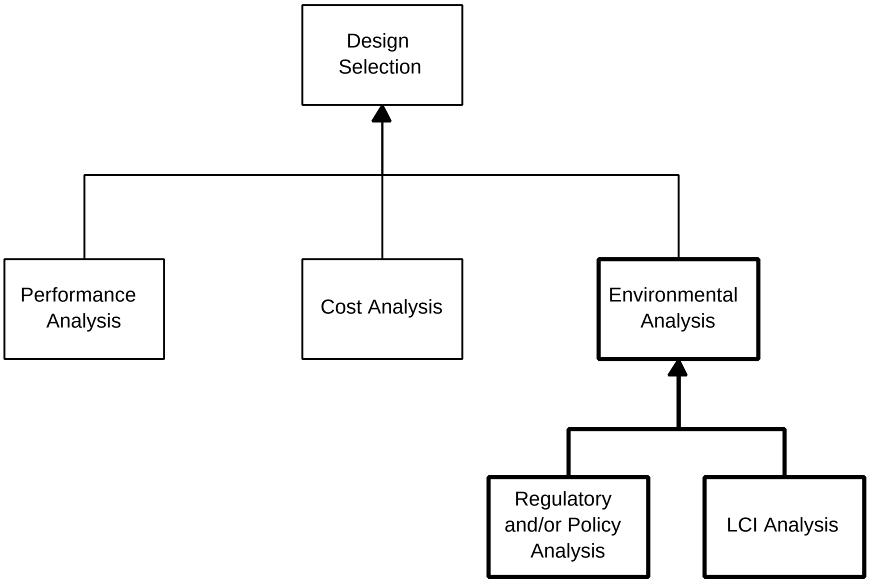

Figure 4-12. Components of the Environmental Analysis

Energy

Currently, no specific corporate guidelines or government regulations and policies encourage a reduction in the total life cycle energy. Several "requirements" are directed at specific stages of the life cycle. For example, Ford's Manufacturing and Environmental Leadership Program seeks to minimize facility energy consumption [54]. CAFE in the US and a voluntary pledge of the German auto industry to reduce CO2 emissions focuses on use phase energy. Among the three manifold designs the nylon composite best meets all energy related requirements and consumes the least life cycle energy, as shown in Figure 4-1 of Section 4.1.1. For this case, no tradeoffs emerge, although an impact assessment may consider the source of energy (coal, natural gas, petroleum, etc.).

Materials

Ford internal requirements addressing life cycle materials include targets for recycled content of plastic resin, substance use restrictions, and vehicle/part weight reductions goals [54]. It is difficult to establish specific guidelines for interpreting the life cycle materials metrics presented in Table 4-5. Ideally, each design would minimize the total materials used including primary and secondary materials, maximize the total materials recycled, and reduce waste. It is well recognized that these criteria can easily conflict with other environmental objectives such as minimizing life cycle energy. The total material mass of the cast aluminum manifold design is greatest but the manifold utilizes secondary aluminum and it is currently being recycled during end-of-life management of the vehicle. The brazed aluminum tubular manifold uses less total material but incorporates primary aluminum. This manifold is also recycled in the end-of-life phase. Both aluminum manifolds use phenol and formaldehyde to form molds for casting. The nylon manifold uses the least total material but incorporates the greatest quantity of primary material, which currently is not recycled during the end-of-life phase.

Table 4-5. Materials Metrics for Intake Manifolds (per IM basis)

	Cast Aluminum	Brazed Aluminum Tubular	Nylon Composite
Product mass (kg)	6.5	3.62	2.74
Primary material content	0.0%	25%	76%
Restricted substances (kg)	0.017	0.017	0

Waste

The inventory category waste includes solid waste, air pollutant releases, and waterborne pollutant releases. The life cycle "waste" inventory results were presented in Figures 4-2 through 4-6. Interpretation of the inventory results presents several challenges which are addressed and/or are being investigated as part of life cycle impact assessment methodology.

The aluminum cast manifold generated the least amount of life cycle solid waste as was shown in Figure 4-2. No guideline, however, currently exists at Ford which seeks to minimize life cycle solid waste. Ford internal requirements address both manufacturing waste and end-of-life solid waste minimization. The minimization of material production solid waste is not specified as part of Ford's material procurement guidelines. Consequently, Ford's internal policy would favor the aluminum cast and the brazed aluminum tubular manifolds equally even though a significant amount of solid waste in the form of red mud is generated with the brazed aluminum tubular system. The European guidelines for reducing the amount of waste going to landfill will probably lead to further emphasis on end-of-life waste compared with solid waste generated in other life cycle phases.

Several techniques were tested for characterization of the air emissions and waterborne emissions inventory results. The critical volume approach was applied in an attempt to normalize the set of air pollutant emissions. EPA Criteria Air Pollutant Standards were used for this normalization, however, standards do not exist for all of the pollutants inventoried in this analysis. Similarly, a variety of sources were investigated to normalize water emission data. A comparison of material production inventory data from two different sources showed a much greater variation in results for air and water emissions than was found for energy and solid waste [55]. Consequently, it was recommended that the air and water emissions data not be weighted heavily in the environmental analysis.

4.4 Proposed Environmental Metrics

An important objective of this demonstration project is to develop environmental metrics that could be used by design engineers to evaluate design alternatives. Ideally a comprehensive LCA could be conducted for each design, but data availability, costs, and time constraints currently limit its applicability [56]. Two main criteria were used in proposing environmental metrics: reliability in guiding environmental improvement and data availability to evaluate the metrics. The reliability of the metrics addresses whether the metrics in combination with other environmental requirements will lead to the same outcome as a comprehensive environmental analysis such as an LCA. For the metrics to be practical, design engineers need to be able to evaluate the metrics without having to collect a large set of additional data. Consequently, these metrics should not include emission factors or energy parameters that are not readily accessible from an internal database.

4.4.1 Proposed Metrics

Metrics were proposed by applying the above criteria. The proposed metrics for materials, energy and waste are given in Tables 4-6, 4-7, and 4-8 respectively. Table 4-9 is provided to allow comparison of the proposed metrics to the results of the life cycle analyses.

Table 4-6. Proposed Materials Metrics for Intake Manifolds

	Primary Material in Finished Part (kg)		
	Cast Aluminum	**Brazed Aluminum Tubular**	**Nylon Composite**
Aluminum	–	0.89	–
Nylon	–	–	1.39
Glass Fiber	–	–	0.68
Brass	–	–	0.003
Total	–	*0.89*	*2.07*

Table 4-7. Proposed Energy Metrics for Intake Manifolds

	Energy (MJ)		
	Cast Aluminum	**Brazed Aluminum Tubular**	**Nylon Composite**
Material Production	169	246	268
Operation	1,339	746	565
Total	*1,508*	*991*	*833*

Table 4-8. Proposed Waste Metrics for Intake Manifolds

	Waste (kg)		
	Cast Aluminum	**Brazed Aluminum Tubular**	**Nylon Composite**
Part Solid Waste (end-of-life)	0	0	2.07
CO_2 Mat. Production	5.59	13.88	9.25
CO_2 Operation	84.09	46.66	35.32

Table 4-9. Summary of Life Cycle Analyses for Intake Manifolds

	Cast Aluminum	**Brazed Aluminum Tubular**	**Nylon Composite**
Life Cycle Energy (MJ)	1798	1131	928
Life Cycle Materials			
Product mass (kg)	6.5	3.62	2.74
Primary material content	0	25%	76%
Restricted substances (kg)	0.017	0.017	0
Life Cycle Waste			
Life cycle solid waste (kg)	2.18	4.18	3.91
Life cycle GWP (CO2 kg equivalents)	107.9	73.8	73.6

4.4.2 Discussion

The reliability of the environmental metrics in estimating life cycle environmental burdens can be tested by comparing the results provided in Tables 4-6 to 4-8 with the life cycle inventory data reported in Figures 4-1 to 4-6. With the exception of the part solid waste metric, close agreement between metrics and inventory results indicates that the metrics are reasonable surrogates.

For the three intake manifold designs, the mass of primary product material input into the manufacturing stage can be approximated by analyzing the mass of primary material in the finished part. No primary material is required in manufacturing the cast aluminum design. For the brazed aluminum manifold the mass of primary aluminum in the extruded tubes was estimated to be 0.887 kg while the inventory analysis calculations indicated that 1.08 kg of primary aluminum from bauxite is used. The difference is largely determined by the material efficiency for part fabrication. For part fabrication steps with large scrap rates, the environmental metric based on the mass of finished part will be a less accurate indicator of primary material usage.

The energy metrics which address the material production and operation stages of the life cycle account for a large fraction of the life cycle energy consumption. The energy metrics indicate the same trend in energy consumption among the three manifold designs as was indicated by the total life cycle energy data. The use phase energy metric is identical to the calculation made in the life cycle inventory analysis for the use phase. A discrepancy exists between the material production energy metric and the material production energy calculated from the life cycle inventory analysis. This discrepancy originates from two sources. The first source of discrepancy can be attributed to differences in material input requirements which was discussed above. Differences in material production energy data is a second source of discrepancy. The inventory analysis drew on several published data sets whereas the environmental metrics were calculated using data compiled by Ford. The exclusion of manufacturing energy from the energy metrics can introduce significant error for manufacturing processes that are energy intensive, such as casting.

The life cycle waste metrics included part solid waste and carbon dioxide emissions from material production and operation. The solid waste metric only addresses one discrete life cycle stage—end-of-life management. For the aluminum manifolds this metric does not account for any of the total life cycle solid waste. In the case of the nylon composite manifold it accounts for approximately 53 percent. By adopting this metric, however, more emphasis and responsibility would be placed on this stage of the life cycle. The carbon dioxide emissions track closely with energy consumption and the carbon dioxide metrics provide a reasonable estimate of the emissions computed by the LCI. Again the level of discrepancy between the metrics and the LCI depend on the validity of the assumptions in the model used to define the metrics. As more reliable data becomes available, the model can be refined to provide a more accurate description of the system.

In the absence of a life cycle inventory analysis, environmental metrics may be used to improve environmental decision making during design analysis. Caution must be taken in applying the metrics developed in this study to other air intake manifold design applications. Whenever such simplifying assumptions and boundary truncations are applied the comprehensiveness and reliability of the results will be reduced accordingly. These metrics do however direct designers attention to upstream and downstream aspects of the product life cycle that may not otherwise be fully considered. In addition, designers should not make decisions based on individual metrics but rather the entire set. For example, if the solid waste metric was the only criteria used to evaluate plastic vs. metallic materials in automotive applications, then plastics would not likely be used on automobiles. In the case of the manifold, however, the operation phase energy metric favors the nylon composite manifold. Consequently, tradeoffs exist which must be weighed in decision making.

5. Conclusions

This demonstration project with Ford applied the life cycle design framework to air intake manifold design. This project was successful in providing environmental, cost, performance, regulatory, and policy data for enhancing the design analysis of three alternative air intake manifolds: cast aluminum, brazed aluminum tubular, and nylon composite. Significant tradeoffs among the three designs were highlighted and the value of the life cycle design framework was discussed. Limitations of life cycle design methodologies and tools as well as organizational barriers affecting their implementation were also characterized.

The design analysis consists of three basic components: environmental analysis, cost analysis, and performance analysis. The multi-criteria requirements matrix was useful in identifying and organizing key requirements for design analysis. Requirements specified internally by Ford and requirements set externally such as government regulations were compiled using the matrix structure. Life cycle inventory analysis and life cycle cost analysis were specific tools used to evaluate design alternatives.

The life cycle inventory analysis indicated significant environmental tradeoffs among alternative manifold designs. The life cycle energy consumption for the cast aluminum, brazed aluminum tubular, and nylon composite manifolds were 1798 MJ, 1131 MJ, and 928 MJ per manifold, respectively. The use phase energy accounted for a major fraction of this energy: 74% for the cast aluminum, 66% for the brazed aluminum tubular, and 61% for the nylon composite; which indicates the significance of manifold mass on life cycle energy. The solid waste profile had a different distribution across the life cycle. The use phase solid waste originating from the gasoline fuel cycle contributed only a small portion of the total solid waste. The cast aluminum manifold generated the least life cycle solid waste, 218 kg per manifold, whereas the brazed aluminum tubular and nylon composite manifolds generated comparable quantities of 418 kg and 391 kg, respectively. Red mud generated during alumina production accounted for 70% of the total life cycle solid waste for the brazed tubular manifold while the nylon component of auto shredder residue was responsible for 53% of the total waste for the nylon composite manifold.

The life cycle inventory analysis provides a comprehensive set of data to support the environmental analysis of the manifold system. Life cycle inventory analysis results were interpreted with respect to Ford internal environmental policies, guidelines, and goals as well as external environmental requirements such as existing and proposed government policies and regulations. The multicriteria requirements matrices were useful in identifying and recording both regulatory and non-regulatory environmental requirements. No specific Ford policy states that the total life cycle environmental burdens for each automotive part and component should be minimized. Rather different policies and guidelines address discrete stages of the life cycle. Ford and other OEM’s set vehicle weight targets which guide individual part and component development. The life cycle energy results indicated that manifold weight accounted for between 61% and 74% of the manifold life cycle energy. Consequently, weight targets set by manufacturers for vehicles and vehicle subsystems have a strong impact on life cycle energy for an individual part or component.

Corporate Average Fuel Economy (CAFE) is an important regulatory driver influencing vehicle fuel economy targets and weight targets. CAFE standards for passenger cars have been stagnant over the last decade [57] and new car corporate average fuel economy has followed a similar trend. In addition, there is a very weak cost driver for pushing vehicle demand toward more fuel efficient vehicles. On the other hand, pressures to reduce manufacturing and material production energies are primarily economic.

Both internal and external environmental requirements emphasize reduction of post-consumer solid waste to a greater extent than waste generated in other life cycle phases. For example, European guidelines provide specific targets for the reduction of post-consumer solid waste disposed in a landfill. Similar measures for material production and manufacturing stages do not exist. Consequently, from a business perspective it is may appear beneficial to reduce post consumer waste which is governed by external requirements rather than reduce material production waste which is not affected by a specific waste policy. Again economic incentives exist to reduce manufacturing wastes.

The life cycle cost analysis was useful in identifying key cost drivers influencing the economic success of each design alternative. Costs can be organized into current and potential (future) manufacturing costs borne by Ford, customer costs, end-of-life management costs, and externality costs associated with each life cycle phase. The nylon composite manifold had the highest estimated manufacturing costs which were about $10 greater than the two aluminum manifold designs. The stainless steel EGR tube only required for the nylon composite manifold accounted for this differential cost. However, the use phase gasoline costs to the customer over the lifetime of the vehicle, however, was least for the composite manifold. The gasoline costs associated with the composite and the aluminum brazed tubular manifolds were about $6 and $5 less, respectively, than the cast aluminum manifold. The gasoline costs are much more significant in Germany and have a greater influence on vehicle purchasing decisions. As indicated previously, gasoline costs in the U.S. are a relatively weak economic driver for reducing energy consumption in the use phase.

Under take back legislation in Europe the OEM will incur the end-of-life costs. In this case, end-of-life credits resulting from the net salvage value of recycled manifolds would benefit Ford directly. Credits of $4.10 for the cast aluminum manifold and $2.30 for the brazed aluminum tubular manifold would accrue to the OEM. The salvage value of the brass and stainless steel associated with the nylon composite manifold offset waste disposal costs of glass-reinforced nylon. Otherwise, the nylon composite manifold would result in greater costs to Ford under the current European end-of-life management infrastructure.

A total of 20 performance requirements were used to evaluate each design alternative. Each of the three manifolds satisfied basic performance requirements for manufacturing and vehicle operation. Meeting basic performance requirements is an essential first step by which feasible candidates are screened for further design analysis. Particular emphasis was given to several manufacturability performance criteria which have a strong effect on manufacturing costs. Several performance requirements are also interconnected with environmental requirements. For example, durability can have a major impact on the environmental profile of a product. Each manifold met 120K durability requirements but a longer useful life could facilitate manifold reuse as a replacement part. Many manufacturability requirements influence scrap rates which also have a direct impact on environmental burdens.

This project revealed several organizational factors affecting the successful implementation of life cycle design projects. Comprehensive evaluation of the total life cycle system necessitated the participation of a cross functional team with a broad range of expertise. This project educated many members of the team on the life cycle design methodology. The multiobjective analysis served to introduce the project team to the full spectrum of issues constraining the manifold system. It was recognized due to the model complexity and data intensity that a comprehensive evaluation should not be performed in the final stages of design but rather it would be performed in the planning stages. As a planning tool for product development life cycle design can highlight opportunities for improvement by identifying major environmental burdens, costs, regulatory and policy issues to target. As a planning tool alternative materials and design strategies can be explored. The project team also discussed the challenge of predicting trends in future end-of-life management infrastructure that could impact a new vehicle that may not be retired until ten years later. This time lag introduced a significant level of uncertainty into the design analysis process.

Several members of the project team advocated characterizing the different environmental burdens into a single score to facilitate the use of the life cycle assessment methodology by design engineers. A variety of techniques were investigated including translating the environmental burdens into monetary costs, applying the critical volume approach, environmental theme method and other impact assessment methods[58] . None of the approaches were found to be acceptable to the project team due to limitations in evaluating parameters needed for these different models. A single score approach may also limit the design team from exploring how major environmental burdens are distributed across the product life cycle. In addition, the direct relationship between these burdens, and cost, performance, regulatory and policy factors can be more clearly understood if burdens are itemized.

Integration of performance, cost and environmental requirements to form an overall design decision matrix was studied. Emphasis of the project team was more on framing the design decision rather than on actually recommending a preferred manifold design. Each manifold design had a superior set of attributes. The project team favored the aluminum brazed tubular and nylon composite manifolds over the sand cast aluminum manifold due to their weight differentials. For this manifold application, the aluminum tubular design offered significant manufacturing cost savings relative to the nylon composite design. This may have overshadowed the slightly better life cycle energy performance of the nylon composite manifold. An important benefit of the life cycle design framework is that it clarifies the complex set of factors that influence the likelihood for success of a business decision. Tradeoffs are made explicit and interrelationships between design objectives are made apparent.

An air intake manifold is only one component of the powertrain system which is part of the total vehicle system. Consequently, it makes only a relatively small contribution to the overall environmental burdens of an automobile. More widespread application of the life cycle design methodology to other vehicle components and systems, however, can result in substantial opportunities for improvement. This project served to demonstrate the value of life cycle systems thinking in design and will hopefully be extended to other parts and components, as well as higher level vehicle systems in the future.

References

1. Keoleian, Gregory A., and Dan Menerey. *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System*. US EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, Cincinnati, OH, 1993.

2. ———. Sustainable development by design: Review of life cycle design and related approaches. *Journal of the Air and Waste Management Association* 44 (5): 645-668 (1994).

3. Keoleian, Gregory A., Jonathan Koch, and Dan Menerey. *Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal*. US Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH EPA/600/R-95/107, 1995.

4. Keoleian, Gregory A., Werner J. Glantschnig, and William McCann. Life cycle design: AT&T demonstration project. IEEE International Symposium on Electronics and the Environment, San Francisco, 2 May. Piscataway, NJ: Institute of Electrical and Electronic Engineers, 1994.

5. Keoleian, Gregory A. Pollution prevention through life cycle design. *Pollution Prevention Handbook*. ed. Harry M. Freeman, 253-292. New York: McGraw-Hill, 1995.

6. Eyerer, P., M. Schuckert, and Th Dekorsy. *Life Cycle Analysis of Automotive Air Intake Manifolds of Aluminum and PA 6.6 GF 35*. Institut für Kunststoffprüfung und Kunststoffkunde, Universität Stuttgart, Stuttgart, Germany, 1992.

7. Bustamalti, Tony. Deeco Industries, personal communication, January 1996.

8. Steel Recycling Institute. *Recycling Scrapped Automobiles*. Pittsburgh, PA: SRI, 1994.

9. Martchek, Ken. Alcoa, personal communication, August 1995.

10. Franklin Associates. *Appendix A: Energy Requirements and Environmental Emissions for Fuel Consumption*. Franklin Associates, Prairie Village, KS, 1992.

11. Naitove, Matthew H. Blow molding. *Plastics Technology* (Aug): 45-47 (1994).

12. Kalpakjian, Serope. *Manufacturing Engineering and Technology*. Reading, MA: Addison-Wesley, 1995.

13. Dhillon, B. S. *Life Cycle Costing: Techniques, Models, and Applications*. New York: Gordon and Breach, 1989.

14. White, Allen L., Monica Becker, and James Goldstein. *Total Cost Assessment: Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis*. US EPA, Office of Pollution Prevention and Toxics, Washington, DC, 1992.

15. *Material Production Inventory Data for Glass-Reinforced Nylon (PA6.6 GF33) and Brass (UNS 36000)*. David Doyen, and Bill Haaf. Dupont, Wilmington, DE, 1995.

16. Martchek, Kenneth J., Eden S. Fisher, and Richard A. Schultz. The total environmental potential of aluminum in automobiles. SAE Total Life Cycle Conference, Vienna, 16 October. Warrendale, PA: Society of Automotive Engineers, Technical Paper 951834, 1995.

17. Alcoa. *Environmental Life Cycle Considerations of Aluminum in Automotive Structures*. Aluminum Company of America, Automotive Structures, Southfield, MI Environmental Papers 1-4, 1994.

18. SFOEFL. *Ecobalance of Packaging Materials State of 1990*. Swiss Federal Office of Environment, Forests, and Landscape, Berne, Switzerland, 1991.

19. IISI. *Competition Between Steel and Aluminum for the Passenger Car*. International Iron and Steel Institute, Brussels, 1994.

20. Sullivan, J. L., and J. Hu. Life cycle energy analysis for automobiles. SAE Total Life Cycle Conference, Vienna, 16 October. Warrendale, PA: Society of Automotive Engineers, SAE Paper 951829, 1995.

21. Titchell, Ian. Cost and energy savings in aluminum foundries. *The Foundryman* (Apr): 105-108 (1992).

22. Hydro Aluminum. *Aluminum: Today's Automotive Solution*. Livonia, MI, 1994.

23. Arthur D. Little. *Status and Evolution of the US Aluminum Industry: Implications for Natural Gas*. Gas Research Institute, Chicago, IL GRI-88/0025, 1988.

24. Scott, W. D., C. E. Bates, and R. H. James. Chemical emissions from foundry molds. *AFS Transactions* 98: 203-208 (1977).

25. McKinley, M. D., I. A. Jefcoat, and W. J. /Frederick, C. Herz. Air emissions from foundries: A current survey of literature, suppliers and foundrymen. *AFS Transactions* 105: 979-990 (1993).

26. Schwartz, M. *Brazing*. London: Chapman & Hall, 1995.

27. Humpston, Giles, and David M. Jacobson. *Principles of Soldering and Brazing*. Materials Park, OH: ASM International, 1993.

28. U.S. EPA. *Highway Vehicle Emission Estimates II*. US Environmental Protection Agency, Office of Mobile Sources, Washington, DC, 1995.

29. Osterberg, Dick. Huron Valley Steel, personal communication, December 1995.

30. American Metal Market. *American Metals Market*, July 19, p. 6 (1996).

31. Lockhart, Jim. American Petroleum Association. Personal communication, April 1995.

32. APC. *Economics of Recovery and Recycling*. American Plastics Council, 1994.

33. NSWMA. National Solid Waste Management Association, personal communication, May 1995.

34. Franklin Associates. *Material Production Database*. Franklin Associates, Prairie Village, KS, 1995.

35. Jensby, Paul. Chicago Extruded Metals, January 1996.

36. Pacific Environmental Services. *AP-42 Section 12.8 Background Report: Secondary Aluminum*. US Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1995.

37. ———. *AP-42 Section 12.1 Background Report: Primary Aluminum*. US Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1995.

38. Harnisch, Jochen, Reinhard Borchers, and Peter Fabian. Estimation of tropospheric trends (1980-1995) for CF_4 and C_2F_6 from stratospheric data. Proceedings of Pollution of the Troposphere and Stratosphere, 1995.

39. Czadzeck, Jerry. Ford Motor Company, personal communication, August 1995.

40. Ogando, Joseph. Drive retrofits slash energy bills. *Plastics Technology* (Jan): 15-17 (1 1995).

41. Rugg, Michael. Inducto Heat, personal communication, January 1996.

42. Tenzek, Tony. Ajex Magnetothermic Corp., personal communication, January 1996.

43. Bosch. *Automotive Handbook*. Stuttgart, Germany: Bosch, 1993.

44. Ginzburg, Vladimir B. *Steel-Rolling Technology*. New York: Marcel Dekker, 1989.

45. Matsukawa, T., and Y. Yoshibe. *Recent Developments in Reheating Furnaces*. Nippon Steel Technical Report No. 20, 1982.

46. Roberts, William L. *Hot Rolling of Steel*. New York: Marcel Dekker, 1983.

47. Varsity Ford. Varsity Ford, personal communication, August 1995.

48. Gene Butman Ford. Gene Butman Ford, personal communication, August 1995.

49. EIA. *International Energy Annual.*, 1993.

50. D&R Auto Parts, personal communication, May 1995.

51. AAMA. *AAMA Motor Vehicle Facts & Figures*. American Automobile Manufacturers Association, Detroit, MI, 1994.

52. Gottselig, Bernd. *Personal Communication, June 7*. Detroit, MI: Ford Motor Company, 1996.

53. Keoleian, Gregory A., and Jeff S. McDaniel. Life Cycle Design of Instrument Panels: A Common Sense Approach. SAE International Congress and Exposition, Detroit, Michigan, 24 February. Warrendale, PA: SAE International, Technical Paper 970695, 1997.

54. *Ford Information*. Detroit, MI: Ford Motor Company, 2 1996.

55. McDaniel, Jeff. *Application of Life Cycle Assessment and Design Tools to Instrument Panels: Analysis for Common Sense Initiative Pilot Project. Masters Thesis*. Ann Arbor, MI: University of Michigan, 1996.

56. Keoleian, Gregory A. The application of life cycle assessment to design. *Journal of Cleaner Production* 1 (3-4): 143-149 (1994).

57. Keoleian, G. W., K. Kar, M. Manion, and J. Bulkley. *Industrial Ecology of the Automobile: A Life Cycle Perspective*. SAE, 1997.

58. Baumann, Henrikke, and Tomas Rydberg. Life cycle assessment: A comparison of three methods for impact analysis and evaluation. *Journal of Cleaner Production* 2 (1): 13-20 (1994).

Appendix A

Life Cycle Stage : Material Production				
	Aluminum		**Composite**	**Conditions / Assumptions**
Metrics	**Sand cast**	**Multi-tubebrazed**	**Contour**	**MASS OF MATERIALS PROCESSED & MATERIAL COMPOSITION:**
				Sand cast aluminum manifold:
Energy, primary (MJ / IM)	1.17E+02	2.36E+02	2.56E+02	• mass of secondary aluminum ingot = 6.552 kg
Waste				
Solid (kg / IM)	4.04E-01	3.34E+00	9.31E-01	
Air emissions (kg / IM)				**Multi-tube brazed aluminum manifold:**
CO2	5.70E+00	1.61E+01	8.35E+00	• mass of primary aluminum ingot = 1.076 kg
Particulates	2.34E-03	2.20E-02	1.53E-02	• mass of secondary aluminum ingot = 2.496 kg
NOx	2.35E-02	3.96E-02	3.54E-02	
SO2	1.15E-02	1.03E-01	5.96E-02	**Composite manifold:**
CO	1.45E-03	1.83E-02	2.26E-02	• mass of virgin nylon processed = 2.129 kg
CH4	1.70E-02	6.49E-03	8.17E-02	• mass of stainless steel scrap processed = 0.4715 kg
NMHC	5.24E-05	4.08E-03	5.21E-03	• stainless steel is produced in electric arc furnace that use 100% scrap
FC (CF4+C2F6)		5.65E-04		• UNS C36000 brass is produced from 99% scrap and 1% primary ingot
HCl	8.52E-03	3.24E-03	4.51E-04	• mass of primary brass ingot processed = 0.00329 kg
Halogenated HC			3.07E-06	
Heavy metals			3.45E-07	
Fluorine			1.20E-03	**INVENTORY DATA**
H2	4.91E-03	1.87E-03		**Aluminum manifold**
Water effluents (kg / IM)				Energy
Dissolved solids		2.74E-03	7.01E-01	Avg. energy density for sec. Al = 17.9 MJ / kg [Kar & Keoleian, 1996]
BOD		1.37E-03	2.63E-03	Avg. energy density for prim. Al = 177.9 MJ / kg [Kar & Keoleian, 1996]
COD		3.39E-02	2.55E-02	Waste
Suspended solids		1.40E-05	1.16E-01	• most data are obtained from [Eyerer et al., 1992] for European condition
Acids	7.21E-04	4.13E-03	2.66E-03	• the Stuttgart data for European condition are representative of typical
Heavy metals	1.97E-04	1.12E-03	3.29E-07	US conditions [Kar & Keoleian, 1996]
Tar/oil		2.15E-06	1.54E-03	• Average red mud of 2.63 kg / kg for primary aluminum production is
Fluorides		1.08E-06		incorporated into solid waste [Martchek, 1995][Eyerer et al., 1992]
Chlorides			5.10E-02	• Following data are obtained from other sources:
Nitrates			1.64E-05	- CO2 [Alcoa, 1994], FC [Harnisch & Borchers, 1995]
Water consumption (l / IM)	1.04E+01	1.63E+01	2.02E+01	- SO2, NOx - alumina production [Martchek, 1995],
				- solid waste, water consumption [Martchek, 1995]
				Composite manifold
				• nylon, glass fiber and brass data are obtained from [DuPont, 1995]
				• stainless steel data are obtained from [Franklin, 1996]

Appendix A

Life cycle stage : Manufacturing				
	Aluminum		**Composite**	**Conditions / Assumptions**
Metrics	**Sand cast**	**Multi-tube**		**Sand cast manifold**
Energy (MJ / IM)	2.97E+02	1.25E+02	3.40E+01	• energy density for sand casting = 39.36 MJ/kg [Titchell, 1992]
electricity (utility)		2.89E+00	3.32E+01	• natural gas fired furnace for melting and holding [Titchell, 1992]
natural gas (comb)	2.97E+02	1.22E+02	7.57E-01	• efficiency factor for natural gas = 0.89 [Franklin, 1992]
Prim. energy, elec		9.02E+00	1.04E+02	• primary energy equivalent = Energy for sand casting / 0.89
Prim. energy, Natlgas	3.34E+02	1.38E+02	8.51E-01	• recycling efficiency of sand, salt slag and scrap = 95%
Prim. energy, TOTAL	3.34E+02	1.47E+02	1.05E+02	• energy and waste for the production of green sand not included
Waste (process+elec)				• total waste = energy (natl. gas) waste + process waste
Solid (kg / IM)				• energy wastes are obtained from [Frankiln, 1992]
- processing scrap loss	1.10E+00	4.32E-01	9.52E-03	
- electricity/natl. gas	1.86E-01	1.37E-01	7.97E-01	**Multi-tube brazed manifold**
TOTAL Solid	1.28E+00	5.69E-01	8.07E-01	• energy(natl. gas) density for sand casting = 39.36 MJ/kg [Titchell, 1992]
Air emissions (kg / IM)				• energy (primary) density for extruding aluminum = 16.76 MJ / kg
Particulates	1.24E-03	2.34E-03	2.17E-02	• M(aluminum cast) = 2.731 kg, M(aluminum extruded) = 1.537 kg
CO2	1.76E+01	6.94E+00	6.61E+00	• E (electricity) for brazing = 1.9E-03 MJ / IM
NOx	2.74E-01	1.02E-01	3.11E-02	• energy for brazing is obtained using engg. model
SO2	1.69E-03	5.60E-03	5.74E-02	• total waste = energy(natl. gas+electricity) waste + process waste
CO	4.71E-02	1.76E-02	6.93E-03	• energy wastes are obtained from [Franklin, 1992, 1995]
CH4		3.52E-06	4.05E-05	• 95% internal recycling of sand, salt slag and scrap
NMHC	2.12E-01	7.70E-02	5.94E-03	**Composite manifold**
Aldehydes	1.70E-05	6.58E-06	5.05E-06	*Nylon*
Kerosene		1.70E-07	1.96E-06	M(process)=2.129kg,M(virgin resin)=2.073kg,M(recycled scrap)=0.056kg
Ammonia	1.76E-05	6.79E-06	5.05E-06	• inductive melting of tin-bismuth alloy, 250 kW, 1.5 min. cycle time
Lead		3.29E-09	3.78E-08	• E(electrical) for melting furnace = 22.5 MJ / IM
H2S	2.24E-04	8.09E-05		• Average injection molding energy density = 4.54 MJ / kg
HCN	3.17E-05	1.15E-05		• E(total electrical) = 4.54*2.129+22.5 = 32.165 MJ
Acrolyn	5.67E-07	2.05E-07		• Energy for transfer by robot, washing and insertion is neglected
Aromatic amines	5.67E-06	2.05E-06		• 95% of in-house scrap recycled, 55 solid waste
Benzene	1.64E-04	5.94E-05		*Brass*
Toluene	1.70E-05	6.14E-06		• M(billet extruded)=0.329 kg
Xylene	1.13E-05	4.10E-06		• E(melting) = 1.18 MJ / kg (induction furnace)
Napthalene	5.67E-06	2.05E-06		• E(extrusion)=0.32 MJ / kg using engg. model, E(cutting) = 0.08745 MJ / IM
Phenol	3.51E-05	1.27E-05		• E(total) = 0.581 MJ / IM
Water effluents (kg / IM)				• 95% of in-house scrap recycled, 5% solid waste
Dissolved solids	2.49E-01	9.00E-02	2.65E-03	*Stainless steel (SS)*
Suspended solids		6.73E-07	7.73E-06	• tubes and fasteners are extruded, brackets are rolled and stamped
BOD		4.39E-07	5.05E-06	• M(extruded) = 0.22425 kg, M(rolled/stamped) = 0.24725 kg
COD		1.24E-06	1.42E-05	• E(extrusion) = 0.53 MJ/kg(electricity)+1.27 MJ/kg(natl. gas), engg. model
Acids		2.23E-07	2.56E-06	• E(rolling) = 0.177 MJ/kg (electricity)+1.91 MJ/kg (natl.gas), engg. model
Oil		2.23E-07	2.56E-06	• E(stamping) =1.16 MJ/kg (electricity), [IISI, 1994]
Metal ions		1.11E-07	1.28E-06	• E(total electricity) =0.45 MJ/IM, E(total natl. gas) = 0.757 MJ/IM
Sulfides		4.19E-04	4.81E-03	• 95% of in-house scrap recycled, 5% solid waste
Phenolics		1.11E-07	1.28E-06	**Total composite manifold**
Iron		4.13E-04	4.75E-03	• solid waste = product waste + waste associated with energy production
				• energy production wastes are obtained from [Franklin, 1992, 1995]

Appendix A

Life Cycle Stage : Use				
	Aluminum		**Composite**	**Conditions / Assumptions**
	Sand cast	**Multi-tube**		
Mass (kg / IM)	6.5 kg	3.62 kg	2.74 kg	• life of intake manifold (LIM) is assumed to be 150,000 miles
Energy (MJ / LIM)	1.34E+03	7.45E+02	5.64E+02	• vehicle type = Contour, 1995
Waste				Energy
Solid (kg / LIM)	1.37E-01	7.64E-02	5.78E-02	• energy is obtained from fuel economy to weight correlation
Air emissions (kg / LIM)				• test eight of vehicle = 3250 lb = 1471 kg
CO2	8.38E+01	4.67E+01	3.53E+01	• fuel economy = 31.5 mpg
CO	3.37E-01	1.92E-01	1.42E-01	• 10% weight reduction = 4% fuel economy reduction
CH4				• total energy = combustion + precombustion energy
NMHC	2.56E-01	1.43E-01	1.08E-01	Waste
NOx	1.64E-01	9.14E-02	6.91E-02	• tail pipe combustion emissions are obtained from US EPA's
Particulates	1.60E-02	8.92E-03	6.74E-03	National Vehicle and Fuel Emissions Laboratory, Ann Arbor under the
SO2	1.21E-01	6.73E-02	5.09E-02	Freedom of Information Act
Aldehydes	1.52E-03	8.49E-04	6.42E-04	• total waste = (combustion+precombustion) waste
Ammonia	1.52E-03	8.49E-04	6.42E-04	• precombustion wastes are obtained from [Franklin, 1995]
Lead	1.14E-05	6.37E-06	4.82E-06	
Water effluents (kg / LIM)				
BOD	1.52E-03	8.49E-04	6.42E-04	
COD	4.19E-03	2.34E-03	1.77E-03	
Suspeneded solids	2.29E-03	1.27E-03	9.63E-04	
Dissolved solids	3.08E-01	1.72E-01	1.30E-01	
Metal ion	3.81E-04	2.12E-04	1.61E-04	
Oil	7.62E-04	4.25E-04	3.21E-04	
Phenol	3.81E-04	2.12E-04	1.61E-04	
Sulfide	3.81E-04	2.12E-04	1.61E-04	
Acid	7.62E-04	4.25E-04	3.21E-04	

Appendix A

Life Cycle Stage : Retirement				
	Aluminum		**Composite**	**Conditions / Assumptions**
	Sand cast	**Multi-tube**		
				Recycling conditions
Mass (kg / IM)				**Sand cast aluminum manifold**
- recycled into manifold	6.18E+00	2.58E+00	7.32E-01	• 95% of manifold recycled, 5% disposed tp landfill
- recycled into other products		8.62E-01		• 6.175kg aluminum from manifold recycled into the manifold
- recycled to manifold as ingot	6.18E+00	2.50E+00		• 0.377 kg of secondary ingot is supplied from other products
- recycled to manifold as scrap		8.10E-02	7.32E-01	**Multi-tube brazed aluminum manifold**
- disposed to landfill	3.25E-01	1.81E-01	2.10E+00	• 95% of manifold recycled, 5% disposed tp landfill
Shredders (.097 MJ/kg)				• 3.439 kg aluminum from manifold recycled
Energy, E (MJ / IM)	6.31E-01	3.51E-01	2.66E-01	• 2.577 kg of aluminum recycled back into the manifold
Separation				• 0.862 kg of aluminum leaves the manifold system
Energy, E (MJ / IM)				**Composite manifold**
- aluminum	6.18E-01	2.58E-01		• 100% nylon appears as ASR and is disposed to landfill
- brass			3.69E-02	• 95% of brass and stainless steel recycled, rest 5% disposed to landfill
- stainless steel			4.23E-02	• mass of brass recycled = 0.247 kg
- ASR			6.83E-02	• mass of stainless steel recycled = 0.39 kg
E(Sepn., MJ / IM)	6.18E-01	2.58E-01	1.48E-01	• recycling metrics for brass and stainless steel also include the other
E(Shred+Sepn) (MJ/IM)	1.25E+00	6.09E-01	4.13E-01	scrap recycled
TOTAL electricity (MJ / IM)	1.25E+00	6.09E-01	4.13E-01	
TOTAL electricity	3.90E+00	1.90E+00	1.29E+00	**Energy**
converted to primary energy				Shredding energy obtained from Texas Shredder
Transportation				Energy = 0.097 MJ / kg
- ASR-landfill, 200 miles	1.47E-01	8.18E-02	9.51E-01	Separtion energy obtained from Huron Valley Steel
- metal recycled, 300 miles	4.19E+00	1.75E+00	4.96E-01	Energy (ASR) = 0.033 MJ / kg
TOTAL diesel energy	4.33E+00	1.83E+00	1.45E+00	Energy (aluminum) = 0.1 MJ / kg
TOTAL diesel energy	5.16E+00	2.18E+00	1.72E+00	Brass and stainless steel requires additional energy
converted to primary energy				to separate
				Additional energy for SS = 2.53 kJ / kg
TOTAL primary energy	9.06E+00	4.08E+00	3.01E+00	Additional energy for brass = 41.85 kJ / kg
				Energy (SS) = 0.10253 MJ / kg
Waste (kg / IM)				Energy (brass) = 0.14185 MJ / kg
Solid (kg / IM)	3.55E-01	1.95E-01	2.11E+00	Shredders andd separators are elctricity operated
Air emissions (kg / IM)				Transportation is through diesel trucks
CO2	5.90E-01	2.65E-01	1.96E-01	Energy = 2.05 MJ / ton-mile
CO	3.22E-03	1.38E-03	1.08E-03	All energies are converted to primary enrgy by
NMHC	1.47E-03	6.33E-04	4.89E-04	dividing with appropriate efficiency factors
CH4	1.52E-06	7.43E-07	5.04E-07	Efficiency factor (elctricity) = 0.32
Kerosene	7.36E-08	3.59E-08	2.44E-08	Efficiency factor for diesel = 0.84
NOx	4.44E-03	1.95E-03	1.48E-03	Waste
Particulates	1.28E-03	5.92E-04	4.24E-04	Electricity and diesel waste are obtained from
SO2	3.08E-03	1.44E-03	1.02E-03	Franklin database [1992]
Aldehydes	7.96E-05	3.36E-05	2.66E-05	95% of metals are assumed to be recovered and 5%
Ammonia	5.60E-06	2.38E-06	1.87E-06	are disposed to landfill
Lead	4.19E-08	1.78E-08	1.40E-08	

Appendix A

Water effluents (kg / IM)			
BOD	5.60E-06	2.38E-06	1.87E-06
COD	1.54E-05	6.53E-06	5.14E-06
Suspended solids	8.38E-06	3.56E-06	2.80E-06
Dissolved solids	1.17E-03	4.98E-04	3.90E-04
Metal ion	1.40E-06	5.94E-07	4.67E-07
Oil	2.79E-06	1.19E-06	9.33E-07
Phenols	1.40E-06	5.94E-07	4.67E-07
Sulfides	1.82E-04	8.89E-05	6.04E-05
Acids	9.62E-08	4.69E-08	3.19E-08
Iron	1.78E-04	8.71E-05	5.91E-05

Appendix A

CUMULATIVE INVENTORY			
	ALUMINUM		COMPOSITE
	Sand cast	Multi-tube	Lost core
ENERGY, MJ / IM			
Matl. processing	117.28	236.10	256.29
Manufacturing	334.21	146.54	104.59
Use	1337.39	744.77	563.76
Retirement	9.06	4.08	3.01
TOTAL	1797.94	1131.49	927.65
SOLID WASTE, kg / IM			
Matl. processing	0.40	3.34	0.93
Manufacturing	1.28	0.57	0.81
Use	0.14	0.08	0.06
Retirement	0.36	0.20	2.11
TOTAL	2.18	4.18	3.91
CO2, kg / IM			
Matl. processing	5.70	16.13	8.35
Manufacturing	17.60	6.94	6.61
Use	83.80	46.70	35.30
Retirement	0.59	0.27	0.20
TOTAL	107.69	70.04	50.45
Total Life Cycle			
Air emissions, kg / IM			
CO2	107.69	70.04	50.45
CO	0.39	0.23	0.17
NMHC	0.47	0.22	0.12
NOx	0.47	0.23	0.14
SO2	0.14	0.18	0.17
CH4	0.02	0.01	0.08
PM-10	0.02	0.03	0.04
Water effluents, kg / IM			
Dissolved solids	5.58E-01	2.65E-01	8.34E-01
Suspended solids	2.30E-03	1.29E-03	1.17E-01
BOD	1.53E-03	2.22E-03	3.28E-03
COD	4.21E-03	3.62E-02	2.73E-02
Acids	1.48E-03	4.55E-03	2.98E-03
Oil	7.65E-04	4.26E-04	3.24E-04
Heavy metals	5.79E-04	1.33E-03	1.63E-04
Cost, $ / IM			
Material cost	12.38	7.15	6.01
Manufacturing cost	26.28	33.65	44.14
Gasoline cost	9.82	5.47	4.14
End-of-life cost	1.81	1.00	0.42
Scrap value	-5.93	-3.30	-0.68
TOTAL cost	44.36	43.97	54.03

Appendix B. 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 B-1.

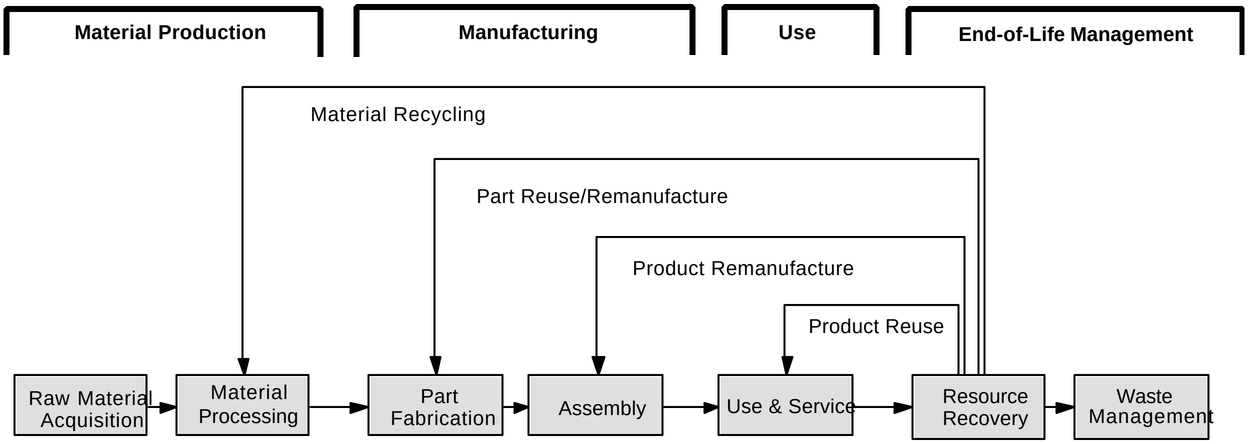

Figure B-1. Product Life Cycle System

Product, process and distribution components further characterize the product system for each life cycle stage as shown in Figures B-2 and B-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.

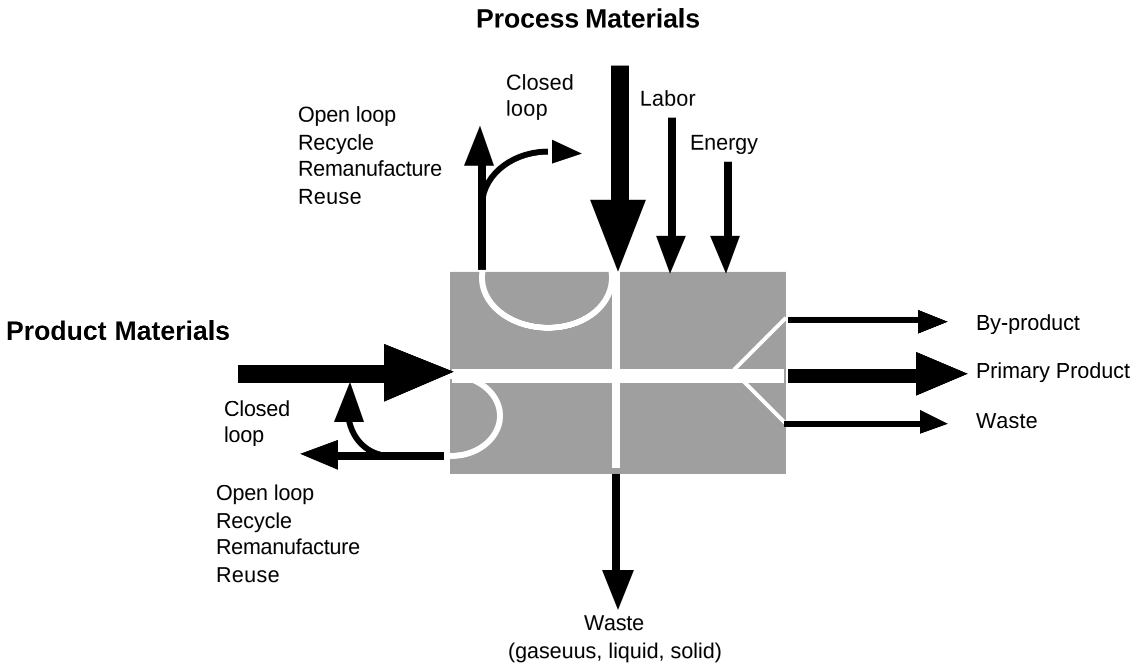

Figure B-2. Flow Diagram Template for Life Cycle Subsystem

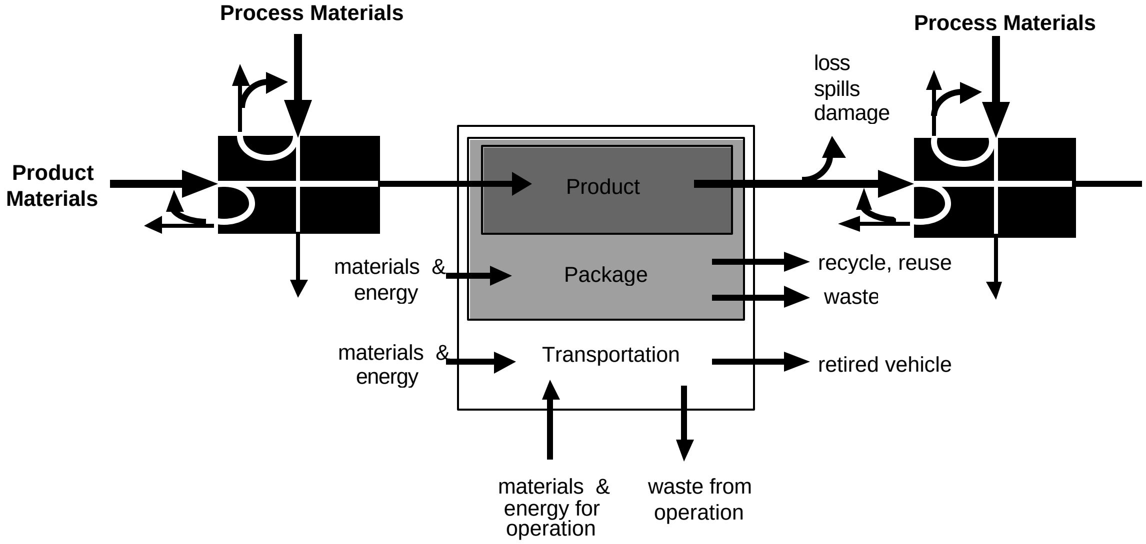

Figure B-3. Distribution Component Flow Diagram

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 B-4. For life cycle design this process takes place within the context of sustainable development and life cycle management.

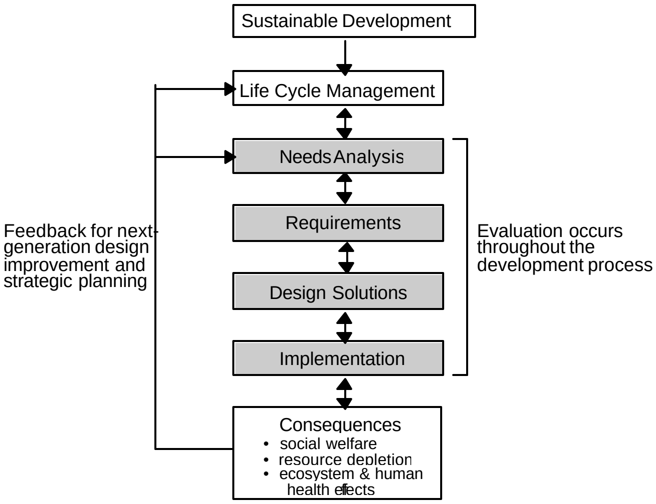

Figure B-4. Life Cycle Development Process

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 B-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.

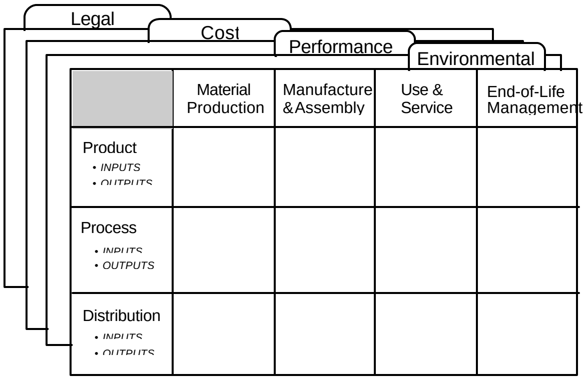

Figure B-5. Multicriteria Requirements Matrix

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.

References

Allenby, Braden R. 1991. Design for environment: A tool whose time has come. *SSA Journal*, no. September: 6-9.

Curran, Mary Ann. 1993. Broad-based environmental life cycle assessment. *Environmental Science and Technology* 27, no. 3: 430-436.

FSI. 1993. *The Product Ecology Report: Environmentally-Sound Product Development Based on the EPS System*, Federation of Swedish Industries, Stockholm, Sweden.

Gatenby, David A., and George Foo. 1990. Design for X (DFX): Key to Competitive, Profitable Products. *AT&T Technical Journal* 69, no. 3 : 2-11.

Gause, Donald G., and Gerald M. Weinberg. 1989. *Requirements: Quality Before Design*. New York: Dorset House.

Graedel, T. E., B. R. Allenby, and P. R. Comrie. 1995. Matrix approaches to abridged life cycle assessment. *Environmental Science and Technology* 29, no. 3: 134-39.

Guinée, J. B., H. A. Udo de Haes, and G. Huppes. 1993. Quantitative life cycle assessment of products 1: Goal definition and inventory. *Journal of Cleaner Production* 1, no. 1: 3-13.

Guinée, Jeroen. B., Reinout Heijungs, Helias. A. Udo de Haes, and Gjalt. Huppes. 1993. Quantitative life cycle assessment of products 2: Classification, valuation and improvement analysis. *Journal of Cleaner Production* 1, no. 2: 81-91.

Heijungs, R., J. B. Guinée, G. Huppes, R. M. Lankreijer, H. A. Udo de Haes, A. Wegener Sleeswijk, A. M. M. Ansems, P. G. Eggels, R. van Duin, and H. P. de Goede. 1992. *Environmental Life Cycle Assessment of Products - Guide*, Center of Environmental Science, Leiden, Netherlands.

Keoleian, Gregory A. 1994. The application of life cycle assessment to design. *Journal of Cleaner Production* 1, no. 3-4: 143-49.

Keoleian, Gregory A., Jonathan Koch, and Dan Menerey. 1995. *Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal*, EPA/600/R-95/107. US Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Keoleian, Gregory A., and Dan Menerey. 1993. *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System*, US EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, Cincinnati, OH.

———. 1994. Sustainable development by design: Review of life cycle design and related approaches. *Journal of the Air and Waste Management Association* 44, no. 5: 645-68.

Marguglio, B. W. 1991. *Environmental Management Systems*. New York: Marcel Dekker.

SETAC. 1991. *Workshop Report - A Technical Framework for Life-Cycle Assessment* Washington, DC: Society of Environmental Toxicologists and Chemists.

———. 1993a. *Workshop Report - A Conceptual Framework for Life-Cycle Impact Assessment* Pensacola, FL: Society of

Environmental Toxicology and Chemistry.

———. 1993b. *Workshop Report - Guidelines for Life-Cycle Assessment: A Code of Practice* Pensacola, FL: Society of Environmental Toxicology and Chemistry.

SNL. 1993. *Life Cycle Cost Assessment: Integrating Cost Information into LCA, Project Summary,* Sandia National Laboratories, Albuquerque, NM.

Sullivan, Michael S., and John R. Ehrenfeld. 1992. Reducing life-cycle environmental impacts: An industry survey of emerging tools and programs. *Total Quality Environmental Management* 2, no. 2: 143-57.

Svensson, Göran. 1992. Experience from the inventory phase of LCA studies. *First NOH European Conference: Design for the Environment*, 1.1.1, 1-8.

US EPA. 1989. *Environmental Audit Program Design Guidelines for Federal Agencies,* EPA/130/4-89/001. US Environmental Protection Agency, Office of Federal Activities, Washington, DC.

———. 1995. *An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms*, US Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, DC.

Vigon, B. W., D. A. Tolle, B. W. Cornary, H. C. Latham, C. L. Harrison, T. L. Bouguski, R. G. Hunt, and J. D. Sellers. 1993. *Life Cycle Assessment: Inventory Guidelines and Principles* , EPA/600/R-92/245. US Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH.

Weitz, Keith A., and John L Warren. 1993. *Life Cycle Impact Assessment: Framework Issues, Draft*, US Environmental Protection Agency, Office of Air Quality, Planning and Standards, Research Triangle Park, NC.

White, Allen L., Monica Becker, and James Goldstein. 1992. *Total Cost Assessment: Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis*, US EPA, Office of Pollution Prevention and Toxics, Washington, DC.

White, Allen L., and Karen Shapiro. 1993. Life cycle assessment: A second opinion. *Environmental Science & Technology* 27, no. 6: 1016-17.

Appendix C

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
		PB 93-164507AS	NTIS
	summary report	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	PB 98-100423	NTIS
	summary report	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 In-Mold Surfacing Film			
	full report	EPA600/R-01/058	EPA
Life Cycle Design of Air Intake Manifolds: Phase II: Lower Plenum of the 5.4L F-250 2.0 Air Intake Manifold, Including Recycling Scenarios			
	full report	EPA600/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*.

Appendix D

Table D-1. Acronyms

APC	American Plastics Council
ASR	Automotive Shredder Residue
CAFE	Corporate Average Fuel Economy
DFE	Design For Environment
EGR	Exhaust Gas Return
ELV	End-of-Life Vehicle
EPA	United States Environmental Protection Agency
GWP	Global Warming Potential
IM	Intake Manifold
LC	Life Cycle
LCA	Life Cycle Analysis
LCD	Life Cycle Design
LCI	Life Cycle Inventory
NPPC	National Pollution Prevention Center
NRMRL	National Risk Management Research Laboratory (EPA)
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturer
SETAC	Society of Environmental Toxicology And Chemistry