2001-01-3726

Life Cycle Assessment of Aluminum Casting Processes

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Abstract

In recent years, the environmental impact of automotive products and processes has become an issue of increasing competitive importance. Life cycle analysis (LCA) provides a tool that allows companies to assess and compare the environmental impact of a variety of material and process choices. This enables companies to manufacture environmentally sound products of exceptional value by environmentally conscious processes. In this study, we used LCA to compare the environmental burdens associated with three aluminum casting processes: lost foam, semi-permanent mold, and precision sand. We obtained data from one primary and one secondary facility for each of the three processes studied. These data included all of the environmental burdens associated with raw material and energy consumption, gaseous emissions, and waste generation. In addition, we modeled the environmental burdens associated with the production and transport of the materials used during the manufacturing processes. Both capital and operating environmental costs were also considered. In general, the environmental burdens associated with the lost foam and semi-permanent mold processes were very similar while the burdens associated with the precision sand process were higher for each of the parameters studied. Overall, lost foam was determined to be the most environmentally friendly way to cast aluminum heads and blocks.

Introduction

In recent years, we have seen a growing awareness and concern among the general public about environmental issues. The automotive industry has been affected by this increased awareness of environmental issues. Industrial pollution and automotive emissions have become subject to increased governmental control. Now, automotive manufacturers must consider not only improving fuel economy and reducing emissions, but must place increasing effort into making the vehicles more recyclable. In addition, not only the products but the processes used to make those products need to be environmentally friendly. This is accomplished by reducing waste, consuming fewer natural resources, and reducing air pollutants released during the manufacturing process. To do this, the automotive industry must have a way of measuring the environmental impact of both products and processes. Life Cycle Analysis (LCA) is one such tool. It allows engineers to assess the environmental impact that a material or process change will have on the overall environment. Life cycle assessment involves the analysis of the environmental impacts associated with a process or product at every stage of its life cycle from the extraction of raw materials from the earth to the final disposal.

Casting processes and casting technology are critical in the automotive industry. Several different casting processes are currently being used in the manufacture of aluminum cylinder heads and blocks. This has raised questions regarding the relative environmental impacts of these technologies. To address these concerns, an LCA was conducted on lost foam, semi-permanent mold (SPM) and precision sand casting of aluminum engine heads and blocks. The scope of the LCA included raw material consumption, energy consumption, CO_2 emissions, air emissions (hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides and particulate matter), solid wastes and environmental costs.

Experimental

This study has considered the environmental burdens associated with the manufacturing of cast aluminum products produced by three different casting processes: lost foam, precision sand, and SPM. The products produced by these processes include heads and blocks made via lost foam and precision sand, and heads produced by SPM. This study considered the following life-cycle inventory (LCI) categories:

- Energy and raw material consumption
- Air emissions of CO_2, CO, NMHC, CH_4, NO_X, SO_X, N_2O, and PM (particulate matter)
- Solid waste generation, both land-filled and recycled

These burden categories were considered for the production and transport of all raw materials used, as well as the burdens of the manufacturing phase. Use phase and product end-of-life were not considered. All data have been reported on a normalized basis, with the basis being burden (emissions, energy consumption, etc.) per 1000 kg of degated “to-spec” product.

Two facilities for each of the three processes were visited, with detailed data acquired from one primary facility using each process. A second facility using each process was visited to determine that the primary facility was typical for that process. We also collected production quantities, scrap rates, and part masses to enable these data to be reported on a normalized basis, as defined above. All data were based on the 1996 production year. **Table I** shows the parts produced, their masses – both before and after degating, the quantities produced, and the overall mass of aluminum poured and present as final degated product.

Table I. Production Data From Primary Facilities

Process	Component	Mass Poured (kg)	Degated Mass (kg)	Quantity	Mass Poured (kg)	Degated Mass (kg)
Lost foam	2V Head	12.88	10.18	134,577	1,733,653	1,370,441
Lost foam	4V Head	15.88	13.09	184,450	2,928,328	2,413,779
Lost foam	Block	29.98	21.27	316,465	9,488,557	6,732,426
SPM	3.3 L head	14.68	9.89	400,000	5,871,398	3,957,751
SPM	3.5L head	26.99	13.46	395,000	10,662,526	5,317,467
SPM	2V head	26.39	18.12	536,000	14,142,849	9,713,514
SPM	4V head	29.26	20.00	136,000	3,978,979	2,719,771
SPM	Quad 2 head	26.51	11.76	35,000	927,952	411,442
SPM	Quad 4 head	26.54	11.81	290,000	7,697,955	3,424,900
SPM	1.5L 4V head	25.33	15.94	52,000	1,317,109	828,713
Precision	1.25L head	19.20	11.25	248,100	4,763,520	2,791,125
Precision	1.4L head	19.25	11.30	39,200	754,600	442,960
Precision	1.25L block	30.55	16.15	247,400	7,558,070	3,995,510
Precision	1.4L block	30.45	16.10	37,400	1,138,830	602,140
Precision	LVPP block	27.45	17.75	11,600	318,420	205,900

The lost foam process data were collected from Saturn in Spring Hill, TN (primary) and the GM foundry in Massina, NY (secondary). The companies providing SPM and precision sand data are confidential.

Of the three processes studied, speciated hydrocarbon emission measurements were only available at Saturn. Most air emissions data from SPM were based upon AP42 (**2**) estimates. The precision sand facility provided measurements on air emissions, but these did not include speciated hydrocarbons.

Within the material production stage, we have considered the LCI categories for all materials consumed during the manufacturing stage as well as the acquisition of fossil fuels and the generation of electricity used during the manufacturing stage. **Table II** shows the breakdown of factors considered within each of the two life cycle stages studied.

A number of assumptions have been used in determining the LCI. These assumptions are listed in **Table III**. For example, all three casting facilities use 100% secondary aluminum to produce their products. We have calculated the inventory for the collection and the melting of scrap aluminum only. No burdens for the production of primary aluminum have been calculated. For electricity, we have used US average values for efficiency and energy sources (hydro, coal, natural gas, etc.).

The lost foam and SPM facilities were located near the aluminum suppliers, which supplied aluminum in the molten state. The precision sand facility was not located near an aluminum supplier, hence their aluminum was delivered in ingot form. As a result, the precision sand facility utilized additional energy to remelt the aluminum. In our analysis, we have assumed that all facilities received aluminum in the molten state. To accomplish this, we have subtracted from the precision sand facility's total energy consumption the amount of energy required to remelt the aluminum ingots. This was done to provide a process dependent comparison, independent of the location of the casting facility relative to aluminum suppliers.

Table II. Assignment of Factors within Life Cycle Stages

Life Cycle Stage	Factors Included
Materials Production Stage	• The burdens associated with the production of all materials consumed during the manufacturing stage. • The burdens associated with the generation of all electricity used during both material production and manufacturing stages. • The burdens associated with drilling and delivery of natural gas used during the manufacturing stage. • The transport of all materials to the manufacturing facilities. • The collection and melting of scrap secondary aluminum.
Manufacturing Stage	• All air emissions generated directly by the manufacturing facilities. • All solid waste generated by the manufacturing facilities, both landfilled and recycled. • Energy and raw material consumed by the manufacturing facilities. • The transport of landfilled wastes from the manufacturing facility.

Except for plant specific data, most LCI data were acquired from Boustead (**1**), except where otherwise noted. Air emissions data from the combustion of natural gas by the manufacturing facilities were estimated by AP42 (**2**).

The transport of all materials to the casting facilities, as well as the transport of all landfilled wastes, has also been modeled. Where possible, specific data on truck size, load capacity, and frequency of deliveries have been acquired and used in the transport model. We have assumed that all of our casting facilities were located at fixed distances from suppliers so as to not preferentially reward or penalize manufacturers for the location of their facilities. The burdens associated with transport were acquired from Boustead.

Environmental costs associated with the three casting processes were also determined. Environmental costs were categorized as capital and operational costs associated with collecting, abating, and disposing of waste and/or emissions. These costs will be defined for each specific process within the Results section.

Table III. Major Assumptions Used in the LCI

Material or Process	Assumptions
Electricity	We have used US average data for generation efficiency and energy sources.
Aluminum	We have assumed that all aluminum is 100% secondary and that it is provided to all three casting facilities in a molten state.
Transportation of Manufacturing Materials and Landfilled Wastes	We have assumed a "generic" plant with suppliers located at fixed distances from each facility. These distances were modeled after the actual distances for the lost foam and SPM facilities.

LOST FOAM The process flow diagram for the production of aluminum castings via lost foam is shown in **Figure 1.** In this diagram, the steps for generating an aluminum lost foam casting move from left to right. Each box represents a process or material that is necessary for the process. The flow diagram shown can be simplified and explained in the following major steps:

1) **Cluster making:** A series of polystyrene molds are produced and glued together to form a "cluster" that has the desired shape of the final net part. The cluster is then coated with a clay-like material and baked in an oven to dry the coating.
2) **Sand compaction:** The coated cluster is placed into a "flask", and sand is added and compacted around the cluster.
3) **Melting/pouring:** Molten aluminum is poured into the cluster, burning away the polystyrene and leaving the final shape of the part.
4) **Cleaning:** The casting is removed from the flask, and the casting is mechanically shaken to remove the sand from within and around the casting. Subsequently, the casting is cleaned using plastic beads as shot blast to remove soot and residual sand from the casting.
5) **Degating:** Gates and risers, which are channels for directing the molten metal into the cluster, are removed from the casting to produce a "degated" product.
6) **Heat Treatment:** The castings are heated to strengthen the metal.

All of the environmental burdens associated with these steps were acquired directly from Saturn Corporation. The materials required for each of these process steps, as well as the burdens associated with these steps, are listed in **Table IV** and discussed in detail below.

As shown in **Figure 1**, the process steps leading to cluster making include the expansion of polystyrene (EPS) beads. These beads originally contain 7% (by weight) pentane. After expansion, these beads contain approximately half this amount. Therefore, pentane is a major compound emitted in the process. Zinc stearate is added to the beads as a lubricant to prevent clumping during bead expansion. Polystyrene beads are then blown into molds and further expanded to form polystyrene molds. Several molds are glued together to form "clusters". The clusters are then coated with a refractory material and oven dried. Finished clusters are inserted into flasks and sand is compacted around the cluster. Plastic sandwich bags are used to cover the sprues during compaction to prevent sand from being entrapped within the casting.

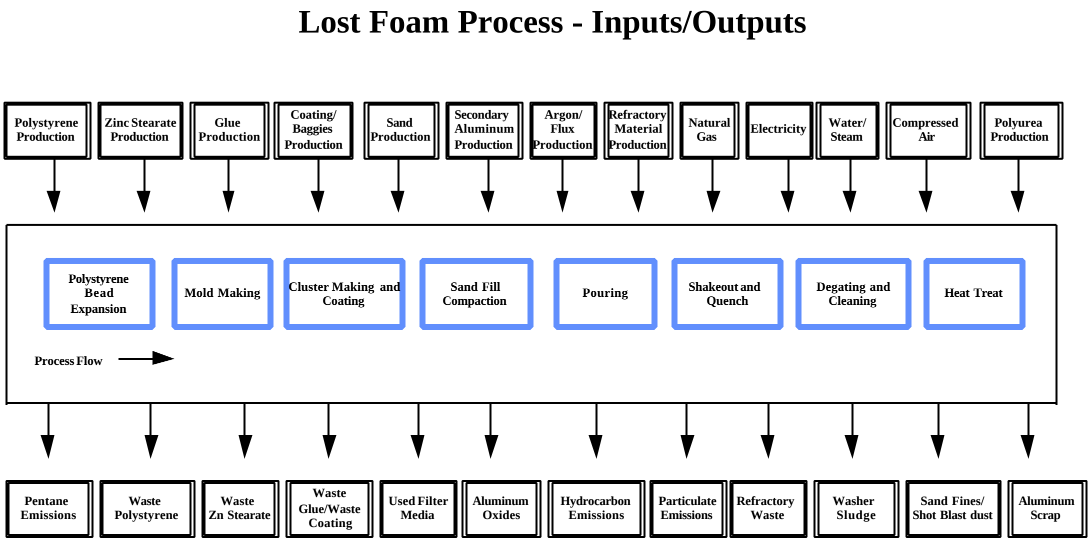

Figure 1. Lost foam process flow diagram showing major inputs and outputs.

Waste beads and scrap uncoated clusters were, at the time of this study, sent to a recycler. Coated clusters, waste glue, and waste cluster coating are sent to a landfill.

Silica sand is used for compaction around the clusters. After use in the casting process, the sand is contaminated with polystyrene combustion products. Without reclamation, this sand is unfit for re-use. To reclaim the sand for re-use, 10% of the used sand is incinerated to remove the contaminants. This reclaimed sand is combined with unreclaimed used sand and size segregated. Sand fines are removed and delivered to a recycler for use in road construction. The remainder of the sand is reused in the casting process. Newly purchased sand is used to replenish the waste sand fines. The newly cast heads and blocks are cleaned using plastic shot blast media to remove soot and residual sand from the castings. For blocks, this plastic is polymethylmethacrylate (PMMA), and for heads, it is polyurea. Due to abrasion during use, these plastic beads disintegrate into a dust that is no longer useable as a shot blast medium. This plastic dust is returned to the supplier to be recycled.

Aluminum is supplied to Saturn in a molten state. Saturn maintains this aluminum in a molten state and also remelts their own internal aluminum scrap. Argon gas is used during the process to degas the molten aluminum and to minimize oxidation. Fluxes and alloys are also added to the molten aluminum. Aluminum chips generated during the removal of gates, risers, and sprues are returned to an aluminum recycler. The gates, risers, and sprues are remelted at Saturn. The degated blocks and heads continue on to be machined. However, the machining processes are not included in this analysis.

In addition to the major sources of emissions listed for the manufacturing phase in **Table IV**, air emissions from the combustion of natural gas at the lost foam casting facility and the emissions associated with the production of electricity used by the

Table IV. Lost Foam Process Steps and Major Environmental Burdens

Process Step	Material and Energy Inputs	Waste and emissions
Cluster Making	• Expandable polystyrene (EPS) • Glue • Zinc stearate • Steam (water and energy) • Compressed air (energy) • Coating (consisting of muscovite, kaolin, mica, quartz, Attapulgite, pyrophyllite, acrylic acid homopolymer, and water) • Energy for drying of coated clusters • Bags (low density polyethylene)	• Pentane emissions from EPS expansion • Waste polystyrene - beads, molds, and uncoated clusters (recycled) • Coated clusters (landfilled) • Waste glue (landfilled) • Waste coating (landfilled) • Bags (low density polyethylene)
Sand Compaction and Reclamation	• New sand • Reclaimed sand • Bags (low density polyethylene) • Energy for sand reprocessing	• Sand fines (recycled) • Air emissions
Melting/Pouring	• Molten aluminum • Flux/additives to aluminum • Inert gases (argon) • Energy for melting and holding aluminum and incineration of air emissions • Refractory materials	• Air emissions from EPS combustion • Dross (recycled) • Scrap aluminum (recycled) • Waste refractory materials (landfilled) • Inert gas
Shakeout and Cleaning	• Plastic shot blast media (urea formaldehyde and acryllic) • Energy for shot blast process • Water	• Shot blast dust (recycled) • Washer sludge - shot blast dust and sand fines (recycled) • Hydrocarbon emissions
Degating	• Energy for removing gates and risers	• Aluminum scrap (recycled)

facilities are also included in our results. The major areas of natural gas consumption for lost foam casting are: steam generation, ovens used for the processing of used sand, reactive thermal oxidizers (RTO) used for incineration of hydrocarbon emissions generated during the casting process, the melting/holding furnaces for aluminum, and space heating. Air emissions are abated by baghouses and incinerators. Baghouse filters are landfilled.

The environmental burdens for producing most of the raw materials associated with lost foam casting were acquired from Boustead (**1**). However, burdens for many materials were not available and had to be simulated using surrogate materials. **Table V** shows the assumptions used to approximate the burdens for the production of materials where data were not available.

Environmental cost data have also been acquired for both capital investments and annual operating costs. At Saturn, capital costs were collected for baghouses, incinerators for abating hydrocarbon air emissions, and incineratorsfor processing used sand, as well as theductwork and fans specifically associatedwith each of these. Capital costs wereallocated equally over seven years to providean annualized capital cost. Operating costsincluded the natural gas used for theincinerators, the cost of filter cartridges forbaghouses, the cost of electricity for fansassociated with the baghouses andincinerators, and the cost of generalmaintenance of baghouses and incinerators.Operating costs also included the costsassociated with landfilling of solid wastes. All manpower costs were excluded from consideration.

Table V. Material Production Burdens for Lost Foam

Material	Approximations	Ref.
Expandable polystyrene	None	1
Zinc stearate	Sum of burdens for zinc chloride, stearic acid and 0.5 MJ electricity to mix	1,3
Cluster coating	Mining, milling, and grinding of muscovite and 0.5 MJ/kg of electricity to mix	1,3
Low density polyethylene (baggies)	None	1
Glue	Sum of burdens for viscose, polypropylene, butene, and 0.5 MJ electricity to mix	1,3
Secondary aluminum	Collection of aluminum cans and energy for melting and holding molten aluminum	1
Argon	Twice the burdens of producing liquid oxygen	1,3
Sand	None	1
Polyurea (shotblast)	Sum of viscose, formaldehyde, urea, and 0.5 MJ/kg of electricity to mix	1,3
Polymethylmethacrylate (shotblast)	None	1
Natural gas delivery	None	1
Natural gas combustion	None	1
Electricity	US Average	1
Flux	Omitted	

SPM SPM is a casting process that utilizes sand and resin to make sand cores. These cores are assembled into core packs that represent the internal cavities of the casting and are placed in permanent steel dies which are used to determine the outside structure of the casting. This process is shown schematically in **Figure 2** and consists of the following major process steps:

1) **Coremaking:** In this operation, sand and resin are mixed, formed into the correct shape, and cured using a catalyzing gas. The cores are then assembled and placed in a metal mold.
2) **Melting and Pouring:** Molten aluminum is poured into the mold filling the spaces left by the sand cores.
3) **Degating:** The gates and risers used in pouring the metal are removed from the rest of the casting.
4) **Shakeout:** The casting is removed from the die and mechanically shaken to remove the internal sand cores.
5) **Heat Treatment:** The castings are heated to 500° C to strengthen the metal.

The materials used and the major environmental burdens associated with each of these steps are shown in **Table VI** and discussed in detail below.

During coremaking, a ratio of 5% virgin and 95% reclaimed sand along with Borden Sigma Cure Resin Part I and Part II are mixed in a sand dryer and mixer. The sand/resin mixture is poured into a core box where it is formed and cured with triethylamine (TEA) gas. Several cores are assembled into corepacks using small amounts of glue and transferred to a carousel station where they are placed inside a metal mold that has been pre-treated with a release agent. The major air emissions for this operation include: TEA, MDI (methyl-di-isocyanate), VOC, and PM emissions. The major solid and liquid waste include: spent scrubber solution, sand filter

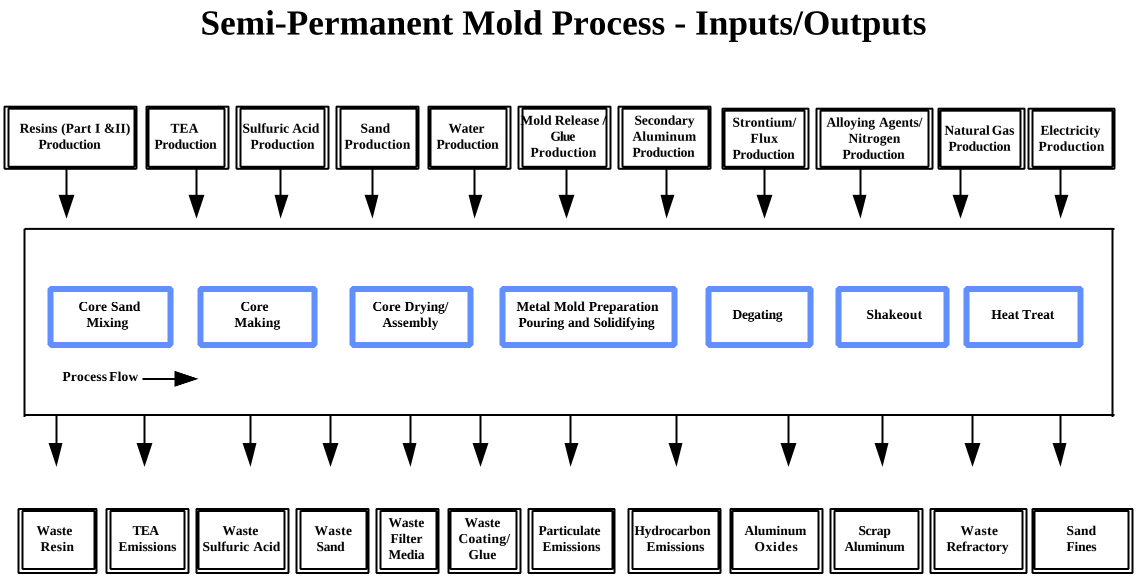

Figure 2. Process flow diagram showing major inputs and outputs to SPM process.

media, sand fines, and waste sand. The exhausted TEA emissions are controlled using a wet scrubber that captures the TEA and neutralizes it with sulfuric acid. The scrubber solution is reclaimed by an outside contractor. The particulate emissions are controlled using dust collectors. The MDI and VOC's are uncontrolled. The sand fines and sand filter media are landfilled. The waste sand is sent out for beneficial reuse. Defective cores and contaminated sand are reclaimed on site and are not considered wastes.

Molten aluminum is received and mixed with strontium and flux and held in nitrogen to prevent oxidation of the aluminum. The molten aluminum is then poured into the metal mold and corepack. In-house scrap is melted in a natural-gas-fired melting furnace and returned to a holding furnace.

The air emissions from the melting and pouring operations include NO$_x$, CO, CO$_2$, VOC's, SO$_2$ and particulate matter. Controls on air emissions consist only of baghouses for the collection of particulate matter. Solid wastes include dross with sand, dross, flashing, and refractory material. The dross, dross with sand, and flashing are recycled offsite. Scrap aluminum is recycled onsite and is not considered waste. Refractory material is landfilled. The cast part is cooled and the sand is mechanically removed via a shakeout operation. The major outputs include: NO$_x$, CO, VOC's, SO$_2$, particulate emissions, sand fines, and sand filter media. These emissions are uncontrolled except for the particulates which are captured in a baghouse. The sand fines and sand filter media are landfilled. The parts are heat treated

Table VI. SPM Process Steps: Inputs and Outputs

Process Step	Material and Energy Inputs	Waste and Emissions
Coremaking	• Sand • Resin I • Resin II • TEA • Mold release agent • Glue • Sulfuric acid • Energy • Water • Coating	• Waste sand (recycled) • Sand fines (landfilled) • Filter media (landfilled) • Waste resin and glue (landfilled) • Waste sulfuric acid (recycled) • TEA emissions • Air emissions
Melting/Pouring	• Aluminum • Strontium • Flux • Nitrogen • Release agent • Alloying agents • Energy	• Air emissions • Dross (recycled) • Dross with sand (recycled) • Flashing (recycled) • Refractory material (landfilled)
Degating	• Energy	• Aluminum scrap (recycled)
Shakeout	• Energy	• Air emissions
Heat Treatment	• Energy • Water	• Air emissions

in furnaces at 500^{o} C. The expected emissions from this operation include: NO_x, CO, VOC's, SO_2, and particulate. These emissions are all uncontrolled.

The environmental burdens for the materials used in the SPM process were acquired directly from databases or by using surrogate materials. These materials, or substitute materials, and the databases used to supply the data are listed in **Table VII**. Sand, glue, secondary aluminum, flux, natural gas delivery and combustion, and electricity generation and distribution were modeled as listed for lost foam. The environmental costs for SPM included the capital and operating costs of baghouses, the sand reclaim furnace, and the amine scrubber. The SPM facility did not have incinerators for hydrocarbon emission abatement. Operating costs include the energy to operate the abatement equipment as well as the costs associated with landfilling solid wastes. All manpower costs were excluded from consideration.

PRECISION SAND Precision sand casting is referred to as an all core process. It is a casting process that utilizes sand and resin to make sand cores for both the internal cores as well as the external surfaces of the casting. These cores are assembled into complete core packs that determine both the internal cavities as well as the outside structure of the casting. For aluminum casting, the precision sand process consists primarily of the following steps:

1) **Coremaking:** In this operation, sand and resin are mixed, formed into the correct shape, and cured using a catalyzing gas. The cores are then assembled to form complete core packs.
2) **Melting and Pouring:** Molten aluminum is poured into the mold filling the spaces left by the sand cores.
3) **Heat Treatment/Shakeout:** The castings are heated to high temperatures which serve both to strengthen the metal and to loosen the sand from the castings. The castings

Table VII. Material Production Burdens for SPM

Material	Approximation	Ref.
Phenol formaldehyde resin	Sum of phenol and formaldehyde and 0.5 MJ/kg electricity to mix	1,3
Isocyanate resin	Sum of methyldiisocyanate and polyol and 0.475 MJ/kg electricity, 0.1 MJ/kg kerosine, and 1.584 MJ/kg natural gas to process	1,3
Core coating	Mining and processing of mica and koalin plus 0.5 MJ/kg electricity to mix	1,3
Carbon dioxide	None	1
Nitrogen	None	1
Sulfuric acid	None	1
Hydrochloric acid	None	1
TEA	Simulated as aniline	1

are vibrated to assist in the removal of the sand from the castings. In the process, the sand is reclaimed for future use.

4) **Degating:** The gates and risers used in pouring the metal are removed from the rest of the casting.

These operations are outlined in **Figure 3** and described in more detail below. **Table VIII** lists the major materials and environmental burdens associated with each of these steps.

During coremaking, a ratio of 2% virgin and 98% reclaimed sand is mixed with Ashland Isocure Resin Part I and Part II and poured into a core box machine where the cores are formed and cured with dimethylethylamine (DMEA) gas. The cores are assembled into a core pack using a small amount of glue. In some cases, blocks are fitted with steel cylinder liners. These liners are subjected to a shotblast process prior to insertion into the core assembly. The core packs are then transferred to the pouring operation.

The major air emissions from coremaking include DMEA, MDI, phenol, formaldehyde, hydrocarbons, and particulate emissions. Waste streams include spent scrubber solution, defective cores, sand filter media, sand fines, iron dust, and waste sand. The exhausted DMEA emissions are controlled using a wet scrubber that captures and neutralizes the DMEA gas with sulfuric acid. The scrubber solution is reclaimed offsite. The particulate emissions are controlled using dust collectors. During the core assembly process, a cross draft of air is used to capture some of the residual DMEA, MDI, phenol, formaldehyde, and hydrocarbons being emitted from the cores. This air is routed into an incinerator. The sand fines and sand filter media are landfilled. The waste sand and defective cores are recycled.

Aluminum is received in ingots and melted in a furnace for use in the melting and pouring operations. The molten aluminum is mixed with alloying agents, strontium and flux. An inert gas, argon, is used to prevent oxidation of metal exposed to air. The molten aluminum is poured into the assembled corepacks.

Precision sand is the only process of the three studied that receives aluminum in an ingot form. The SPM and lost foam facilities receive aluminum in a molten state. To maintain a consistent comparison between the three processes, we have performed an analysis that assumes that the precision sand facility also receives aluminum in the molten state. To accomplish this, we have subtracted the energy necessary to melt the aluminum (except the internal scrap) from the manufacturing energy consumed.

The outputs from the pouring operation include: NO_x, CO, CO_2, hydrocarbons, and particulate emissions. The air emissions of hydrocarbons and particulate matter are abated via incinerators and baghouses, respectively. Other wastes include refractory material, sand/Al mix, Al dust, flashing, and dross. The dross, dross with sand, and flashing are recycled offsite.

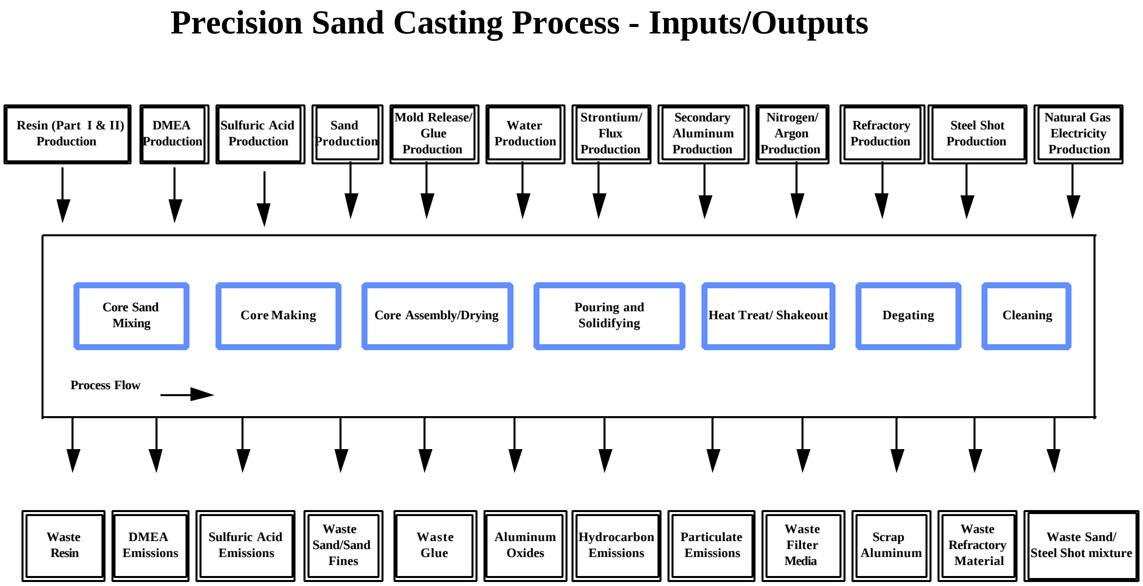

Figure 3. Precision sand process flow diagram showing major inputs and outputs.

For the most part, scrap aluminum is recycled onsite and not considered waste.Scrap blocks, which already have steel liners installed, are recycled offsite.

The heat treatment operation serves three purposes: heat treatment, core removal, and sand reclamation. The expected emissions from this operation include NO_x, CO, hydrocarbons, and particulate matter. The air emissions from this operation are also abated via incinerators and baghouses.

The environmental burdens for the production of sand, glue, argon, and secondary aluminum, as well as the delivery and combustion of natural gas, and the generation and distribution of electricity were modeled as listed for lost foam. Core resins and nitrogen were modeled as listed for SPM. DMEA burdens were acquired from Boustead (**1**) using aniline as a surrogate. The burdens for sodium hydroxide were acquired directly from Boustead (**1**).

Environmental costs for precision sand included the capital andoperating costs associated with incinerators,baghouses, filtration equipment for sand finesat the heat treat and sand silo areas, and theamine scrubber. It should be noted that sandreclaim is done simultaneous to heat treat,hence these costs are associated with dualfunctions in the process. Capital costs wereallocated over seven years to determineannual capital costs. Operating costsincluded the cost of energy to run the airabatement equipment, the costs of baghousefilters, and landfill costs. The precision sandfacility operating costs were provided asestimates and (unlike data for SPM and lostfoam) include the costs associated with laborassociated with maintaining the abatementequipment. Hence, direct comparisons ofenvironmental cost data are not valid.

Table VIII. Precision Sand Casting Process Steps: Inputs and Outputs

Process Step	Material and Energy Inputs	Waste and Emissions
Coremaking	• Sand • Resin I • Resin II • DMEA • Mold release agent • Glue • Sulfuric acid • Energy • Water	• Waste Sand (recycled) • Sand fines (landfilled) • Filter media (landfilled) • Waste sulfuric acid (recycled) • DMEA emissions • Air emissions
Melting/Pouring	• Aluminum • Strontium • Flux • Nitrogen • Argon • Refractory materials • Energy	• Air emissions • Dross (recycled) • Dross with sand (recycled) • Flashing (recycled) • Refractory material (landfilled)
Heat Treatment and Shakeout	• Energy	• Air emissions
Cleaning and Degating	• Steel shotblast media • Energy	• Shotblast dust (recycled) • Aluminum scrap (internally recycled)

Results

The results will be presented in five burden categories: 1) material consumption, 2) energy consumption, 3) air emissions, 4) solid waste, both recycled and landfilled, and 5) environmental costs. Environmental costs have only been determined for the manufacturing stage. These results will be presented in terms of burden (consumption, emissions, costs, etc.) per 1000 kg of degated product.

MATERIAL CONSUMPTION The materials consumed by each casting process, and their quantities, are listed in **Table IX.**   In addition to the burdens associated with mining or producing these materials, we have included within the material production stage, the burdens associated with transporting these materials to the casting facilities. The transport of liquid and solid wastes from the manufacturing facility to the landfill have been included within the manufacturing stage. Transportation of waste materials to recyclers has not been included.

The major material consumption issues surrounding aluminum casting processes are related to the use of sand and aluminum. The results for consumption of these materials are shown in **Figure 4.** Most other materials are used in lesser quantities and are not common between the three processes. The fossil fuel consumption due to producing hydrocarbon-based materials shows up in the energy consumption category of **Table IX**. The remaining non-hydrocarbon based compounds utilized in each of the processes is different and unique to each process.

The use of aluminum is comparable between each casting process and varies only by the degree that chips and scrap are not internally remelted. The numbers reported in **Table IX**, represent the quantity of aluminum required to produce 1000 kg of degated product. Much of the waste aluminum generated during the process is internally remelted and used at each facility. Hence internal scrap eventually becomes finished product and does not contribute to the values reported in **Table IX**. However,

Table IX. Materials and Energy Consumed (per 1000 kg of degated product)[a]

Material	Lost Foam	SPM	Precision
Expandable Polystyrene	15.3		
Cluster Coating	64.3		
Plastic Shot (PMMA)	15.0		
Plastic Shot (polyurea)	34.7		
Plastic Baggies	0.09		
Zinc Stearate	0.03		
Liquid Argon	4.7		2.37
Glue	0.32	0.03	0.08
Natural Gas (MJ)	15,983	22,814	24,983
Electricity (MJ)	6,838	5,679	12,425
Molten Aluminum	1110.3	1019.0	1112.1
Sand	235.4	381.3	976.5
Hydrochloric Acid		0.005	
Core Coating		0.37	
CO_2		21.84	
Nitrogen		22.82	55.1
Phenolic Resin		9.19	51.38
Isocyanate		9.24	51.51
TEA/DMEA		4.01	10.08
Sulfuric Acid		1.63	25.31
Sodium Hydroxide			1.62
Steel Shot			8.34

[a] All values are in kg, except energy, which is in MJ.

since considerable energy is required to remelt aluminum, this internal scrap contributes to energy consumption. It is useful, therefore, to compare the amount of aluminum that must be poured to generate a given mass of finished product. These quantities for lost foam, SPM, and precision sand are 1431, 1913, and 1765, respectively, per thousand kilograms of degated product. The differences between these masses and those listed in **Table IX** are the masses of internally remelted scrap, e.g. sprues, gates, and risers, which contribute to the inefficient use of molten aluminum. These masses, in conjunction with other process differences contribute to the difference in energy consumption by each type of casting process.

Significant differences exist in the consumption of sand by the three casting processes. The least amount of sand is consumed by lost foam, followed by SPM, then precision sand. These differences result from how sand is used and handled in the processes. The numbers listed for sand consumption in **Table IX** represent only the sand required to replace the waste sand generated. Each facility studied reclaims used sand thereby reducing the consumption of new sand. Sand consumption is dictated not only by the total amount of sand needed per casting, but by the rate at which sand becomes no longer re-useable. Process differences dictate each of these. Lost foam uses sand (without resin) to compact around polystyrene clusters. SPM and precision use resin-based binders to form sand cores. Also, lost foam reclaims only 10% of the sand that is re-used during each casting cycle, whereas SPM and precision reclaim 100% of used sand. Hence, sand used in the SPM and precision sand processes is exposed to conditions that probably increase the rate at which degradation occurs. As the sand degrades to smaller particle sizes, it becomes un-useable. These “sand fines” are usually either landfilled or used in road construction projects.

SPM clearly uses less sand than precision sand, due to the mass of cores required for each process. This is a direct consequence of SPM’s use of a permanent mold rather than a sand core to determine external casting dimensions. Several other materials are also used by both SPM and precision sand. For all materials utilized by both processes, precision sand has the largest consumption. The consumption of more raw materials by the precision sand process means that energy consumption in the production of these raw materials is also higher for precision sand.

ENERGY CONSUMPTION As seen in **Table IX**, material production for lost foam requires the least amount of energy and precision sand the most. The major contributor to energy consumption in the material production stage of all three casting processes is due to the generation of the electricity used by each facility. Another major contributor to energy consumption in the material production stage is associated with melting aluminum. The pie charts, **Figures 5, 6, and 7**, show the relative

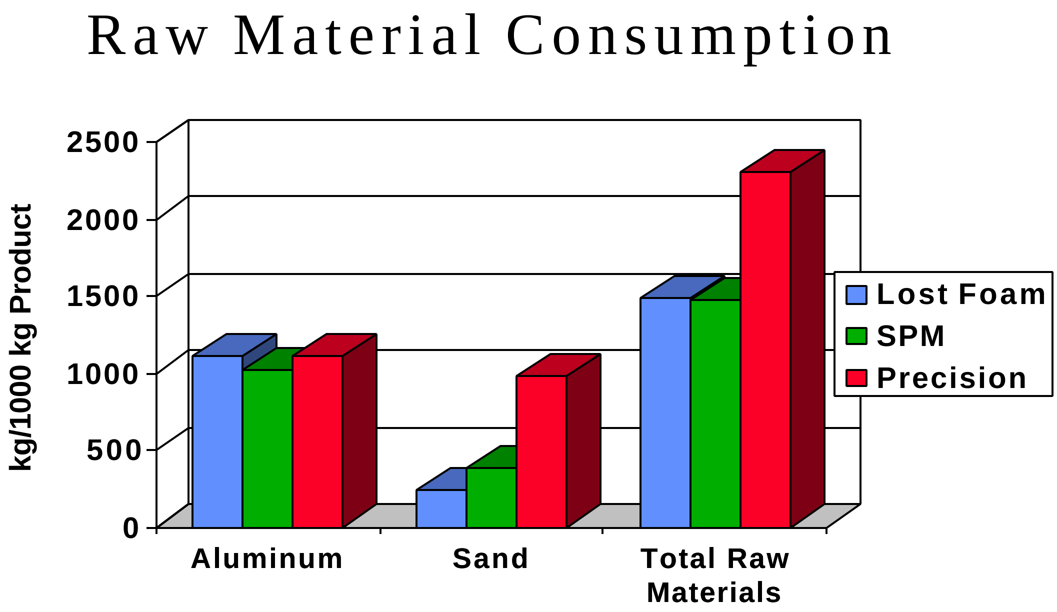

Figure 4. Consumption of raw materials used in manufacturing phase.

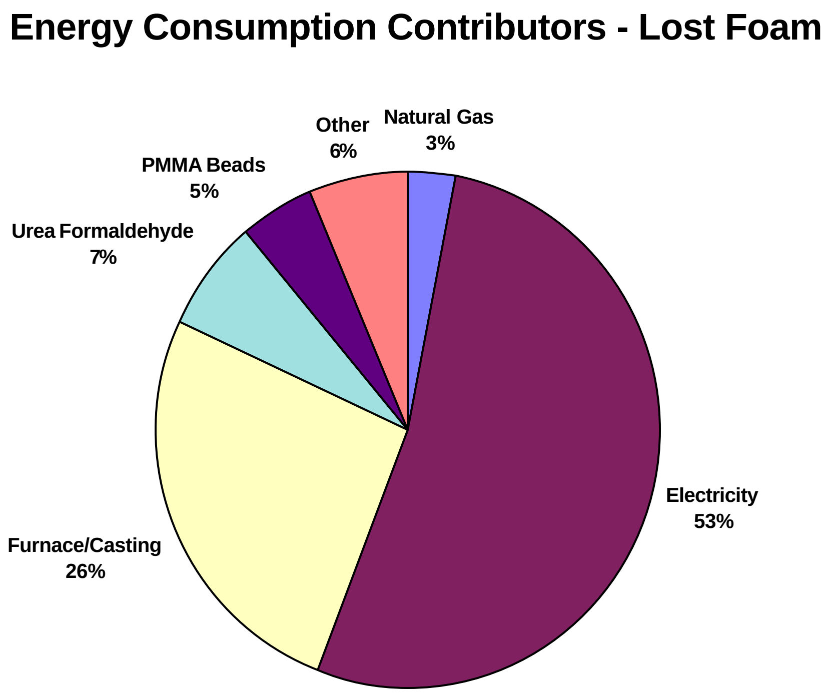

Figure 5. Distribution of the energy consumed during the production of materials used in the Lost Foam process.

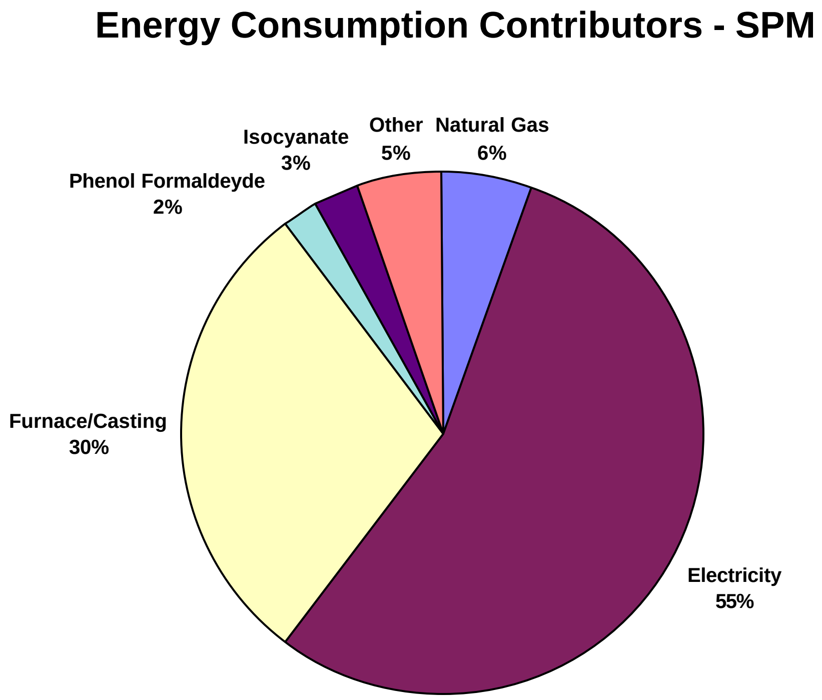

Figure 6. Distribution of the energy consumed during the production of materials used by the SPM process.

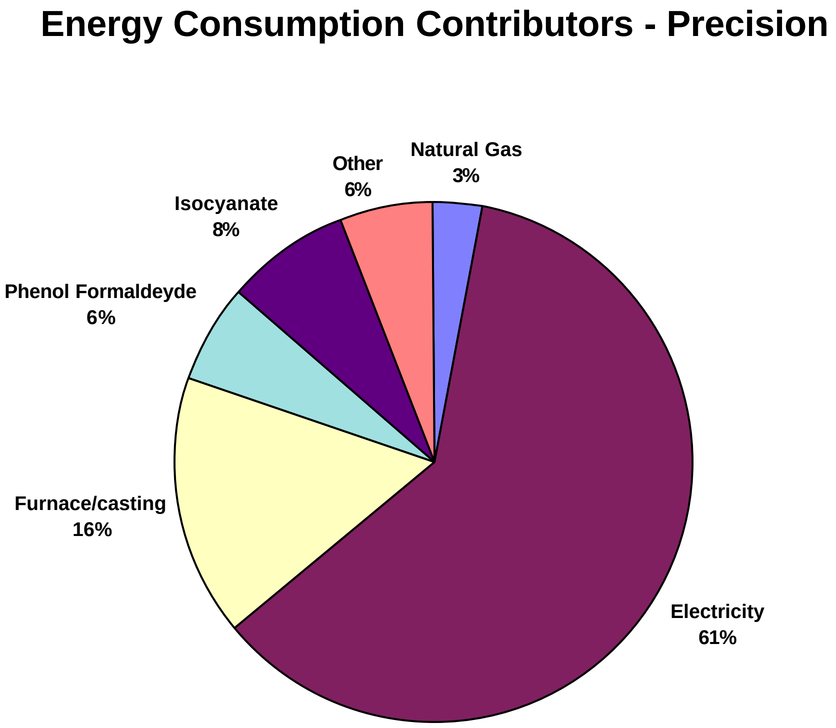

Figure 7. Distribution of the energy consumed during the production of materials used for precision sand casting.

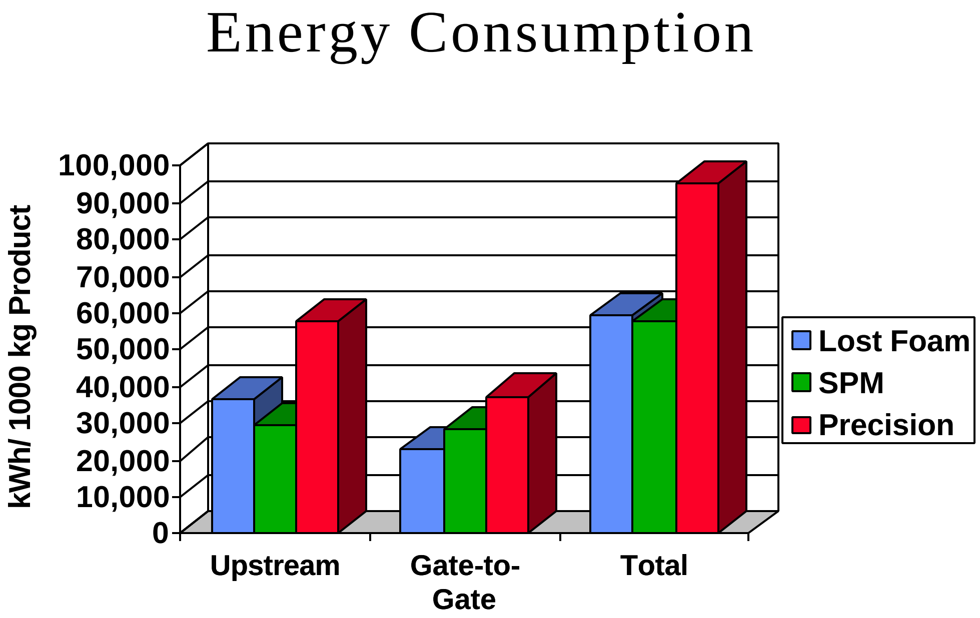

Figure 8. Comparison of the energy comsumed by each of the three processes studied.

contributions to energy consumed to produce the materials used by each of the casting processes. The production of electricity is responsible for 52.8% of the total for lost foam (19,412.1 MJ), 54.7% for SPM (16,124.7 MJ), and 60.9% for precision sand (35,271.7 MJ). After electricity generation, the molten aluminum that is delivered to each casting facility is the next major source of energy consumption. Production of molten aluminum consumes 16.4% of the total material producion energy for precision sand (9,518.1 MJ), 25.9% for lost foam (9,502.7 MJ), and 29.6% for SPM (8,721.3 MJ). The next largest consumer of energy during the material production stage for each process is the production of shot blast at 11.7% for lost foam (4,299.6 MJ), 13.7% for production of resin used in the precision sand process (7,954.6 MJ), and 4.8% for production of resin used in the SPM process (1,424.9 MJ). Hence, the use of electricity and molten aluminum clearly dominate the energy consumption issues related to material production.

During the manufacturing stage, lost foam utilizes the least amount of energy and precision sand the most. The distribution of energy consumption within each casting facility is not available since these data (except that provided by Saturn) were provided on a plant-wide basis. **Figure 8** shows the energy used by each process during the material production stage, the manufacturing stage, and the overall energy consumed.

AIR EMISSIONS Emissions of CO_2 are largely dictated by the consumption of energy, due to its dependence on combustion of fossil fuels. For the material production stage, SPM generates the least CO_2 and precision sand the most. This is primarily due to the low electricity consumption required to produce the materials used in the SPM process and the much higher electrical energy required to produce the materials used in the precision sand process. During the manufacturing stage, the vast majority of CO_2 emissions are due to the combustion of natural gas. The primary areas of natural gas consumption are furnaces for melting and holding aluminum, incinerators for processing used sand, furnaces for heat treating finished castings, and in the case of lost foam and precision sand, the incinerators for abatement of hydrocarbon emissions. During the manufacturing stage, lost foam generates the least amount of CO_2. Overall, the CO_2 emissions from the SPM process are comparable to that of lost foam, and the emissions from precision sand greatly exceed those of either lost foam or SPM. These emissions are shown in **Figure 9**.

The emissions of HC, CO, NO_X, SO_X, and PM (particulate matter) are shown in **Figure 10**. The data shown represent emissions (after abatement) released to the environment. For each of these air emissions (except HC), SPM generates the least and precision sand the most. For HC, lost foam generates the least and precision sand the most. It can also be seen from **Figure 10** that the manufacturing stage dominates over the material production stage in the generation of HC and CO, whereas the material production stage is dominant for generation of NO_X, SO_X, and PM.

For precision sand, the HC data includes total HC, whereas the other two processes include only non-methane HC. Also, the SPM HC emissions are largely based on AP42 estimates, rather than actual measurements. Hence a valid comparison between the magnitude of HC emissions is not available for the three processes.

SOLID AND LIQUID WASTES Solid and liquid wastes have been categorized into two general types: landfilled and recycled. These data are shown in **Figure 11**. Precision sand generates the most landfilled and recycled wastes. SPM generates the least landfilled waste and lost foam generates the least recycled waste. In considering the total waste generated (landfilled and recycled), lost foam generates the least and precision sand the most.

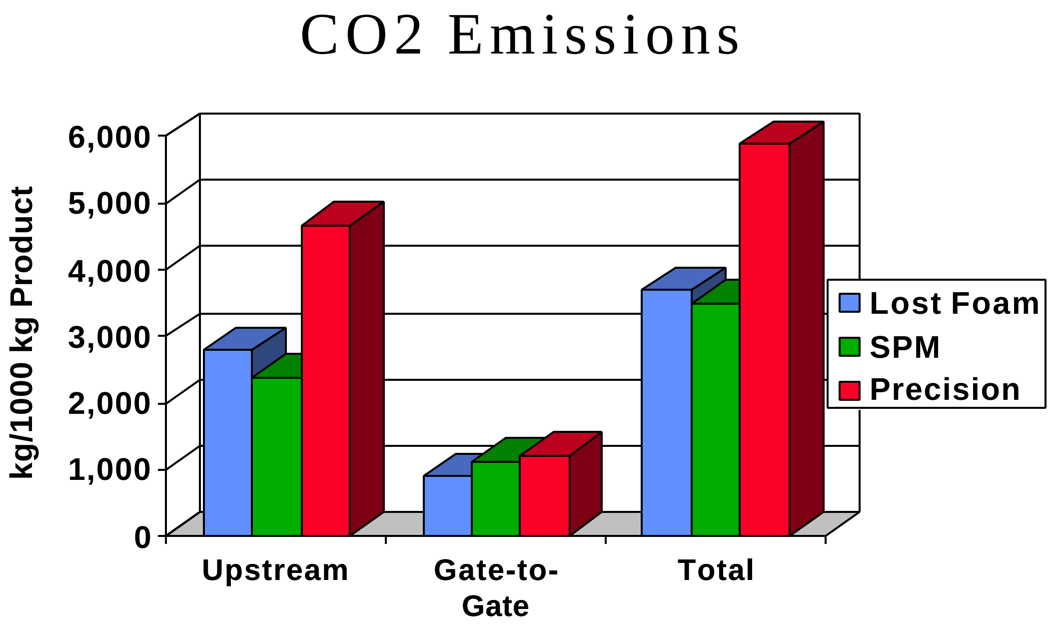

Figure 9. Analysis of CO_2 generated by each of the three processes.

ENVIRONMENTAL COSTS Data for environmental costs are shown in **Figure 12**. As with air emissions and solid/liquid waste, the environmental costs are reported on a per thousand kilogram of product basis. However, these costs are reported for the manufacturing stage only. For capital costs, this was accomplished by allocating costs over seven years, at 1996 production rates. For both operating and capital costs, SPM costs are lowest and precision sand costs are the highest. SPM costs are lowest due to the absence of incinerators to abate HC emissions and less reliance upon baghouses for reduction of PM emissions. Precision sand operating costs appear higher due to the inclusion of manpower costs for maintenance of the incinerators, baghouses, and amine scrubber. These manpower costs were not included in data provided by the SPM or lost foam manufacturers.

Discussion

SENSITIVITY ANALYSIS The sensitivity of environmental burdens associated with the material production phase was evaluated by reducing, in a stepwise fashion, the quantity of each material consumed. For this analysis, the decrease in overall environmental burdens in the material production phase was calculated for a 20% reduction in material consumption. This sensitivity analysis can be considered a measure of the dependence of the overall environmental burdens due to the consumption of an individual material. Alternatively, this analysis shows the sensitivity of the overall upstream burdens to a change in the burdens of an individual material. Consequently, this analysis also indicates the dependence of the results upon the accuracy of the material production data. These results are shown first in **Table X.** This table shows which material change has the largest impact upon an environmental burden category and the degree of impact which results from a 20% change in that material's consumption. **Table X** does not consider the impact of electricity

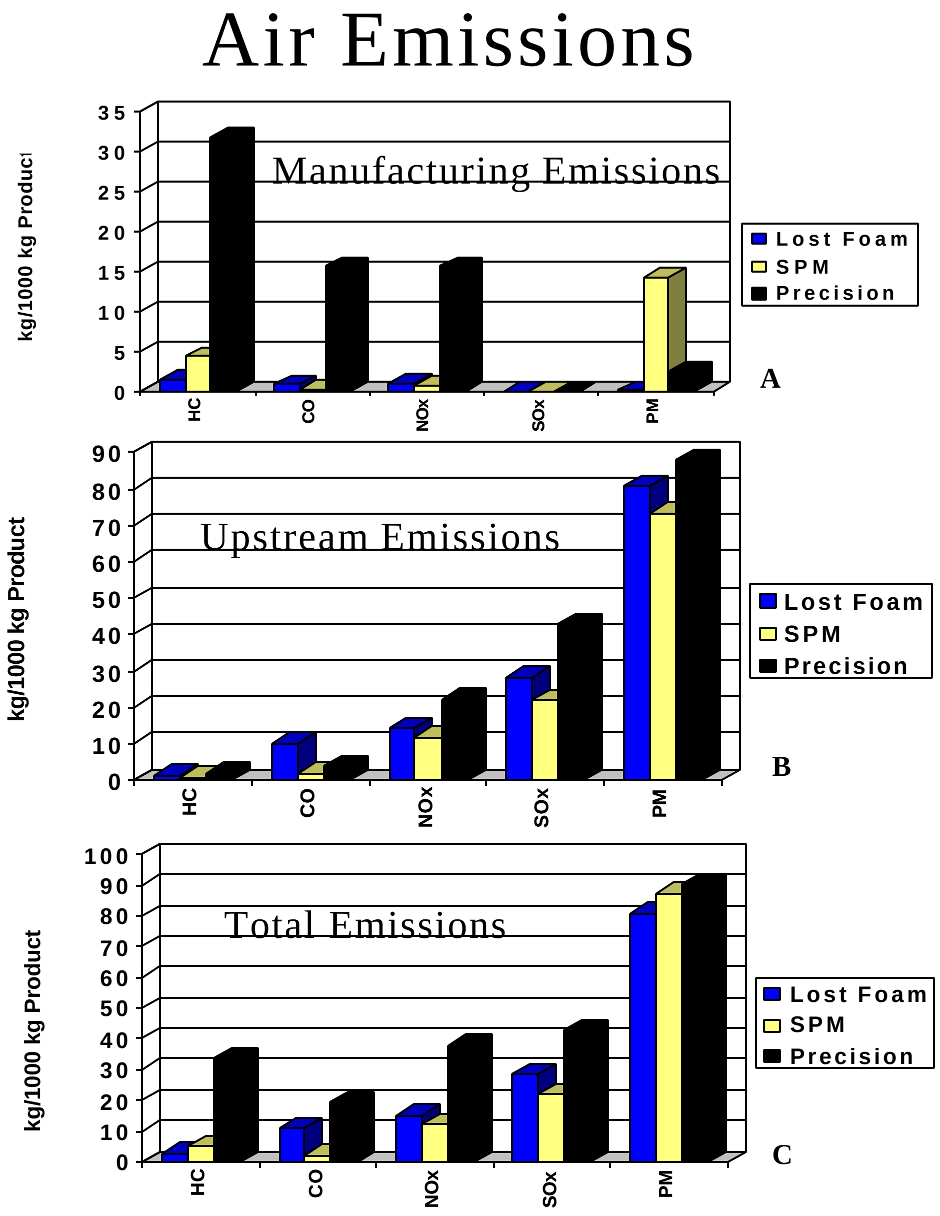

Figure 10. Comparision of specific air emissions released during the manufacturing (A) and upstream (B) phases for each of the three processes.

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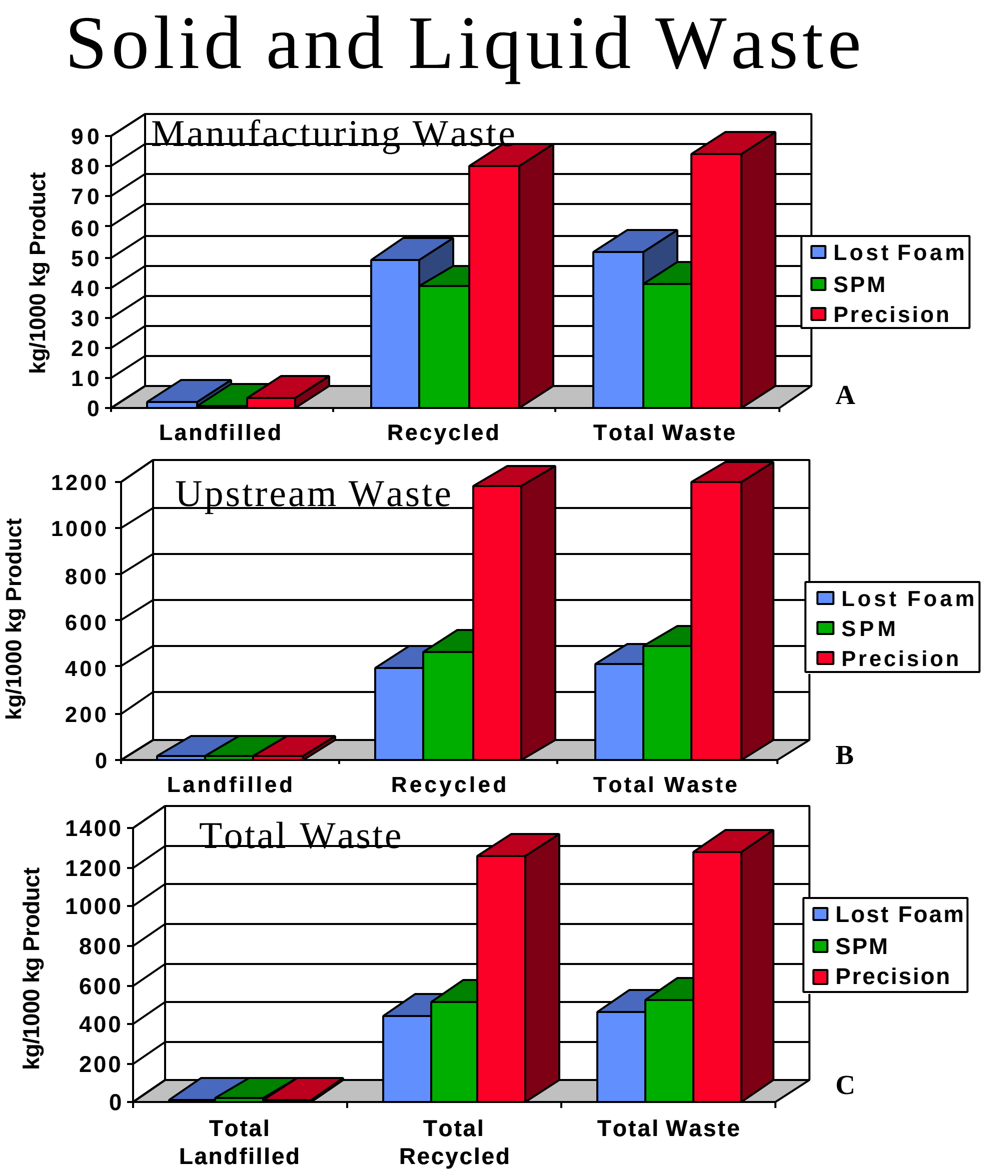
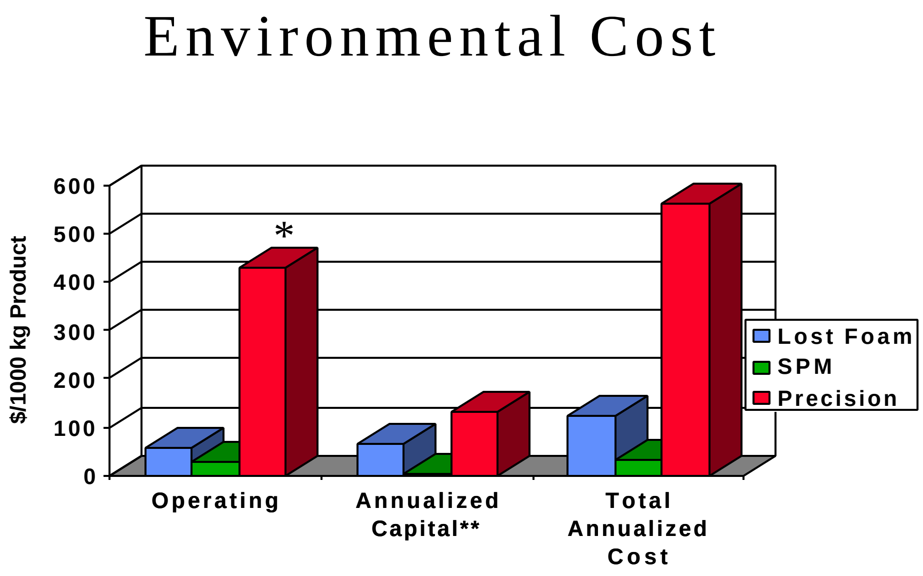


Figure 11. Solid and liquid wastes (both landfilled and recycled) were compared for each of the three processes for the manufacturing phase (A) and the upstream phase (B) and total (C).



* Precision operating costs include labor
** Capital costs are annualized over 7 years

Figure 12. Comparison of environmentally related capital and operating costs.

consumption. From this table, it can be observed, for example, that when aluminum consumption decreases by 20%, the generation of mineral waste from the lost foam process changes by 3.9%. For precision sand and SPM, mineral waste is most impacted (changing by 5.2% and 4.4%, respectively) by a 20% change in sand consumption. It should be noted that as the percent of change in the overall environmental burdens approach 20%, the burdens are more nearly tied directly to that material. That is, if the consumption of a material is decreased by 20% and this leads to a 20% reduction in an environmental burden, then that burden is due solely to that material.

Some of the environmental burdens are impacted more by changes in the consumption of electricity at the casting facility than by changes in material consumption. **Table XI** shows analogous data to that shown in **Table X** but includes consideration of the changes in the environmental impacts due to a 20% change in electricity consumption as well as changes in material consumption.

These data show that many of the material production phase burdens are most dependent upon either the consumption of aluminum or electricity. Opportunities for reducing consumption of aluminum can be focused on the design of gates, risers, and sprues, i.e. the portion of the casting that does not contribute to the net shape of the finished part.

Although this study did not include the burdens associated with machining, the amount of aluminum machined away from the finished casting also has the potential to contribute significantly to those burden categories heavily influenced by aluminum consumption. For lost foam, the ability to cast in many features that reduce required machining is potentially a significant environmental advantage.

For the lost foam process, the consumptions of polyurea and PMMA are the major contributors to several

Table X. Sensitivity of Environmental Burdens during Material Production to Changes in Material Consumption[a]

	Lost Foam		Precision Sand		SPM	
Environmental Burden	**%Change in Burden**	**Due to 20% Change in Material**	**%Changein Burden**	**Due to 20% Change in Material**	**%Changein Burden**	**Due to 20% Change in Material**
Energy Consumption	3.2	Aluminum	2.0	Aluminum	3.0	Aluminum
Particulate Matter	17.9	Aluminum	16.4	Aluminum	18.1	Aluminum
Carbon Monoxide	15.5	Polyurea	3.8	Aluminum	6.8	Aluminum
Carbon Dioxide	4.9	Aluminum	2.9	Aluminum	5.2	Aluminum
Sulfur Dioxide	4.4	Aluminum	2.9	Aluminum	5.2	Aluminum
Nitrogen Oxides	4.9	Aluminum	3.1	Aluminum	5.4	Aluminum
Nitrous Oxide	10.9	PMMA	15.8	Isocyanate	12.6	Isocyanate
Hydrocarbons	5.4	EPS	3.6	Isocyanate	5.5	Aluminum
Methane	2.1	Aluminum	1.4	Aluminum	1.6	Aluminum
Mineral Waste	3.9	Aluminum	5.2	Sand	4.4	Sand
Mixed Industrial Waste	5.8	PMMA	13.8	Isocyanate	10.8	Isocyanate
Slags/Ash	4.7	Aluminum	2.9	Aluminum	5.3	Aluminum
Inert Chemical	13.4	Polyurea	18.5	Isocyanate	17.1	Isocyanate
Regulated Chemical	19.2	Polyurea	16.8	Isocyanate	14.6	Isocyanate

[a] Only the material with the greatest impact on the environmental burden category is listed.

environmental burden categories. These materials are used for cleaning heads and blocks, respectively. Reduction in environmental burdens might be possible using alternative materials or processes.

For precision sand and SPM, consumption of isocyanate and sand are major contributors to several environmental burden categories. These materials are used in the creation of cores. Reduction of these burdens are possible either through the use of alternative binders or reduction in the generation of sand fines, which is responsible for sand consumption.

For all three casting processes, the consumption of electricity at the casting facility is a major contributor to most environmental burden categories. For most environmental burden categories for which electricity is the largest contributor, more than half the burden is due to electricity. Hence, improved efficiency of electricity consumption will have direct environmental benefits.

IMPLICATIONS Life cycle assessment studies often go beyond the acquisition of inventory data and estimate environmental impacts. The impacts that are often considered include tropospheric ozone and smog formation, surface water eutrophication and/or acidification, stratospheric ozone depletion, greenhouse warming potential, and toxicity to human and/or terrestrial life. However, it is often technically difficult, if not impossible to calculate these. In some cases, it is inappropriate to use life cycle data to calculate the impacts. For example, smog formation occurs over short time scales and limited geographical regions. But the emissions of smog precursors such as NO_X, HC, and CO that result from the life cycle of cast aluminum products occurs over a wide geographical and temporal scale. Therefore, it is inappropriate to sum these life cycle emissions and use them to estimate smog formation as an impact. This is often also true for surface water eutrophication and/or acidification.

Table XI. Sensitivity of Environmental Burdens during Material Production to Changes in Material and/or Electricity Consumption

	Lost Foam		Precision Sand		SPM	
Environmental Burden	**%Change in Burden**	**Due to 20% Change in Material**	**%Change in Burden**	**Due to 20% Change in Material**	**%Change in Burden**	**Due to 20% Change in Material**
Energy Consumption	8.8	Electricity	10.0	Electricity	7.5	Electricity
Particulate Matter	17.9	Aluminum	16.4	Aluminum	18.1	Aluminum
Carbon Monoxide	15.5	Polyurea	10.7	Electricity	9.7	Electricity
Carbon Dioxide	13.6	Electricity	14.8	Electricity	13.3	Electricity
Sulfur Dioxide	13.2	Electricity	15.9	Electricity	14.1	Electricity
Nitrogen Oxides	11.7	Electricity	13.6	Electricity	11.8	Electricity
Nitrous Oxide	10.9	PMMA	15.8	Isocyanate	12.6	Isocyanate
Hydrocarbons	6.4	Electricity	7.3	Electricity	7.9	Electricity
Methane	4.8	Electricity	5.6	Electricity	3.4	Electricity
Mineral Waste	11.5	Electricity	11.0	Electricity	11.0	Electricity
Mixed Industrial Waste	5.8	PMMA	13.8	Isocyanate	10.8	Isocyanate
Slags/Ash	14.1	Electricity	2.9	Aluminum	14.3	Electricity
Inert Chemical	13.4	Polyurea	18.5	Isocyanate	17.1	Isocyanate
Regulated Chemical	19.2	Polyurea	16.8	Isocyanate	14.6	Isocyanate

Stratospheric ozone depletion and greenhouse warming are phenomena that are caused by gas phase species that have long atmospheric lifetimes relative to the life cycle of an automobile. Hence, these phenomena are more relevant to life cycle assessment studies. Stratospheric ozone depletion is a phenomenon associated primarily with chlorofluorocarbon (CFC) emissions. In the case of this study, CFC emissions are insignificant, hence stratospheric ozone depletion is not an impact category of concern. Greenhouse warming is a phenomenon associated primarily with species such as CO_2, CFC's, methane, and N_2O. Casting processes and the production of materials used during casting do generate CO_2, N_2O, and methane emissions, so this is an impact category of concern.

For the manufacturing phase, we do not have measurements of CO_2 and N_2O emissions from any of the casting processes and only have measurements of methane from the lost foam process. To estimate the methane emissions from SPM and precision sand, and the CO_2 and N_2O emissions from all three casting processes, we have used the AP42 estimates of these emissions from the combustion of natural gas. The lack of data for emissions from sources other than natural gas combustion means that the CO_2 equivalent greenhouse gas emission values are probably underestimates. For the material production phase, Boustead data were used (**1**). The life cycle greenhouse gas emissions of the three casting processes are summarized in **Table XII**. The total emissions are adjusted for the global warming potentials (GWP) of methane and N_2O relative to CO_2. These data show that the GWP of all casting processes are dominated by the emissions of CO_2. Since the majority of CO_2 emissions are a consequence of fossil fuel combustion, either directly from natural gas combustion at the casting facility or from the generation of electricity, these data indicate the importance of energy conservation as a means to reduce GWP.

OVERALL ENVIRONMENTAL PERFORMANCE

The data for material and energy consumption, emissions of each pollutant to the atmosphere, wastes (both recycled and landfilled), and environmental

Table XII. Greenhouse Warming Potentials of the Casting Process Life Cycles

Compound	GWP (relative to CO_2)[c]	SPM[a]	Precision Sand[a]	Lost Foam[a]
CO_2	1.0	3495.5[b]	5874.8[b]	3689.8[b]
Methane	21	22.52[b]	29.82[b]	18.98
N_2O	310	0.0061[b]	0.0067[b]	0.0043
Total (mg *x* GWP)		3970.3[b]	6503.1[d]	4089.7

[a] Values are kilograms emitted per 1000 kilograms of degated product.

[b] Values from AP42 estimates of emissions from natural gas combustion. Other process emissions are unknown.

[c] Greenhouse warming potentials are based upon a 100 year time frame (**4**).

[d] Contribution from methane emissions only include methane emitted from natural gas combustion, not from other sources in the casting process.

Summary

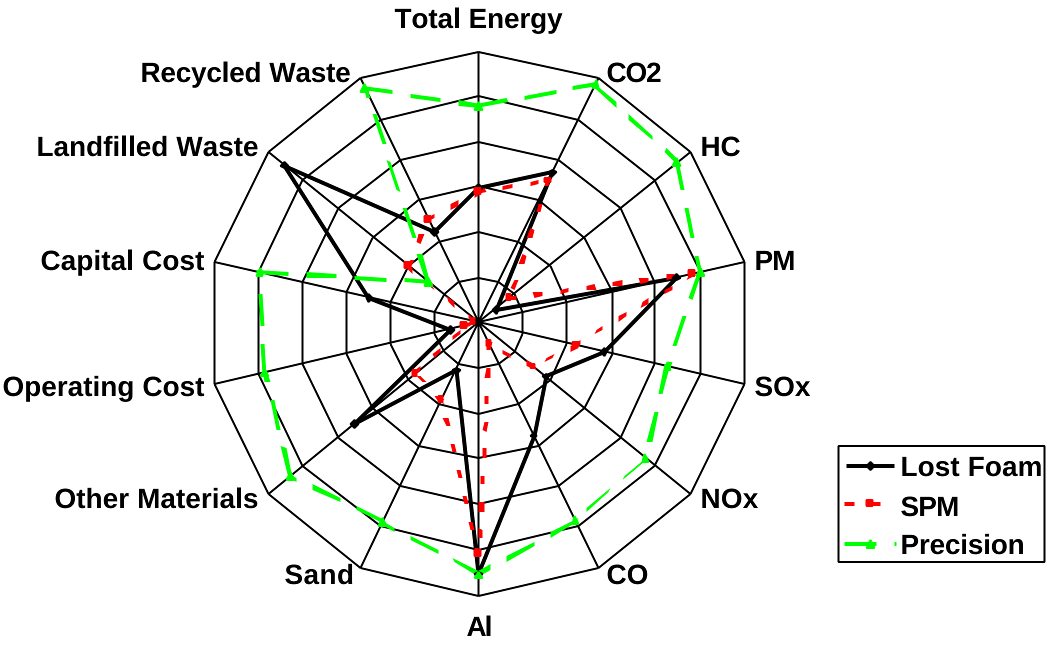


Figure 15. Summary of environmental burdens analyzed in this study.

costs (both capital and operating) have been summarized in a spider chart shown as **Figure 15**. This figure shows, at a glance, the overall values for each environmental burden summed over material production and manufacturing, except in the case of raw material consumption and environmental costs, which were calculated for the manufacturing stage only. On this figure, an optimal value would be zero, located at the center of the chart.

We have evaluated these data and have identified the parameters that would most influence an environmentally-based choice of one of these three casting processes. These data are summarized in a spider chart shown as **Figure 16**. These burden categories are raw material and energy consumption, solid and liquid wastes (summed over recycled and landfilled wastes), HC, CO_2, and PM emissions, and total environmental costs.

Conclusions

A thorough life cycle analysis of aluminum lost foam, precision sand, and semi-permanent mold casting has been completed. Inventories of material and energy consumption, air emissions, and liquid and solid wastes have been performed. We have mass-normalized the results on the basis of 1000 kg of degated product. Our analysis omits the use-phase and end-of-life phase burdens of the products, which should be approximately equal for all processes on the basis of mass of product. Also, we have not considered the burdens associated with machining. In addition to the inventory analysis, a sensitivity analysis has been performed on the material production burdens and the life cycle CO_2 equivalent greenhouse gas emissions have been calculated.

For all processes, the manufacturing phase electricity and aluminum consumption are major contributors to the material production stage burdens. Other major contributors are shot blast media and polystyrene for the lost foam process and resins and sand for the precision sand and SPM processes.

This analysis indicates that, for most categories, lost foam and SPM burdens are comparable. For all categories, the burdens from precision sand are the highest. Although lost foam and SPM burdens are nearly equal, SPM has slightly lower environmental costs, while lost foam has lower HC and PM emissions, and less total waste. SPM and lost foam have nearly equal material and energy consumption as well as CO_2 equivalent greenhouse gas emissions. However, the data probably underestimate the methane emissions from the SPM process. Overall, our analysis indicates that lost foam casting of aluminum heads and blocks has less environmental impact than either SPM or precision sand casting.

Summary

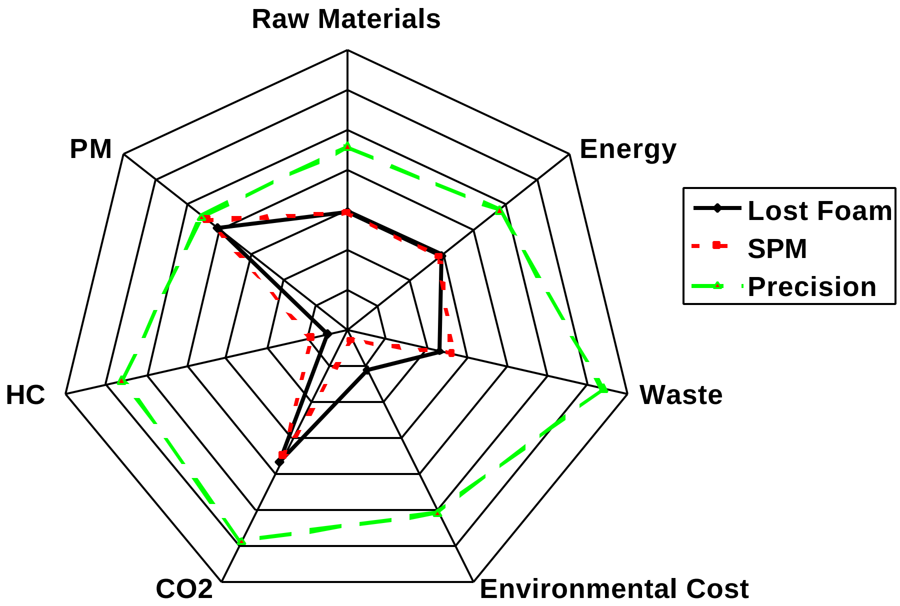


Figure 16. Summary of the major environmental burdens analyzed in this study.

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