Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting

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Conventional manufacturing techniques have not been subject to much scrutiny by industrial ecologists to date. Many newer techniques and products draw more attention as they rise quickly from research to global scales, accentuating their environmental consequences. Despite the presence of new technologies and increased overseas production, casting is not being displaced from the US, and represents a stable component in the national economy. Data from the US government, US industry groups, and UK mass balance profiles facilitate an understanding of sand casting and comparison across manufacturing processes. The figures in the US and UK are similar in terms of diversity of metals (where the US is 76%, 13%, 8% and the UK 72%, 13%, 10% for iron, aluminum, and steel, respectively), energy per ton of metal (10.1 and 9.3 MBtu/ton in the US and UK), and overall emissions, with notable similarities in benzene and particulate emissions. One notable discrepancy is in sand use, where the US sends to waste 0.5 tons of sand per ton of cast metal, whereas the UK sends 0.27 tons.

1. Introduction

Although we live in an age where new technologies demand exotic manufacturing techniques, most products still require traditional manufacturing processes and carry along their inherent environmental ramifications. Developing countries entering mass production, in particular, are taking on an increased environmental burden in manufacturing.

Complex products like semiconductors (Williams, 2002) and cars are frequently subjected to life cycle assessments as a part of or in conjunction with environmental impact analyses. For conventional processes like sand casting, such an evaluation is uncommon.

Although sand casting has reached a stable market size in the United States, international production is growing (Modern Casting, 2000). China alone increased shipments 60% over the years 1997 to 2002, and in 2002 shipped 16.2 million tonnes of cast metal. Global casting production showed a 3% overall increase in 2002. Each kilogram of cast material requires substantial energy, often in the form of fossil-fuel generated electricity or direct firing of coke or natural gas. Most of this energy is used to melt the metal for casting, but increased quantities of energy and materials are required to meet customer demands of surface specifications. The highest material demand, besides the metal which forms the final product, is the sand used to create the mold. Organic compounds are used as binders, and burned out as gaseous releases during mold formation. More organic compounds are used in cleaning and finishing.

As in many processes being assessed, there is little consensus on the magnitude of the impacts. Some firms keep relatively good information, but publicly available aggregate data and sector analyses are scarce. The lack of evidence that the environmental impact is well understood or well addressed exemplifies the suitability of this sector and need for life cycle research.

2. System Boundaries: Process Materials and Energy Use

The system boundary outlines the sand casting manufacturing process and the boundaries of this inventory. The resources considered (Figure 1) are the material and energy inputs and outputs for mold preparation, metal preparation, casting, and finishing stages and their subprocesses.

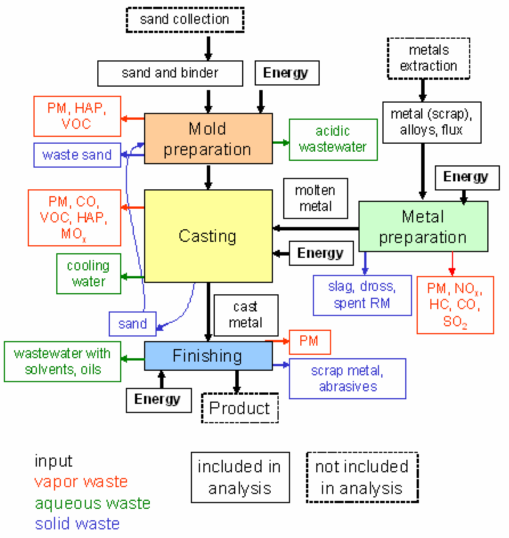

Figure 1. System boundaries of analysis and materials flow of sand casting.

Note that the manufacture of materials (e.g., extraction of metals or sand and water purification) is not within the system boundary. Also, equipment manufacture is not included. Furnace service life is long enough that manufacturing impacts are in the distant past and end-of-life impacts are yet in the distant future. Therefore, they can be neglected as the environmental impact of dealing with them decreases over a long time frame, much like the future value of currency in economics.

The limited body of literature available suggests greater concern about the energy implications of sand casting than the material challenges of reducing sand and water consumption. The US Department of Energy (DOE) has published an energy and environmental profile of the casting industry, as has the US Environmental Protection Agency (EPA). Some sand casting foundries must also file a Toxic Release Inventory (TRI) with the EPA.

TRI applies to companies with manufacturing operations in Standard Industrial Classification (SIC) codes 20 through 39 – casting is in 33 – TRI applies to companies with more than 10 employees that use 25,000 pounds of approximately 600 designated chemicals or use more than 10,000 pounds of any designated chemical or chemical category (EPA, 2004). 654 of some 2,800 US foundries were required to file a TRI in 1995 (EPA, 1999) – 33% of foundries do not have 10 employees, and the other 44% who do have more than 10 employees do not use enough regulated material to be required to file a TRI.

Energy data is available from the Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS). Although the results are obtained from self-reporting questionnaires, the numbers tend to agree with other surveys and with approximations calculated from basic information. Even though sand casting is relatively uniform in concept, the myriad parameters complicate the derivation of accurate systematic estimations on a national scale from individual foundries and equipment. Consequentially, determining concordance between individual foundry data and reported data is an exercise of coincidence.

At least three gaps in the known literature on sand casting must be addressed. Two of these are in common with those which have not been addressed in semiconductors (Williams, 2002), demonstrating an issue in life cycle analysis which extends beyond this process. There is a noticeable lack of process data, like input and output materials. This is particularly true of the cleaning process and the components in and reactions of sand binders. Second, of the process data that does exist, no comparisons have been made between the self-reported numbers and experimentally-derived models. Finally, there is a lack of data which is not self-reported. Addressing this issue is beyond the scope of this study, but critical in attaining confidence in the life cycle analysis of a process.

The manufacturing process (Figure 2) begins with the formation of a single-use mold from sand and binders, which hold the sand mold together. A lot of the sand comes from the sand reclamation process, where sand from previous molds gets reclaimed for use in new molds. Cores are also made at this point for parts that have internal cavities.

In the green sand casting process, molds are made from a mixture of sand, clay, water, and carbonaceous additives (e.g. bituminous seacoal, anthracite, or ground coke). About 85% of the mold (EPA, 1998), by mass, is sand. The clay (4 to 10%) and water (2 to 5%) act as the binder system from which the mixture derives its strength. Although the carbonaceous additives are a very small component by mass, they are needed to prevent the metal from oxidizing as it solidifies. They burn off on contact with the molten metal, creating an assortment of hazardous air pollutants (HAPs).

Green sand casting is often accompanied by the use of chemical binding systems. Many parts require cores, internal cavities that must be strong enough to hold together as the metal falls in around it. Therefore, binders other than clay are used, including synthetic resins. Many of these binders have to be cured at high temperatures, though new techniques are being adopted to allow curing at room temperature. The resulting core is harder and stronger than the green sand mold. A few foundries use chemical binder systems in molds, too, but this is uncommon because the green sand process is inexpensive, relatively clean, and flexible.

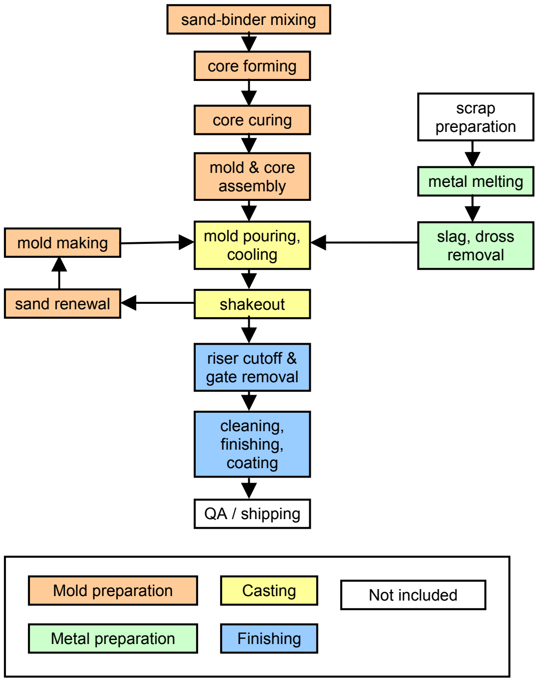

Figure 2. Process flow for a typical sand casting foundry. Adapted from Kotzin, 1992.

At the same time, the metal is being prepared for casting. The metal is melted in a furnace, and is sometimes shuffled to holding furnaces to keep it ready for production. Furnaces vary significantly in size, fuel, and efficiency. Sand casting can be used for almost any metal, but iron, aluminum, and steel are the most common. A high percentage of the metal feed is recycled material.

The molten metal is then poured into the mold. Many foundries use noncontact cooling water systems to hasten the process, bringing the cast product to shakeout that much faster. In shakeout, the sand mold is broken with vibration or high pressure water to remove the cast product. The sand is sent to reclamation, where it will be cleaned for use in another mold.

Even after shakeout, the product is not yet ready for the customer. Sprues, runners, flashing, and other excess metal are removed by cutting or grinding. Additional improvements can be made to the surface before cleaning fluids or resin coatings are applied to protect the finished product.

3. Energy use in Sand Casting

Sand casting is an energy intensive manufacturing process because it requires the melting and shaping of significant quantities of metal. According to EIA results (EIA, 2001) from self-reported questionnaires sent to foundries nationwide, US foundries[a] used 216 trillion BTUs in 1998, or 14.6 million Btu per ton of saleable casting. 1997 data (154 trillion Btu, 14.1 ton cast metal) gives only 11 million Btu per ton. The discrepancy, over such a short time frame and from the same data sources, suggests that an aggregate national value may not tell the whole story over the years. Though a good approximation, it does not make distinctions on the effects of, for example, the market's shift towards lighter metals or the changing efficiency of production.

Government survey data can be compared with published data from industry and researchers. The EIA results are comparable to typical industry estimates within the range of 13 to 15 million Btu per ton (Stevenson, 1995).

Mold preparation.

Mold and core preparation are becoming increasingly benign in energy use with new developments. Green sand molds can be used only once, which may be considered inefficient compared to permanent molds, but they are also inexpensive and easy to make and change. Each mold made requires little energy, but doing it repeatedly can add up. In addition, high curing temperatures are often required to cure binders in green sand cores. Increased use of no-bake binders, which cure at room temperature, has reduced energy requirements of this step.

Green sand can be reused many times without significant treatment. It is filtered to remove binder remnants and fine-grained particles too fine for remolding. After each run, 10% of the green sand is removed from the foundry cycle (DOE, 1999). Green sand filtration produces lots of dust which has to be controlled and disposed of properly. For chemically bound sand, reclamation includes the removal of binder residue from sand before reuse within the industry, recycling to other industries, or landfilling. Thermal sand reclamation is the most common method used. Heat or infrared radiation can be applied to combust binders and

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[a] Does not include die-casting. Does include losses in electricity generation.

contaminants (Heine, 1983). The application of heat is similar to what happens near the sand-metal interface during casting, and leads to the release to air of many of the same organic pollutants. Heat reclamation changes the properties of the sand over time, eventually preventing its reuse in casting. These processes take, on the outside, 1 MBtu per ton of sand processed (EPA, 1995b), or approximately 5.5 MBtu per ton of metal cast (ETBP, 1998). Thus the 10% sand loss is not insignificant, as each ton of cast metal requires about 5.5 tons of sand, of which approximately half a ton is disposed of.

The mold preparation stage, in total, requires about 1.0-3.0 MBtu/ton saleable casting (DOE, 1999) for green sand foundries and additional energy in foundries using chemically bound sand. This is in line with industry group analysis (CMC, 2002) which concludes that moldmaking and coremaking contribute about 20% of total energy use (Figure 3).

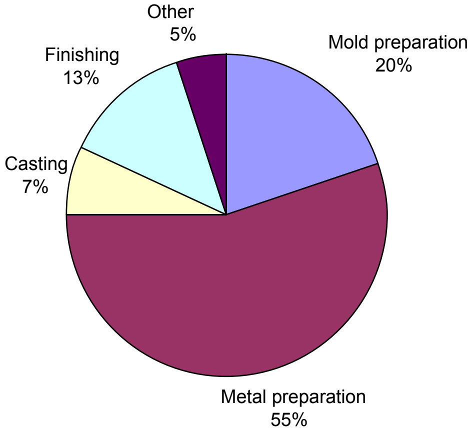

Figure 3. Energy requirements by stage. The total energy requirement is around 10 MBtu/ton, but varies by metal and furnace type.

Metal preparation.
In any foundry, the melting of source metal is the most energy-intensive part of the process. EIA MECS results (EIA, 2001) show that 55% of foundry energy use is in process heating. However, energy requirements and therefore environmental impact vary greatly among furnaces, which differ in size, age, and fuel source (Figure 4). The large share of natural-gas-fueled furnaces reflects their low energy costs. Coke requires more energy per ton of metal and has greater emissions. In today's environment, it plays a less important role in the foundry than it has in the past. Electricity use is hard to interpret from this data, since it also includes electricity used in other parts of the casting process and supporting activities within the foundry.

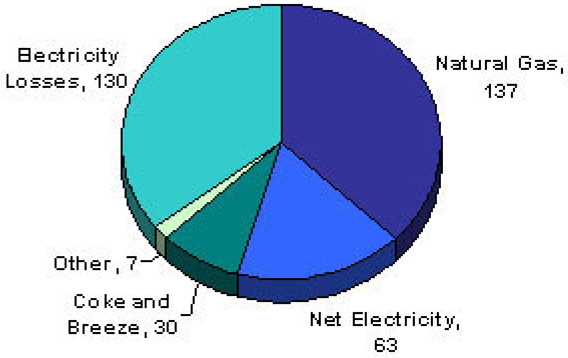

Figure 4. Foundry energy consumption by fuel in trillion Btu. Source: EIA, 2001.

There are five types of furnace commonly used in sand casting foundries. A foundry will choose a furnace type based on capacity, alloy mixture, available fuels, and capital cost. *Reverberatory furnaces* use wall mounted burners to radiate heat from the refractory wall to the metal inside. Electric reverberatory furnaces are available, but are primarily used as holding furnaces. The *electric arc furnace* (EAF) is circular, with movable electrodes mounted in the roof. Once charged, the electrodes are lowered to the surface of the metal and an arc is struck to provide radiative heat for melting. *Cupolas* consist of a vertical cylindrical steel shaft with counterflow heat exchangers. They are traditionally fueled by coke but cokeless cupolas, powered by natural gas or electricity, are becoming more common. The *electric induction furnace* has a metal coil structure in the middle of the refractory through which alternating current is passed, creating a magnetic field. The magnetic field induces current on the metal surface and conducts heat throughout the refractory. *Crucible furnaces* are the oldest furnaces. The crucible has a steel shell with a clay-graphite lining. In production, crucibles are only used for low-melting temperature alloys, and they are smaller than furnaces of modern design.

Furnaces for commercial casting are 0.5 tons on the small end and upwards of 150 tons at the largest. The wide range in energy requirements are partly explained by equipment, like reverberatory and electric arc furnaces, which can span the entire range of furnace sizes (Gale Group, 2004). Another contribution to the range is the variety of metals cast in the US. Cupolas are only used for melting iron, so their energy characteristics are more narrowly defined. The other furnaces are used for different metals, like iron and aluminum (71% and 13% of US castings, respectively), whose heat capacities vary by over a factor of two.

Fuel source	Furnace Type	MBtu/ton
Fuel-fired	Crucible	1.8-6.8
	Reverberatory	2.5-5.0
	Cupola (coke)	5.8
	Cupola (NG)	1.6
Electric	Induction	4.3-4.8
	Electric arc	4.3-5.2
	Reverberatory	5.2-7.9
	Cupola	1.1

Table 1. Energy requirements at the foundry in MBtu/ton saleable cast material for foundry furnaces. Source: DOE, 1999.

Casting.

The pouring stage is less energy intensive than other parts of the process. Improvements here most need to be made in material releases, like those of dust and HAPs to air. Energy improvements can mostly be made in heat loss.

Once the metal is melted, it is transferred from the furnace to a pouring ladle, which holds anywhere between 100 pounds and 35 tons of metal (DOE, 1999). Heat loss can be substantial, and restricts the amount of time that the metal can be treated while in the ladle. These are often heated to control the temperature of the molten metal throughout the pouring process. Most of these processes are powered by electricity or natural gas and require approximately 0.6 MBtu/ton (DOE, 1999).

Finishing.

Finishing stages of a cast part include grinding, heat treatment, and blowing. Again, the chemicals used in this stage are more of a concern than the energy. These processes remove sprues and runners and transform the cast surface to customer specifications. Combined, they require some 1 million Btu/ton of foundry energy (DOE, 1999). The Cast Metals Coalition (2002) reported Post Cast process energy as 7% of total energy costs.

4. Material use in Sand Casting

There are a limited number of material inputs in sand casting. Metals used for the final product are important, but cannot be processed without supporting materials like sand. Sand is used to make each mold, at a ratio of about 5.5 tons of sand to one ton of cast product. Complexities of the process arise through reactions when sand and binders are exposed to heat in the casting stage, releasing a wide variety of organics. A number of these products are hazardous and regulated federally by the federal Clean Air Act or Clean Water Act, and at state and county levels. Publicly available data on emissions are from government resources of aggregate statistics. More detailed relationships for some pollutants have been established in specific systems by government- (particularly EPA) and industry-sponsored experiments. Such experiments have resulted in correlations between HAP production and the type and concentration of binder. The particular reactions behind their formation are not explored as deeply as are their presence and relative quantities of formation in varying casting parameters.

Mold preparation.

The preparation of molds and cores involves significant quantities of sand. In a green sand foundry, the addition of water and clay, followed by mechanical "ramming," are the only remaining steps to making a mold. A foundry that uses chemically-bonded sand uses less energy in ramming but this saving is made at the expense of increased pollution from chemical binders.

Green sand is typically used for parts under 1 ton and is almost never used for making cores (DOE, 1999). Therefore, a green-sand-only foundry is unusual. Particulate emissions are negligible during mold preparation.

When greater mold rigidity is required, binders stronger than clay are added to the sand. The categories of binders include furane binders, phenolic urethane binders, and phenolic ester binders (Donohoe, 2001). The choice of binder depends on the size and pressure of the process and the type of metal cast. Emissions from binders are usually associated with the casting stage, but curing in mold preparation releases pollutants (Table 2) from heat-decomposed and unreacted components. All of the pollutants listed are classified as HAPs, and must be reported to the EPA in the foundry's TRI. Other pollutants like CO_2, H_2S, and NO_x are also associated with this stage.

	Benzene	Methanol	Phenol	Toluene	Formaldehyde	MMDI
Furane	•	•	•	•		
Phenol urethane			•		•	•
Phenol ester			•		•	

Table 2. Some pollutants associated with binders used in Mold Preparation. MMDI is an acronym for Monomeric Methylene Diphenyl Diisocyanate. Sources: DOE, 1999, Donohoe, 2001, and LaFay and Neltner, 2002.

Metal preparation.

Metal and fuels are the key inputs in metal preparation. Sand casting uses a large quantity of scrap metal as feedstock, upwards of 50% in some cases. Undesirable outputs (Table 3) are related to the combustion of fuels, and therefore include large amounts of particulates and carbon monoxide (CO), along with smaller amounts of SO_2 and VOCs.

	PM	CO	SO_2	VOC
Fuel-fired	1.1	unknown	n/a	unknown
Induction	0.5	~0	~0	unknown
EAF	6.3	0.5-19	~0	0.03-0.15
Cupola	6.9	73	0.6S*	unknown

Table 3. Approximate on-site emissions from various furnaces in kg/tonne of metal. Does not include emissions from electricity generation or fuel extraction. Source: EPA, 1995b.

*** S is the % sulfur in the coke.**

Pollutant production can be significantly reduced through the use of pollution control technologies. Many foundries use a baghouse or scrubbers to clean air before releasing it from the foundry. The same amount of pollution is created, but it can be properly treated and disposed of instead of being released directly to the atmosphere.

The baghouse, a fabric filter, is commonly used to collect furnace emissions. They can be installed on all types of furnaces – almost all EAFs have them, along with 25% of induction furnaces and about one-third of cupola furnaces (DOE, 1999). Baghouses can also be used in conjunction with sand reclamation and other steps in casting.

Wet scrubbers bring a polluted gas stream in contact with liquid to absorb the pollutant. The contaminated liquid can be treated and properly disposed. They are less common in foundries than in other industries, and found almost exclusively on cupolas. Low use rates can be attributed to the high capital costs of wet scrubbers and high treatment and disposal cost and flow rates for the scrubber liquid. Most foundry wastewater comes from wet scrubbers, which can have an output of wastewater as high as 3,000 gallons per minute in facilities with large cupola furnaces (EPA, 1998b). Thus in a tradeoff for cleaner releases to air, the foundry now has to deal with the treatment and disposal of a large quantity of water.

The metal inputs are, of course, significant. Of the approximately 15 million tons of metal cast each year, nearly three-quarters of it is iron. (Figure 5).

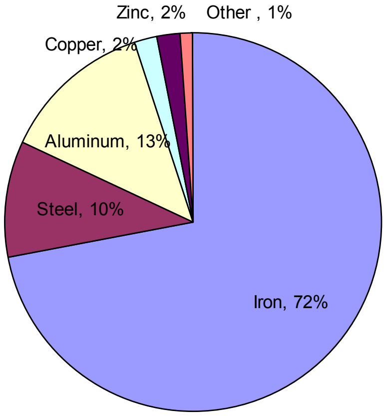

Figure 5. Cast metal distribution in the United States, measured by mass. Source: DOE, 1999.

Steel and aluminum are also widely cast, but are each only around 10% of the share of metals cast. Nonferrous castings are typically only used for products that require specific mechanical properties.

Casting.

The stage of pouring metal into the waiting mold is the leading source of hazardous pollutants in the sand casting process. Metal fumes come from the molten metal while in the ladles, and organic emissions occur when the metal comes into contact with the sand and binder. These emissions continue throughout the cooling process.

The cooling process itself is often driven by high rates of water use. After the mold is poured, plain or chemically-altered water is used to quench the metal and mold without direct contract, reducing cooling times. This water can be reused within the plant, and can typically be discharged to treatment systems or to surface waters (EPA, 1998b). Additional water is sometimes used in shakeout – high pressure water aimed at the mold breaks up the sand, but creates a slurry of untreated sand mixed with binders and water.

In general, emission factors for molds with cores are higher than for those without (NCMS, 1999). Molds with cores require additional binders in core preparation, and more commonly use phenolic binders. Phenolic binders substantially increase the emissions of phenol from incomplete conversion.

The most thoroughly studied foundry pollutant is benzene. LaFay and Neltner (2002) derived experimentally a function of benzene emissions for a given casting system. It agrees well with other experiments which determine benzene emissions to be between 0.06 lbs/ton (Kauffmann and Voigt, 1997) and 0.05 lbs/ton (NCMS, 1999) over a variety of metals and binder systems.

Experimental benzene data can be scaled up to match national data fairly well. 1995 TRI results report 239,000 pounds of benzene emitted. By treating this as one representative foundry, the above results suggest this foundry produced 4.3 million tons of cast products, about 27% of the national total. In fact, 23% of U.S. foundries filed TRI in that year. The fact that not all TRI foundries reported benzene as an emission suggests that its creation is not uniform across the industry.

After the metal cools, the cast product is removed from the mold during "shakeout." Collapsing the mold with vibrations produces significant quantities of dust and metallic particulates.

Shakeout emissions (Table 4) are related to the binder system. The two most common systems, Green sand and no-bake, have similar emissions but demonstrate the emissions tradeoffs between different technologies. The additional benzene emissions during shakeout imply that the lower bound of benzene emission determined by NCMS may be too low, as a national data point, and that the Kauffmann and Voigt (1997) point may be a better estimate of real foundry practices.

	Benzene	Formaldehyde
Green sand	0.0083	0.0039
No-bake	0.0053	0.008

Table 4. Average emissions factors of benzene and formaldehyde during shakeout in lb/ton of metal from a survey of Wisconsin foundries. Source: Lindem, 1996.

Finishing.

The finishing stage brings the rough cast product to a stage which will be accepted by foundry customers. All products must have sprues and runners, which are used to funnel metal into the mold, removed. Most must be cleaned and have surface treatments performed. Cleaning the product can involve the use of organic solvents, abrasives, pressurized water, or acids, often followed by protective coatings. Although particle, HAP, and effluent pollutants are created in this stage, they are largely contained by filters and closed systems.

The cleaning stage removes extra sand from the surface of the part. Common techniques include vibrating, wire-brushing, or blast cleaning (DOE, 1999). These processes can create significant quantities of dust and metallic particulates. This is also true of finishing – using band saws and cutoff wheels to remove sprues, runners, and flashing. Emissions can be controlled with hoods and ducts which pass the particulates into scrubbers.

Hazardous Materials.

Owing to the organics used in binders and cleaning, a number of hazardous materials are released during the sand casting process. Other releases from foundries include metals and metal compounds. Metal casting facilities report disposal and releases of toxic chemicals and a designated list of HAPs on the EPA TRI. The

TRI provides a base understanding of the toxic materials used, though care should be taken in its generalization to the entire industry.

The use and disposal of foundry chemicals are regulated by the federal government under at least one of the

1. Resource Conservation and Recovery Act (RCRA), which regulates management of solid waste, hazardous waste, and underground chemical storage.
2. Clean Water Act, which forms the basic structure for regulating discharges of pollutants into US waters. The most relevant sections are CWA§307 (Toxic and pretreatment effluent standards) and CWA§311 (Oil and hazardous substance liability).
3. Clean Air Act and its 1990 amendments, which were written to keep US air clean despite increasing industrialization and urbanization. The 1990 amendments set limits on how much of a pollutant can be in the air anywhere in the US.

Regulated foundry process chemicals (Table 5) also turn up in the TRIs and in the process mass balance.

	RQ	Code
Methanol	1	RCRA §3001
Phenol	1000	CWA §311(b)(4), CWA §307(a), RCRA §3001
Formaldehyde	1000	CWA §311(b)(4), RCRA §3001
Toluene	1000	CWA §311(b)(4), CWA §307(a), RCRA §3001
Benzene	5000	CWA §311(b)(4)

Table 5. Some federally regulated process chemicals and relevant statutes. RQ are reportable quantities in pounds per year.

The casting industry is challenging to model by TRI data alone. First, only 23% of foundries file TRI, and those that file are not necessarily representative of the industry as a whole. The small fraction is a result of the small size of the average foundry in a bimodal distribution. Fully 33% of U.S. foundries do not meet the 10 employee minimum needed to report TRI (EPA, 1998) and of those that do, only some meet the use requirements.

Second, foundries reported 58 different materials as releases or transfers during 1995. The chemical most frequently reported was copper, which was reported by only 38% of those responding. Over half of the chemicals were reported by fewer than 10 foundries (EPA, 1998). The wide variety of chemicals reported is a result of the myriad variations on the process specifications.

Recycled Materials.

On the surface, casting appears to be as materials intensive as it is energy intensive. The search for cheaper materials and the aversion to disposal have increased the amount of recycled material going through the manufacturing process over the years.

Up to 90% of sand can be reused in a green sand foundry after filtration for fine dust and metal particles (DOE, 1999). Chemically bound sand must be reused at much lower rates due to degradation from treatment between runs. Sand that is not reused within the industry is repurposed, primarily in asphaltic concrete (Ahmed, 1993). Metal slag skimmed from the top of a furnace is also used in asphaltic concrete and other concrete products. In 1992, 14 million metric tons of blast furnace slag – a portion of which came from sand casting foundries – was sold for recycling in other products (Schroeder, 1994).

The small amount of metal filtered from sand can be sent back to the furnaces with significant quantities of purchased scrap metal. Ferrous foundries obtain 85% of raw material as scrap, paying almost $1 billion for 13.3 million tons of scrap metal (OIT, 2000b). Aluminum scrap concentrations may be even higher. Nationally, some 31% of ferrous products are recycled (EPA, 1996) and rates for aluminum are even higher, between 50% and 65%. The material and economic advantages are significant. Using iron scrap instead of primary iron saves over 100,000 MJ of energy (de Beer, et al, 1998) over one year of US production. Energy savings add to these advantages, since the use of scrap aluminum requires 5% as much energy as the extraction of new aluminum (OIT, 2000a).

5. International comparison.

Only one other group has attempted a mass balance of the foundry industry. Biffa, a waste management group in the United Kingdom, sponsored a study of the materials flow of casting in the UK. Data used in the Biffa study were collected from 89 representative companies in the UK, representing 18% of the country's 1.3 million tonnes (Modern Casting, 2000) of annual production. The energy data corresponds well. There are some more interesting comparisons to be made in the materials realm.

Energy.

For each short ton of saleable cast metal, around 9.3 MBtu of energy were consumed. This is a very close comparison to the numbers derived from United States statistics, though a little lower. The difference may be attributed to different energy sources (e.g., increased electricity use in the US may mean more losses in generation relative to plants not powered by electricity and therefore more energy per ton cast), different furnace technologies (where most energy is expended), or, of course, error.

Power sources in the US and UK do differ, especially in electricity distribution (Table 6).
The US uses approximately 10% more electricity in the foundry industry than the UK does. A modest increase in proportions of electricity use in the US (3%) would show up as a 10% increase when including losses, as seen in Table 6 (EIA, 2001). Although coal for coke is widely available in both countries, natural gas is preferred because of reduced emissions, higher melting efficiency, and lower heating and melting time (OEE, 2003).

	US	UK
Natural Gas	21.4%	38.8%
Electricity	58.5%	48.5%
Coke	18.9%	12.0%
Fuel Oil	1.2%	0.6%

Table 6. Power source distribution between the US and the UK, including losses in electricity generation. Sources: DOE, 1999, and Donohoe, 2001.

Materials.

The supporting process materials in the UK are the same as in the US. Sand and water are still used in larger quantities than any other materials. The same metals are cast on both sides of the pond, and their relative proportions are not so different. Other individual chemicals are more difficult to compare, but categories like particulates and air emissions can be explored.

Similar though they may be, practices worldwide are not uniform. Evidence for this can be found in comparing sand landfill numbers between the two countries. In the US, 7 to 8 million tons of sand (or around 0.5 ton sand/ton cast metal) is landfilled annually from foundries, and sand comprises nearly 70% of foundry solid wastes (DOE, 1999). The same industry in the UK disposes of 347,451 tonnes of sand per year, or 0.27 tons sand for each ton of cast metal. Spent sand is 73% by mass of the foundry solid waste stream. Although the exact reasons are unclear, it could be related to increased UK reuse efficiency or a denser variety of sand in the US.

The foundry mass balance found that UK foundries use almost 1.9 million tonnes of water annually (Donohoe, 2001), or 1.5 tonnes of water for each tonne of cast product. Though no comparable estimate was found for US consumption, it should be in the same range on a tonne per tonne basis because the prevalence of green sand casting (water binder), iron processing (cupola use and therefore wet scrubber use), and need for rapid cooling are similar in both countries.

Demand for the various cast metals does not vary between the two regions, either. Market share of metals in foundries is remarkably consistent (Figures 5 and 6)

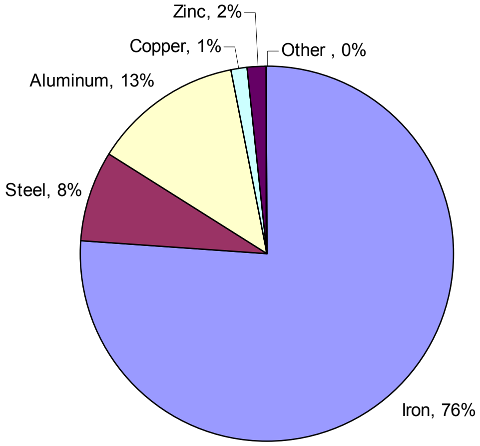

Figure 6. Cast metal distribution in the United Kingdom. Source: Modern Casting, 2000.

A slightly larger share of the UK market is iron, as compared to the US. In the US, some of this has been replaced by steel, copper, or less commonly cast metals.

With similar results so far, it is not surprising that pollutant numbers such as particulates may correspond as well. The US and UK released 21,000 tons and 935 tonnes, respectively, of total particulates (DOE, 1999 and Donohoe, 2001) in 2000. The emissions correspond to rates of 1.42 and 1.33 lbs particulate per ton of cast metal, respectively. The difference is small enough to be negligible but, if it is observable on the foundry scale, may be related to stricter emissions laws in the UK.

Recycling.

Sand recycling is common in the UK, as it is in the US. The Biffa profile found a wide range of sand recycling rates – anywhere from 0% in the smallest foundries which could not afford to treat their sand to 95% in large foundries which had equipment dedicated to the process. 82% of sand is recycled overall, and in disposal it represents 54% of the total foundry waste stream. At a Landfill Tax of £13 per tonne in addition to regular charges, there is a small incentive for foundries to recycle as much sand as possible.

Scrap metal purchase rates for aluminum are in line with American estimates, around 55% of consumed aluminum comes from scrap sources. A surprisingly low percentage of iron feedstock comes from scrap purchases, compared to the US. Only 33% of UK iron is scrap purchase, compared to 85% in the US. This discrepancy may be accounted for by the cost of scrap iron, the amount of iron in circulation which is recycled, and the prevalence of primary production facilities throughout the UK.

6. Discussion.

From start to finish in the process, decisions about the part and the process affect the magnitude of the environmental consequences of manufacturing. These two categories of fundamental choices can be considered in the design of new projects as well as the opening of new foundries or the modernization of older facilities.

Environmentally benign design parameters include minimizing the need for cores and potentially substituting increased machining for core-produced cavities. Where cores are still needed, the environmentally conscious designer will move away from hotbox processes, whose high temperature curing requires significant energy and produces HAPs. No-bake processes should often be a viable alternative. The metal used in each mold can be made with increased recycled content. One goal of the government-industry partnership in casting is to move to 100% recycled metal content (DOE, 2003), thus eliminating the dependence on imported stock.

Melting that metal is still the most energy intensive activity in the foundry. The energy and pollution control requirements suggest the need to re-evaluate the fuel source, furnace type, and pollution control method when modernizing foundries. The process should be moved away from coke, which has greater emissions at the foundry than other sources. Electricity should also be reconsidered to take into account the source of the electricity and therefore its losses and emissions in generation. Improvements can be made by choosing natural gas as a fuel for a cupola or reverberatory furnace. Baghouses should be preferred as a pollution control method, alleviating the foundry of the need for huge quantities of water for a wet scrubber.

Similar tradeoffs must be made in sand reclamation. It is important that the sand is reused, but its lifespan in the foundry should be increased, as should the opportunities for reuse outside of the foundry. Wet reclamation has far greater water needs than other methods, but lower emissions, and allows longer use of sand in the foundry. Thermal reclamation has low material requirements, but needs energy and creates organic and particulate emissions from small sand grains and binder residues. There is no direct metric to compare the two, and the decision may realistically have to be made on the economic viability of each process.

Achieving these standards within the sand casting industry cannot be an instantaneous development. Foundries replace their equipment infrequently because of sheer size or limited capital, so changes requiring significant capital investment like new furnaces or a change in pollution control technology will come slowly. Customer selectivity – giving business to foundries seen as running a more environmentally conscionable business – can induce changes by demonstrating customer preferences for environmentally responsible business partners.

7. The future of casting.

Like other manufacturing industries, foundries are looking towards the trends of the future to understand the challenges which will be faced in coming years. Trends in casting business structure, technology, and regulation will all have environmental consequences.

Offshore production will continue to increase. As recently as 2001, the US was the number one producer of cast parts. US production has stayed constant, but production in countries like China and Mexico has increased rapidly in recent years (DOE, 2003). Overseas production is preferred because of low labor costs and reduced emissions standards and therefore costs of pollution control. China in particular still uses a large portion of virgin material in casting **(reference)**, increasing costs and the rate of depletion of natural resources.

Foreign competition, combined with the current business environment and economic situation, has driven the consolidation of businesses in the US, including foundries. Growing corporations must make choices with direct environmental consequences. Large foundries are also under greater environmental scrutiny than smaller foundries. The combined result may be greater environmental degradation in areas near large foundries, but reduced overall consequences as the larger foundries are forced to choose more environmentally benign manufacturing process parameters and equipment.

The process parameters are not entirely decided by the foundry. Customers are switching to lighter metals particularly for automotive applications. In the next few years, the market share of aluminum can be expected to increase at the cost of steel parts.

Foundries in search of better pollution control technologies have already been a part of increased research on novel technologies like advanced oxidation (Land, et al, 2002) and other non-incineration treatments of filtered emissions. Success of novel pollution control technology can eliminate the use of wet scrubbers and the large associated water needs.

The major drive behind this research is tighter emissions regulations across the US. Although increased regulation is economically unfavorable in the competitive global environment, foundries are subject to more national and local regulations each year. The biggest recent change has been the EPA Maximum Achievable Control Technology Standards, known as the MACT hammer. Section 112(j) of the Clean Air Act requires the EPA to develop a list of hazardous air pollutants that cause or contribute to death or serious illness – established in the 1990 Clean Air Act amendments – and to establish National Emission Standards for Hazardous Air Pollutants (NESHAPs) for each (Winek and Shannon, 2002). Deadlines to set rules for some categories passed in November of 2000, and the EPA's failure to set rules for 31 standards in some 59 source categories meant that cases were decided on a case-by-case "potential to emit" standard. This standard makes it much more difficult for foundries to be exempted from major source status, thus increasing their interest in improved pollution control technologies.

Needing to meet these regulations, foundries are also looking to form partnerships with government and academia to understand the consequences of current practices and the areas of improvement. For example, the DOE is working with foundries to create an Energy Footprint Study (DOE, 2003) to "measure the effectiveness of the processes and technology improvements in energy saving" across different fuel sources, furnace types, and alloys.

8. Conclusions.

Because sand casting continues to be a significant contributor to metal manufacturing techniques, its environmental impact must be better understood to aid in making choices between conventional techniques like casting and newly developed manufacturing techniques. Although it is an energy and materials intensive process, it may be less so than forthcoming solutions. Furthermore, the casting industry deserves credit for its internal reuse, end-of-life reuse, and intake of recycled materials ranging from metals to sands.

Acknowledgements

Professor Gutowski, people who advise, people who sponsor.

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