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ALTERNATIVE GRANULAR MEDIA FOR THE METAL CASTING INDUSTRY

Final Report

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September 1995

Work Performed Under Contract No. FC07-93ID13231

For
U.S. Department of Energy
Assistant Secretary for
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For
Metal Casting Competitiveness Research Program
Department of Energy
Idaho Field Office
Idaho Falls, Idaho

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1. Introduction

Silica sand for foundry use is inexpensive to purchase, readily transported and widely available. As a result, it is universally used. However, three factors are becoming increasingly significant as more environmental regulations are promulgated. First, the disposal of waste foundry sand has become an excessively burdensome cost, approaching $180 per cubic yard if contaminated by lead. Disposal costs are expected to continue to increase at a rate of 2.5 times the rate of inflation (Philbin, 1994). Second, the phase changes which occur in the silica structure on heating and cooling cause thermal breakdown of the sand into smaller unusable fractions. This not only results in processing complications but it also increases the tonnage of sand for disposal. Third, silica is a relatively weak mineral. When reclamation process are used in foundry sand recycling systems, additional breakdown can be expected, increasing the total reclamation cost.

Alternatives to silica sand which can withstand the rigors of repetitive reuse must be seriously evaluated as a way to control production costs of the domestic metal casting industry and keep it competitive in the world economy. The use of alternatives to silica sand is not a new proposal. Foundries have used alternative materials for decades. Chromite sands, olivine sands and carbon sands have each been successfully used to solve operating problems and thus have developed their specific niches in the foundry materials inventory. However, there are several other materials that are candidates for replacing silica sand, such as fused alumina, sintered bauxite and sintered oil well proppants. These media, and others that are generically similar, are manufactured for specific purposes. Compositions and shapes could be readily tailored for used in a metal casting environment of total recycling and materials conservation.

This study examines materials that are readily available as alternatives to silica sand from a functionality perspective and a cost perspective. Some of the alternative materials are natural and others are synthetic and thus referring to them as "sands" has the potential to cause confusion; the generic term "granular medium" is used in this study to mean any material that could functionally substitute for silica sand in the foundry process. Granular media refers to a class of alternative materials.

2. Functions of Granular Media in Casting Molds

The basic premise of this study is that there are alternatives to silica sand that may offer functional and economic advantages when in-plant recycling processes are used. For reasonableness, the study is limited to clay-bonded green sand. Any alternative material, then, must substitute congruently for silica sand and produce castings equal to or better than conventional processes.

Alternatives to silica sand (usually referred to as specialty sands) have been used in the casting industry for many decades. Most of these materials, such as zircon, chromite, carbon, and olivine sands are naturally occurring with carbon sand as the one exception (Bralower, 1989). In contrast, the materials that are the subject of this study are manufactured and thus their compositions and grain shapes can be customized and closely controlled as required by end-use needs.

In the green sand casting process, castings are made by pouring molten metal into a cavity formed by the mold and cores. During the pouring process, the molten metal and any attendant oxide slags may react with the surface of the mold cavity. The molten metal then solidifies into the shape of the cavity and cools by transferring heat through the mold walls. Since a green sand mold consists of a preponderance of silica sand and lesser amounts of bentonite clays, water and other minor ingredients, the substitution of a naturally occurring mineral or a granular medium for the majority silica sand may affect the solidification process. This functionality issue will be examined in the next three sections by considering the aspects of casting shape, casting surface quality and thermal conduction.

2.1. Casting Shape

Sanders relates the story of an early metallurgist named Berthier who insisted that better refractory materials be given him before he could make a more satisfactory refined iron and thus affirmed the importance of balancing ceramic materials to give satisfactory results in the foundry (Sanders, 1954). Similarly, any alternative molding medium must offer the foundry industry benefits which can be measured in terms of cost, environmental compliance and casting quality. These benefits will not be realized if the functionality of the alternative medium is not considered in terms of sand control.

For the best properties of green sand molding, green sand must meet a number of requirements (Garnar, 1988):

1. It must pack tightly around the pattern and it must be flowable.
2. It should be capable of being deformed slightly without cracking so that the pattern can be withdrawn. (Green sand must exhibit some plastic deformation.)
3. It must have sufficient strength to strip from the pattern and support its own weight without deformation.
4. It must withstand the pressure of molten metal when the mold is poured. (It must have green strength).
5. It must have dry strength to prevent erosion by liquid metal during pouring.
6. It must have refractory properties to withstand the high temperatures involved without melting or fusing to the casting.

The functionality of a molding medium that is to be used on the green sand molding process must relate to ease of molding, casting aesthetics, casting dimensional quality, and casting process cost. The industry has adopted standardized sand tests to measure green sand properties. The information from the tests is used by foundry engineers to control sand and keep it functional. A summary of sand function and control parameters is presented below.

Function	Control Measures
Ease of molding:	Moisture, green strength, sand toughness, green deformation, flowability, and compactability
Casting aesthetics:	Grain fineness, grain distribution, permeability, hot gas pressure, and sintering point
Casting dimensional quality:	Hot strength, hot deformation, expansion and contraction
Casting process cost:	Retained strength and ease of shake-out (dry strength)

Potential alternative molding media must possess similar or superior sand control characteristics to silica sand before they will be seriously considered for use by foundry engineers. The information a foundry engineer uses for sand control is derived from years of testing and research on silica sands. This experience base serves as a starting point for determining if an alternative granular medium will function satisfactorily in the green sand casting process. It is also a foundation from which process parameters can be specified. Exact substitutions are not expected or required, since the process parameters for all green sands are influenced by local conditions and practices and identical mixtures may not give identical properties under varying conditions.

Shape and Surface

The shape of a grain and the nature of its surface influence the amount of surface area per unit weight of sand. The more angular and rougher the surface the greater the amount of binder needed to achieve the same coating thickness and bond strength. This can have a significant effect on mixed sand costs. The grain shape also affects the packing density with angular grains requiring a higher compacting force to achieve the same packing density (Hubbard, 1994).

Specific surface areas can be determined but the usual method of classification is to describe a sand grain as rounded, sub-angular, or angular after examination under a low powered microscope although the use of a high magnification electron microscope does allow the surfaces to be studied in more detail.

The roundness and sphericity of particles may be determined using a visual comparator; a good example of a comparator chart is seen in Krumbein and Sloss, Stratigraphy and Sedimentation, second edition, 1955. This chart is used in visual determination of roundness and sphericity. Visual comparison using this chart is a widely used method of evaluating roundness and sphericity of particles, however this chart is not descriptive for classifying the sometimes compound grain shape in an alternative medium. For this reason the Krumbein and Sloss chart was modified; the limited number of categories for roundness and sphericity was increased and descriptors were included.

In using the visual comparison method, a random sample of 20 to 30 particles of media to be tested is selected. The particles are viewed under a 50 power microscope and their shapes compared to the modified Krumbein and Sloss chart. The chart values for roundness range from 0.1 to 0.9 (0.1 = very angular, 0.3 = angular, 0.5 = sub-angular, 0.7 = sub-round, 0.9 = rounded). The chart values for sphericity range from 0.3 to 0.9 (0.3 = low spherical, 0.5 = medium spherical, 0.7 = spherical, 0.9 = high spherical). The chart values for the individual particles are then averaged on both continuums to obtain a roundness/sphericity value.

A basic requirement for alternative molding media in a green sand process is capability of being bonded together by bentonite clay and water. Moisture, bentonite clay, and grain size are the control variables which most affect the functionality of an alternative molding medium in the green sand process. The following sections discuss these control variables.

Moisture

Water additions cause the bentonite clay structure to plasticize and to form weak chemical bonds with silica sand surfaces. As a result, every strength property of green sand is affected. Green sand may contain both free and combined water. Free water is absorbed by the bentonite clay and is on the surface of the grains. The combined water is united chemically with the bentonite clay.

The minimum quantity of free water required to render clay plastic is termed temper. In the plastic state, the clay bonds with silica sand surfaces and produces maximum strength in the resulting composite structure (Heine 1957). Free water is liberated slowly when green sand is heated during the pouring process. Other green sand qualities related to moisture are discussed below.

Green strength, whether tensile, shear, or compression is usually greatest at or near a moisture content of best temper (usually 7% moisture for silica sand).

Dry Strength measures the anchoring of the grains against erosion by molten metal flow. High initial moisture content promotes good dry strength.

Deformation is the amount which green sand deforms at ultimate green compression strength. Deformation increases rapidly with moisture content.

Toughness is the amount of work necessary to break a green sand specimen. Toughness increases rapidly with moisture content.

Permeability of green sand to evolved steam and gases is highest when the green sand is at correct temper.

Flowability of an uncompacted green sand first decreases, then increases as moisture increases. Flowability is least at or near correct temper.

Mold hardness is low when the sand is dry or wet, and is highest when sand is properly tempered (Heine, 1958).

Strength at elevated temperatures (hot strength) increases with moisture additions.

In addition to the fundamental moisture related properties discussed above it is important that any candidate alternative granular medium not be hygroscopic if it is to be used with the green sand process.

Bentonite Clay

Bentonite clay provides the cohesion between the grains of green sand. An ideal green sand has a thin coating of bentonite clay surrounding each grain. More thorough mixing of sand-bentonite clay-water mixtures yields a more uniform clay coating. The mixing must be thorough and require a minimum of time and effort (Lemon, 1993).

Green strength increases as the percentage of bentonite clay increases (Heine, 1989).

Dry strength is measured at room temperature after sand has been heated at 230 °F for 2 hours. It measures ability of the bond to anchor grains of medium in place to resist washing or eroding by molten metal flow during the casting process. Dry compression is increased as bentonite clay increases. Hot strength, which is dry strength at elevated temperatures, is affected by the relative quantity of bentonite clay, and also by the type of bentonite clay (Heine, 1958).

Deformation is least when just enough clay is present to adequately bond the grains for a particular casting regime (Heine, 1956).

Toughness increases rapidly as clay content increases.

Permeability decreases as clay content increases since excess clay fills interstices.

Flowability decreases as clay content increases. Flowability above 80% is very desirable for production of smooth surfaced castings.

Mold hardness increases as clay content increases but falls off rapidly as clay is reduced below 10% (Heine, 1958).

Mold wall expansion at elevated temperatures is reduced at higher clay contents. This reduces defects such as rat tails and buckles. Some bentonite clays flux readily and lower the sintering temperature of silica and presumably other molding media. Bentonite clay content should be kept at a minimum to obtain the best refractory properties in a molding medium at elevated temperatures.

Any candidate alternative granular medium must be capable of being bonded by a bentonite clay-water combination if it is to be used with the green sand process.

Grain Size

A.F.S. Grain Fineness Number Test Procedure 106-87-S is used to determine the average fineness of foundry sands. The size distribution indicates the range of grain sizes in a given sample. Molding media should have a minimum of extremely fine or coarse particles. Wide distributions are undesirable because fines pack into the interstices between coarser grains and reduce permeability. Good distributions are retained upon as few as three sieves.

Careful control of fineness and distribution is essential for good control of molding media properties (Hoyt, 1987).

Green strength tests for compression and shear show no definite trend as grain fineness changes. However, green tensile strength increases as grain size increases.

Dry Strength increases with grain fineness.

Deformation increases as grain size decreases from 30 mesh to pan (Heine, 1956).

Toughness increases as grain size decreases from 30 mesh to pan.

Permeability increases with coarser grain fineness.

Flowability decreases with coarser grains. Fine grain media rams easily to a smooth mold wall surface.

Mold Hardness increases as grains increase in size. Fine media must be rammed much harder than coarse to obtain equal mold hardness.

Elevated temperature strength increases with finer grain size. The apparent thermal expansion of silica sand decreases as grain size increases. Expansion may also be decreased by reducing fines.

Moisture content required to temper increases as amount of fine grains increases.

Clay content required for bonding to a given compressive strength is greatest when granular media sizes are between 200 mesh and 50 mesh. Compressive strength decreases when grain size is larger than 50 and grains smaller than 200 mesh. If a given green tensile strength is to be maintained, more clay is required as grains become finer.

The preceding discussion indicates granular media that are candidates for use by the green sand molding process must have the following attributes:

Surface texture and chemistry that promotes the adhesion of bentonite clays to develop overall cohesion and strength.

Size distribution to give adequate permeability and strength.

Density so that excess water is not present in pores that would inhibit control of the bentonite clay/water mixture.

If these attributes are apparent in a candidate granular medium, there is a reasonable expectation of making molds by the green sand process that are capable of making saleable castings.

2.2. Casting Surface Quality

An alternative granular medium must be able to withstand the thermal and mechanical parameters of the molding and casting process. In addition, the molding medium should be dimensionally stable and chemically inert when molten metal is introduced into the mold. If the bonded molding medium is not stable there is a tendency for the mold wall to dilate when molten metal is poured into the sand mold. The mold cavity dilates due to a combination of mold thermal expansion and liquid-metal pressure and during solidification, a gap between the casting surface and the mold wall may form.

Mold wall movement is caused mainly by thermal expansion of the sand. Silica sand has a thermal expansion of about 1.2% from room temperature to iron casting temperatures. A portion of this expansion is accommodated by the voids between sand particles, the remainder manifests itself as mold wall movement (Kubo, 1985). Castings poured in green sand, relative to those cast in dry sand, are more susceptible to dimensional problems because moisture evolves as steam and low rigidity increases mold wall movement. The technique used to increase mold/metal contact is to increase the riser head pressure (Kubo, 1986).

2.3. Thermal Conduction

Significant research relating to the thermal conductivity, thermal diffusivity, and specific heat of molding sands has been conducted by Pehlke at the University of Michigan (Hou, 1990). Temperature profiles in sand molds were experimentally measured as a function of time after pouring and then used to calculate the thermal diffusivity of the mold as a function of temperature. The apparent thermal conductivity of the sand as a function of temperature could then be calculated using known values of density and specific heat.

The apparent thermal conductivities of dry bentonite bonded sands poured with aluminum and cast iron increased in proportion to bulk density. The apparent thermal conductivities obtained from steel casting experiments were much greater than those with aluminum, and were slightly greater than those with cast iron.

This is because radiative heat transfer increases with increasing metal-mold interface temperature. The apparent thermal conductivity primarily depends on the bulk density of the molding medium and the type of metal poured.

The calculated thermal conductivities of a given molding sand, however, showed wide scatter (Kubo, 1985). This scatter is due to the fact that the thermal conductivity of molding sand is a function of sand type, mesh size, amount and type of binder, water content, compacting method, hardness, hardness uniformity, and temperature and that all of these variables cannot be exactly controlled in a given experiment.

The bulk thermal conductivity of a green sand made with an alternative medium is proportional to the difference between the thermal diffusivity (thermal conductivity times absolute density divided by specific heat) of the particular medium and the thermal diffusivity of silica sand. However, one cannot draw absolute conclusions about the bulk thermal conductivity of green sand molds made with various media solely on the basis of thermal diffusivity because particle shape effects are not included. Very round particles of a single mesh size alternative medium will pack to a lower bulk density than a mixture of several mesh sizes of the same particles and thus would show a lower bulk thermal conductivity. Similarly, particles with a rounded cube shape will pack to a higher bulk density than will particles with a sharp cube shape, again affecting bulk thermal conductivity. The system is further complicated by the presence of water-containing clay coatings on the particles; their effect on bulk thermal conductivity is unknown. No pertinent data on this subject were found in the literature; it appears that this is an area where substantial experimental and theoretical effort should be expended.

3. Alternatives to Silica Sand for Metal Casting

In the following section of this report, alternatives to silica sand are discussed. Some of the alternative media have been used in green sand molds in place of silica sand for several decades. Others have the potential to be substituted for silica sand but such application has not been demonstrated.

Specialty sands, a common industry term, are discussed first. Then, in turn, calcined granular media, sintered granular media and fused granular media are discussed. The various alternatives are then compared on the basis of their chemical composition, thermal properties, cost and ability to withstand the mechanical and thermal cycles inherent to a continuous green sand molding operation.

3.1. Naturally occurring minerals

Specialty sands have been used in the foundry industry for several years because they provide certain advantages over silica sand in specialized process applications. The following section of this report is a summary of the background and properties of various specialty sands, including chromite, zircon, olivine, carbon, and aluminum silicate. The advantages and drawbacks are identified for certain specialty sands in comparison to silica sand.

3.1.1 Chromite

Chromite is the mineralogical name of the compound $FeCr_2O_4$. The foundry grade of chromite sand is a solid solution of six spinels. A spinel consists of a divalent and a trivalent oxide, generally represented by $RO.R_2O_3$. In the various deposits of chromite throughout the world, the six spinels found in solid solution are:

Name	Composition	Melting Point
Chromite	$FeO.Cr_2O_3$	3920°F (2160°C)
Magnesio Chromite	$MgO.Cr_2O_3$	4350°F (2400°C)
Hercynite	$FeO.Al_2O_3$	3236°F (1780°C)
Magnesio Aluminate	$MgO.Al_2O_3$	3715°F (2105°C)
Magnetite	$FeO.Fe_2O_3$	2910°F (1600°C)

Chromite ores are mined from several sources including Southern Rhodesia, the U.S.S.R., Turkey, the Philippines, Albania, and South Africa. At this time only South African ore mined in the Transvaal has been found satisfactory and available for the steel foundry industry in North America. The cost per pound is comparable to zircon sand.

Chromite is an excellent molding medium that offers several advantages over silica sand as summarized below (Garnar 1977):

Good thermal stability and highly refractory.

Good cooling properties since the thermal diffusivity of chromite is 27% higher than silica.

Chromite is not easily wetted by molten metals and thus has good resistance to metal penetration, ranked equal to or better than zircon.

Because it has a low uniform expansion rate, expansion defects are usually not a problem.

Chromite is slightly magnetic, thus it can be separated from other sands with a high intensity magnetic separator.

There are a few disadvantages associated chromite for foundry use:

Hydrated minerals and silicates present as impurities may produce surface porosity and erosion defects.

Chromite is much more dense than silica.

Chromite is a crushed sand and therefore its grains tend to angular.

Chromite sand has been successfully bonded with every type of foundry bonding agent, except for acid-catalyzed no-bake binders. This is because of the high acid demand of chromite sands.

3.1.2. Zircon

Zircon is the mineralogical name of the compound zirconium silicate $ZrSiO_4$. Zircon is mined commercially in Australia, Florida and Georgia in the United States, South Africa, Egypt, Malaya, Russia, and China. It often occurs in combination with baddeleyite (ZrO_2) which is mildly radioactive.

Zircon offers major advantages over silica sand (Garnar 1977):

Low thermal expansion such that it has high resistance to thermal shock.

High thermal conductivity and high mass density, which combine to provide a high cooling rate.

Zircon is not easily wetted by molten metals and thus it has good resistance to metal penetration.

Low acid demand values.

There are significant limitations to the widespread used of zircon:

With a specific gravity of 4.4/4.7 and a bulk density of 160/180 lb/ft^3, zircon is the heaviest of the specialty sands.

Zircon grains are smooth and elliptical in shape and has a grain distribution of two to three screens. Only two grades are normally available, AFS/GFN 100 and AFS/AFS 170. The non-ideal grain distribution and the elliptically-shaped grains combine to yield a specialty sand that has poor compactability.

3.1.3 Olivine

Olivine has been used for many years in foundries as a substitute for silica sand (McCracken 1993). It is a natural mineral consisting of a solid solution of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). It is found in Norway in extensive deposits, in the USA in North Carolina and Washington, and in USSR, Japan, Scotland, France, and Sweden. The sand is produced by crushing and grinding open quarry dunite rock.

Olivine offers several advantages over silica sand:

It has good refractoriness to basic and acid iron-oxide rich slags and is used at temperatures up to 1650°C.

It is not a hydrated mineral and thus does not have to be calcined prior to use.

Olivine is not subject to any crystalline inversions on heating and thus has better resistance to thermal shock than silica sand. It is inferior to zircon and chromite sands in this regard (Garnar 1977).

Olivine is the cheapest of the naturally occurring specialty sands on a per pound basis and even more so on a volume basis.

There are a few drawbacks to the use of olivine as a green sand medium:

Olivine is a relatively weak mineral and thus could easily fracture during a mechanical reclamation process, thereby producing a large percentage of fines (Garnar 1977).

Olivine has a high acid-demand limiting the use of acid-catalyzed binders.

3.1.4. Carbon Sand

Carbon sand is the only synthetic specialty sand. It is prepared from calcined petroleum coke and is chemically inert. It has a lower bulk density than other specialty sands. Carbon sand has inherently low thermal expansion and thus provides high resistance to metal penetration (Clausen, 1992). It has about the same thermal stability as zircon sands. Carbon sands conduct heat rapidly since they have a relatively high thermal conductivity. Limited information is available regarding compatibility with various chemical binders and regarding molding properties.

3.1.5. Aluminum silicate sand

Aluminum silicate, $3Al_2O_3$-$3SiO_2$, is a natural material. It is available in North America under the trade name kyanite. The raw material, found in Florida and Western Australia, is mined, then prefired to 600°C and then crushed and sized for use (Garnar, 1988).

Application experience with aluminum silicate sand is limited. With a pH value of 6.4 the sand is almost chemically neutral and the very low acid demand suggests that it should perform satisfactorily with acid catalyzed resin binders. Aluminum silicate is more economical on a volume basis than zircon sand, provided the cost per ton is equal. Among the shortcomings of kyanite are its high porosity and high expansion when it is fired (Wieser, 1972).

3.2 Calcined granular media

In this report calcination refers to heating without melting to drive off volatile components. The calcined granular media mentioned in this section do not have a history of use as foundry sands.

3.2.1. Calcined bauxite

This material is a homogeneous calcined high alumina aggregate. Specially selected high purity bauxite ores are custom processed and calcined to obtain a dense, volume stable aggregate with low apparent porosity. Calcined bauxite is an ideal aggregate to resist abrasion and hot metal erosion.

3.2.2. Calcined bauxitic kaolin

This material is made from kaolin and bauxite ores which are low in alkalis and iron. Proportions of powdered kaolin and bauxite are mixed with water and vacuum extruded to form kiln run pellets. These pellets are calcined for approximately 2.5 hours at temperatures up to 1650°C. The materials are cooled to ambient temperatures, crushed, ground, and sized to standard sieve sizes for packaging.

3.2.3. Calcined kyanite

Kyanite, $3Al_2O_32SiO_2$, is a natural raw material processed in Georgia. When kyanite is heated mullite is formed, liberating SiO_2, which first becomes crystobalite and then converts to a glassy state above 1600°C. The calcined kyanite (mullite) conversion is complete at a temperature of 1650°C. Once converted the material does not expand or retract upon further firing. The major application of this material is in refractories.

3.3. Sintered Granular Media

Sintered granular media are typically manufactured by pelletizing finely ground raw materials and then heating them until sintering occurs to a point of significant shrinkage. If the pelletizing process is carefully controlled, the sintered particles can be almost spherical and closely graded. Other sintered media are made by extruding a moist mixture of finely ground raw materials and then sintering cut-off lengths of the extrudate in the same manner. Particle cross section is controlled by the shape of the extrusion die cavity.

3.3.1. High Alumina Proppant

Gas or oil well proppants are sintered, spherical composite particles comprising a mixture of diaspore clays and bauxite as the major components (Fitzgibbon 1984). The conventional application for sintered proppants are in the production of natural gas or oil. Sometimes the permeability of the subterranean formation holding the gas or oil is insufficient for economic recovery of oil or gas. In such cases, it is necessary to fracture the formation and prop the fracture in an open condition. Such fracturing is accomplished by hydraulic pressure; the proppant particles are carried into the fracture zone with the high pressure fluid. Spherical particles of uniform size are generally acknowledged to be the most effective.

The sintered proppant materials are produced by sintering round particles made from clay and bauxite. The particles are formed in a high intensity mixer from a mixture of the bauxite, clay, water and a temporary binder. After drying at 100°C to 300°C, the particles are sintered in a rotary kiln at temperatures between 1200°C and 1650°C. The final product is a mixture of mullite and alpha alumina.

A wide variety of proppant types may be produced by changing the proportions and types of initial ingredients. For example, higher density and strength proppants can be made by using better quality bauxite ores. Raw materials are readily available.

Proppant has high sphericity/roundness (.9/.9 Krumbien and Sloss), high hardness, relatively low specific gravity, and excellent refractoriness. It also has good domestic availability and thus it is an attractive alternative medium for green sand casting.

3.3.2. Low-Bulk Density Proppant

A lower cost proppant can be made by increasing the concentration of clay that is used in the initial formulation. This results in a final product that has a lower bulk density. The final product is a mixture of mullite and cristobalite.

3.4. Fused granular media

Fused granular media are made by melting raw materials together in an electric arc furnace, possibly allowing refining reactions to occur in the liquid and then cooling the liquid to form an ingot. The ingot is crushed and desired sizes of the final product are screened out.

3.4.1. Fused Brown Aluminum Oxide

Brown aluminum oxide is made by melting and refining calcined bauxite in electric arc furnaces. The bauxites that are used come from any of several deposits in the world, including Australia, the Peoples Republic of China, Guyana and Guinea. The bauxite ore is calcined prior to shipment and crushed to a nominal 10 mm particle size. At the furnacing plant, the bauxite is mixed with coke particles and cast iron chips and then fed by gravity into a direct arc furnace. As the bauxite melts at temperatures of about 2600°C, the coke reduces most of the silica and some of the titania to their metallic state. They alloy with the melted iron borings and sink to the bottom of the furnace. The refined aluminum oxide is periodically decanted off from the metal layer into large molds for solidification. The cooled ingot is crushed with breaking balls, jaw crushers and impact crushers to the desired size range. Final classification is on metal or silk screens.

The final composition of the fused oxide will vary depending on furnace practice and ore type but generally contains 2.0 to 3.5% TiO_2 and 1.0 to 1.5% SiO_2. Higher titania content grains are stronger. The apparent color after crushing is brown. This shifts to blue-black with firing above 1100°C, reflecting a change in the oxidation state of the TiO_2, which also toughens the structure. The grain shape varies with crushing practice from acicular, developed by roll crushing, to rounded-blocky, developed by hammer-milling. The rounded-blocky shapes do not fracture readily upon impact or thermal stresses because they represent the fraction of the original particle population that had a fewer number of structural faults.

Bauxite reserves are virtually unlimited worldwide. Furnacing capacity is about 230,000 metric tons/year in North America and exceeds 1 million metric tons/year worldwide (Austin 1989). New capacity added by the Peoples Republic in recent years for the export market has increased availability and forced prices downward.

3.4.2. Fused Mullite

Fused mullite is made by melting Bayer process alumina and silica sand together in electric arc furnaces. No refining takes place and the final composition reflects the composition of the raw materials, about 75.2% Al_2O_3, 24.5% SiO_2 and 0.2% Na_2O. After melting, the mullite is poured into large water-cooled ingot molds for solidification. The cooled ingots are broken by drop balls further crushed with jaw crushers and hammer mills. As with white aluminum oxide, special care must be taken to prevent contamination from other fused products and from fugitive dusts.

Raw materials for fused mullite are readily available.

3.4.3. Fused Zirconia Mullite

Zirconium Oxide is used to manufacture fused zirconia mullite. Zirconia is made by refining the silica fraction away from zircon sand in an electric arc furnace. Coke is added to the furnace to partially reduce the silica to silicon monoxide fume. The fume oxidizes above the furnace and is captured in dust collectors. The refined zirconia is then poured into ingot molds or blown into hollow bubbles with an air stream.

Pure fused zirconia transforms from a monoclinic structure to a tetragonal structure at 1000°C with an accompanying volume change that produces severe stresses. Additions of 4% CaO stabilize the zirconia into a combination of 75% cubic structure and 25% monoclinic structure that has excellent thermal shock resistance.

Zircon sands are readily available from mining operations in Florida and South Africa. Domestic furnacing capacity is estimated to be about 8,000 tons/year.

Fused zirconia mullite is a variant of fused mullite, made by melting Bayer process alumina, silica sand and zirconia together in electric arc furnaces. No refining takes place and the final composition reflects the composition of the raw materials, about 46% Al_2O_3, 16%SiO_2, 37% ZrO_2 and 0.2% Na_2O. After melting, the zirconia mullite is poured into large water-cooled ingot molds for solidification. Processing is identical to that for conventional mullite, with strict attention to minimizing contamination from other fused products and from fugitive dusts.

Raw materials for fused zirconia mullite are readily available.

3.4.4. Fused Magnesium Oxide

Magnesium oxide ore can be melted in an electric arc furnace, but only at temperatures exceeding 3000°C. As a result, the furnace is generally of the Higgins type, where the ingot is formed from the solidification of a molten upper layer and no pouring takes place. The ingot is surrounded by partially fused material which must be removed prior to crushing. The final grain is hygroscopic. This alone precludes it from further consideration as a molding medium.

High purity magnesite ores are mined in India, Greece and Canada. Magnesium oxide is also extracted from sea-water by ion-exchange processes. Essentially unlimited quantities are available. Domestic furnacing capacity is estimated to be about 6,000 tons/year.

3.4.5. Fused white alpha alumina

Fused white aluminum oxide is made by melting Bayer process aluminum oxide in a direct arc electric furnace and then cooling the molten product in water cooled molds. After solidification, the ingot is broken up into smaller pieces for jaw crushing. The pieces may be sorted to remove material that solidified last and has a higher Na_2O content. The Na_2O is a contaminant from the chemical refining of bauxite and is undesirable since it combines with Al_2O_3 to form beta alumina, a weak intergranular compound having the composition $Na_2O \cdot 11Al_2O_3$ (Coes 1971). Crushing and grading into size fractions is done with conventional equipment. High intensity magnets remove tramp metal particles introduced during crushing prior to final classification. Throughout the furnacing and crushing operations, special care must be taken to prevent contamination from other fused products and from fugitive dusts.

Domestic furnacing capacity is limited by current demand to about 30,000 tons/year but could be readily expanded in any area where low-cost electrical power is available. This capacity represents the total capacity to manufacture white aluminum oxide, mullite, zirconia mullite and other fused products. Most companies campaign the individual products according to market demand, paying scrupulous attention to cleaning out all equipment between runs of different products.

The raw material for white aluminum oxide is Bayer process alumina. Since this use is a small fraction of the total tonnage available, an adequate supply is assured.

3.5. Comparisons and Distinctions

The basic premise of this study is that there are alternatives to silica sand that may offer functional and economic advantages when in-plant recycling processes are used. In previous sections, the functions that green sand molding media have to perform were discussed. Next several media were determined to be possible alternatives to silica. In this section data useful for comparing the available alternatives are presented from which general conclusions are drawn.

Reactivity with Metals and Slags

Table I shows the chemical composition of the candidate alternative media and their phase compositions. All of the materials listed would seem to have low reactivity with the molten metals and slags encountered in the casting of aluminum alloys, copper alloys and cast irons. Their use for steel casting, however, should follow experimental work to assess slag-metal reactions with alternative media that have silica or silicate phases.

Thermal Properties

Table II shows the thermal properties of the candidate alternative media. Two caveats must be considered in using these data. First, the values pertain to solid particles, not granular beds. The thermal properties of a granular bed may have as much to with particle shape and bulk density as with the intrinsic properties of the material that make up the bed. Therefore, the thermal data are presented for comparison, not as absolute values to be used in analytical modeling. The second caveat is that thermal properties, particularly thermal conductivity, are difficult to measure accurately. For consistency, a single published source was used to report thermal data even though other sources report variations as much as 20% on the same parameter.

Thermal conductivity is the heat transfer related material property that considers steady state heat flow. On the other hand, thermal diffusivity is the heat transfer property that considers transient heat flow. For metal casting purposes, ether parameter is interpreted as being more insulating when its value is lower than that of silica. As a result, solidification times are longer and grain structure is coarser. Correspondingly, an alternative media with a higher value of either parameter would be more chilling, such that a finer solidification structure would result. None of the alternative media have a significantly lower thermal conductivity or diffusability than silica sand. However, five have higher thermal conductivity and diffusability. They are:

Carbon sand
Calcined bauxite
High alumina proppant
Fused brown aluminum oxide
Fused white aluminum oxide.

The apparent thermal expansion of silica is high due to an inversion in its crystallographic structure that occurs on heating. Fused magnesia has a comparable expansion. The following candidate media have comparatively low thermal expansion:

Carbon sand
Zircon
Aluminum silicate sand
Calcined bauxitic kaolin
Calcined kyanite
Low bulk density proppant
Fused zirconia mullite.

With the exception of carbon sand, these media have thermal conductivity and diffusivity comparable to or slightly lower than that of silica sand.

Cost

Costs of candidate alternative media are shown in Table III. The most significant parameter to this discussion is cost per cubic foot, since the media will be used to fill flasks. Foundry sand sets a low target at $1.50 per cubic foot. Using that as a base, the alternative media can be grouped into three cost categories:

1 to 10 times the volumetric cost of foundry sand:	
Olivine	$ 4.12 per cubic foot
Aluminum silicate sand	$ 8.76
Calcined bauxite	$10.00
Carbon sand	$10.50
Calcined bauxitic kaolin	$11.50
Low bulk density proppant	$14.70
10 to 25 times the volumetric cost of foundry sand:	
Chromite	$15.60
Zircon	$21.25
Calcined kyanite (mullite)	$17.70
High alumina proppant	$30.00
Fused brown aluminum oxide	$35.40
More than 25 times the volumetric cost of foundry sand:	
Fused mullite	$45.00
Fused white aluminum oxide	$55.00
Fused zirconia mullite	$63.00
Fused magnesium oxide	$80.00

It is a significant fact that several of the materials listed are currently used by the foundry industry for special applications - olivine, carbon sand, chromite, zircon and calcined kyanite. Therefore, an alternative medium that has a volumetric cost within 25 times that of silica sand can be plausibly considered as a substitute.

Table I. Candidate Alternative Media - Chemical and Phase Compositions

Common Name of Medium Type	Al_2O_3 %	SiO_2 %	CaO %	MgO %	Fe_2O_3 %	Other %	Predominant phase
Chromite	15.0	1.0	-	11.0	23.0	50.0 Cr_2O_3	chromite spinel
Zircon	-	32.7	-	-	-	67.2 ZrO_2	zirconium silicate
Olivine	-	41.2	-	49.0	7.1	-	magnesium & iron silicates
Carbon Sand	-	-	-	-	-	~ 100 Carbon	amorphous carbon
Aluminum Silicate Sand	57.0	41.2	-	-	0.75	0.65 TiO_2	mullite, silica
Calcined bauxite (Guyana)	87.0	3.0	-	-	5.0	3.0 TiO_2	alumina
Calcined bauxitic kaolin	59.2	37.3	-	-	1.1		mullite, silica
Calcined kyanite	57.0	41.4	-	-	0.60	0.65 TiO_2	mullite, silica
High alumina proppant	84.0	3.0	-	-	7.5		alumina, mullite
Low bulk density proppant	49.0	47.0	-	-	0.9		mullite, silica
Fused brown aluminum oxide	96.5	0.70	-	-	0.10	2.70 TiO_2	alumina
Fused mullite	75.0	24.7	-	-	-	0.30 Na_2O	mullite
Fused zirconia mullite	45.8	17.5	-	-	-	36.0 ZrO_2	mullite, monoclinic zirconia
Fused magnesium oxide	-	0.5	0.9	98.4	-	-	magnesia
Fused white aluminum oxide	99.6	-	-	-	-	0.40 Na_2O	alumina

Table II. Candidate Alternative Media - Thermal Properties for Solid Particles

Common Name of Medium Type	Particle Density gm/cm^3	Specific Heat cal/gm°C	Thermal Conductivity cal/hr-cm-°C	Thermal Diffusivity $K/\rho C_p$	Thermal Expansion to 1000°C
Foundry Sand	2.3	0.26	16	26.7	1.6%
Chromite	4.4	0.22	16	9.3	0.80%
Zircon	4.6	0.13	17	28.4	0.42%
Olivine	3.4	0.22	13	17.4	1.10%
Carbon Sand	2.2	0.29	270	423.0	0.20%
Aluminum Silicate Sand	2.7	0.26	12	17.1	0.53%
Calcined bauxite	3.2	0.28	43	48.0	0.96%
Calcined bauxitic kaolin	2.7	0.26	12	17.1	0.53%
Calcined kyanite	2.7	0.26	12	17.1	0.53%
High alumina proppant	3.4	0.28	45	47.3	0.96%
Low B. D. proppant	2.7	0.26	12	17.1	0.53%
Fused brown alumina	3.9	0.28	52	47.6	0.96%
Fused mullite	3.2	0.17	14	25.7	0.67%
Fused zirc. mullite	3.6	0.16	12	20.8	0.55%
Fused magnesia	3.5	0.29	22	21.7	1.60%
Fused white alumina	3.9	0.28	52	47.6	0.96%

Adapted from Ceramic Industry Data Book, 1989, P. Janeway, ed.

Table III. Candidate Alternative Media - Nominal Costs

Common Name of Medium Type	Cost per ton, $	Typical bulk density, lb/ft^3	Cost per cubic foot, $
Foundry Sand	$ 30	100	$1.50
Chromite	$195	160	$15.60
Zircon	$250	170	$21.25
Olivine	$ 75	110	$ 4.12
Carbon Sand	$300	70	$10.50
Aluminum Silicate Sand	$126	116	$ 8.76
Calcined bauxite	$175	115	$10.00
Calcined bauxitic kaolin	$200	115	$11.50
Calcined kyanite (mullite)	$255	139	$17.70
High alumina proppant	$500	120	$30.00
Low bulk density proppant	$300	98	$14.70
Fused brown aluminum oxide	$600	118	$35.40
Fused mullite	$1,000	90	$45.00
Fused zirconia mullite	$1,200	105	$63.00
Fused magnesium oxide	$1,600	100	$80.00
Fused white aluminum oxide	$1,000	110	$55.00

3.5.1 Pulverization Resistance

In the previous discussion a number of alternative granular media were identified as candidates to replace silica sand. Certain of the media, such as carbon sand and olivine are known to be weak and brittle. This study is premised on in-plant recycling of the media in a closed system. If the media breaks down in use into smaller fractions, its usefulness to the casting process is lost. The mechanical breakdown is caused by the thermal and impact stresses that occur during mulling, molding, pouring, shareout, cooling, conveying, and reclaiming. The fracture tendency of the particles that make up a given medium is affected by variations in particle size, particle geometry, and structural faults.

The high temperatures, high mechanical stresses, and chemical effects present in foundry processes make evaluations based on published room temperature properties inadequate. Therefore, it is necessary to use room-temperature laboratory tests to evaluate the resistance of different media to mechanical breakdown.

The fused minerals industry uses the American Standard Ball Mill Test for Friability of Abrasive Grain (ASA B74-8-1965) as a measure of the propensity of abrasive grains to fracture. In this test a 100 ± 0.1 gram sample of minus 12, plus 14 mesh material is balled milled using a charge consisting of 2000 ± 15 grams of 3/4 in. diameter steel balls for 850 ± 1 revolutions in a ball mill jar rotating at 77 ± 1 revolutions per minute. The resultant Friability Index is defined as the percentage by weight of milled material passing a 16 mesh screen, in effect, the weight percent of grains broken down by the action of the steel balls. A lower friability number indicates resistance to mechanical breakdown.

There is no testing standard that measures the fracture resistance of media that have potential for replacing silica sand in the foundry. Thus, a laboratory test designated "Pulverizing Test for Foundry Molding Media" was developed from the Friability Index to evaluate foundry media for their ability to withstand pulverization. Like the friability index, the pulverizing index measures the degree of grain fracture and does not deal with the force or stress required to cause fracture.

In this portion of the study, the test procedures were established and the pulverizing index of a number of conventional, specialized, and alternative media was determined. The objective was to identify alternative molding media that have a greater resistance to mechanical and thermal breakdown than silica sand.

3.5.2.1. Pulverizing Test for Foundry Molding Media

This test is designed for new foundry media and is not a measure of basic material toughness, since results are also dependent on grain shape, grain size, surface conditions, and history. Media of any mesh size can be analyzed using the procedure if appropriate sieves and milling conditions are observed. However, it is suggested that grains of either 40, 50, 70, or 100 mesh size be specified when ASTM E-11 testing sieves are used. Mesh sizes less than 40 are considered too coarse for use in the green sand process and mesh sizes greater than 100 are considered too fine for testing with this procedure.

Apparatus and Expendables Required
The following basic apparatus and expendables are used for the pulverization test:

1. Ro-Tap and Timer (W. S. Tyler Co.)
2. ASTM E-11 Testing Sieves/Pan and Cover - AFS approved - U. S. Standard Sieves Numbers - See AFS Mold & Core Test Handbook, Testing Procedure: 105-87-S.
3. Balance - accurate to 0.01 g with a capacity of at least 250 g.
4. Ball Mill Agitator fitted with automatic revolution counter.
5. Ball Mill Jars - ABBE' 1 quart size "double specimen" steel jars are satisfactory. Lifters made from 3/16" steel should be welded equidistant around the interior of the jar. The lifters should be welded at their ends only.
6. Steel Balls - chrome steel - 1/2" diameter steel balls -9.5 ± 0.5 g

Test Procedure:

1. For a given molding medium, regrade one sample to remove coarse and fine particle sizes. The sample should be Ro-Tapped for 10 minutes. A graded sample of approximately 250 g of a specified mesh is required to yield 100 + grams of closely graded materials from the Ro-Tap. (e.g. 50 mesh - through 40 on 50 mesh)

2. Weigh from the graded material a 100 ± 0.1 g ball mill charge for the jar.

3. Mill the sample with the steel balls - as follows:
For specified mesh - 1540 ± 5 g of 1/2" diameter steel balls - 950 ± 1 revolution

4. Ball mill should be operated at 77 ± 1 R.P.M.

5. Empty the mill through a coarse screen to separate the balls. Brush the mill and balls to insure complete recovery of test sample.

6. Sieve the pulverized sample on Ro-Tap for five minutes using the control sieve and a fines pan (e.g. 50 mesh).

7. Record the weight of the minus specified mesh fraction (the material on the pan) and the total weight recovered.

Calculations and Report

8. Normalize the weight passing test sieve to yield percent passing.

$$\frac{\text{wt. of fine fraction} \times 100}{\text{total wt. recovered}} = \text{percent passing}$$

9. Report the percent passing the specified mesh sieve as the pulverizing index.

Pulverization Tests on Granular Media

Several alternative media were selected for testing as described above. Silica sand was used to establish the reproducability of the test and as a base for comparing the alternative media. The results of the tests show that the precision and repeatability of the pulverizing index is very good. In addition, the pulverizing indices of the granular media were established relative to grain size and shape.

The precision of the test is dependent on accurate and reproducible sieving. Table IV shows the reproducability of the test when applied four times to silica sand from the same lot. The sieve analyses after pulverizing show high precision, particularly in light of the use of a 100 mesh screen size, since fine sieve fractions are often difficult to duplicate.

The repeatability of the pulverizing test when applied to fine and coarse mesh sizes of three granular media is shown in Table V.

Tables VI, VII, and VIII show the results of pulverizing tests applied to silica sands, specialty sands, and alternative sands respectively. Note that a smaller pulverizing index indicates more resistance to mechanical breakdown.

Table VI shows that as the average particle size of silica sand is reduced, it is more resistant to breakdown. Nearly all of the grains of a 50 mesh sand were broken in the test while 32% of the grains in a 100 mesh sample survived the pounding of the steel balls.

Table VII shows the relatively poor resistance to pulverization of specialty sands. Carbon sand and chromite are particularly brittle; zircon, olivine and raw kyanite are somewhat better, although only 20% of their particles survived the test without fracture or particle rounding.

Table VIII shows the pulverizing index for ten alternative media. Note that the average particle size of the alternative media were usually coarser than the sands discussed earlier; this should favor the sands since coarser particles are always more prone to mechanical breakdown than finer particles. The data show that the pulverization resistance of granular media increases as particle size decreases. Media having an angular shape, such as fused brown alumina are more susceptible to attrition than the smooth, rounded grains of media such as oilfield proppant. This is because rounded grains present a smaller total surface area to the mechanical action. Oilfield proppant was the medium that showed the most resistance to breakdown; fused brown alumina, fused white alpha alumina and calcined bauxitic kaolin showed intermediate results.

When angular media are retested their pulverization resistance increases as shown by the decrease in pulverizing index of Table IX. This is the result of grains becoming somewhat rounded during the first test sequence. The oilfield proppant is a round grain and the shape does not change appreciably with ball milling; thus the pulverization index for a second test on grains which survived the first test is the same as for the initial test. The pulverizing index for this material is due to the inherent toughness of the material and does not reflect shape changes from the loss of sharp edges. The two fused grains, on the other hand, show a lower pulverization index on a second test, reflecting both inherent toughness and shape change to a more rounded grain. The respective pulverization indices for 100 mesh silica sand are 68 and 70 respectively, reflecting both an inherently less tough material and the rounding-off of an initially angular shape.

TABLE IV. Precision of sieve testing for the pulverizing index.

Test #	Sample Name	Screen Size	Mass (g)
1	Silica Sand	+100	33.2
1	Silica Sand	-100	66.6
2	Silica Sand	+100	33.4
2	Silica Sand	-100	66.6
3	Silica Sand	+100	32.0
3	Silica Sand	-100	68.0
4	Silica Sand	+100	31.6
4	Silica Sand	-100	68.2

TABLE V. Repeatability of the pulverizing test for three alternative media.

Sample Name	Test	Screen Size	Pulverizing Index %
Fused Mullite- Fine	First	50	87.0
Fused Mullite- Fine	Second	50	86.6
Fused Mullite- Coarse	First	40	89.8
Fused Mullite- Coarse	Second	40	89.4
Fused Zirconia Mullite- Fine	First	50	92.4
Fused Zirconia Mullite- Fine	Second	50	92.0
Fused Zirconia Mullite- Coarse	First	40	93.2
Fused Zirconia Mullite- Coarse	Second	40	93.2
Fused Brown Al_2O_3- Fine	First	40	71.6
Fused Brown Al_2O_3- Fine	Second	40	72.4

TABLE VI. Pulverizing Index for various silica sands.

Sample Name	Shape: (Roundness/ Sphericity)	Screen Size	Pulverizing Index %
Silica Sand	0.9/0.7	50	91.0
Silica Sand	0.9/0.7	70	77.4
Silica Sand	0.9/0.7	100	68.0

TABLE VII. Pulverizing Index for various specialty sands.

Sample Name	Shape: (Roundness/ Sphericity)	Screen Size	Pulverizing Index %
Carbon sand	0.7/0.9	70	99.0
Chromite	0.3/0.9	70	95.0
Raw Kyanite	0.1/0.3	70	85.0
Olivine	0.7/0.3	100	83.2
Zircon	0.3/0.7	100	79.7

TABLE VIII. Pulverizing Index for various alternative sands.

Sample Name	Shape: (Roundness/ Sphericity)	Screen Size	Pulverizing Index %
High Alumina Proppant	0.9/0.9	40	27.1
Fused Brown Aluminum Oxide	0.1/0.7	40	71.6
Fused Brown Aluminum Oxide	0.3/0.7	50	73.3
Calcined Mullite	0.3/0.7	50	87.6
Fused Magnesia	0.3/0.5	50	91.6
fused Zirconia Mullite	0.1/0.7	50	92.4
Calcined Kyanite	0.1/0.3	50	99.6
Fused White Alpha Alumina	0.3/0.7	70	60.4
Calcined Bauxitic Kaolin	0.5/0.7	70	67.4
Calcined Bauxite	0.3/0.7	70	78.4

TABLE IX. Change in pulverization index from an initial test to a second test on surviving grains.

Sample Name	Test	Screen Size	Pulverizing Index %
Fused Mullite- Fine	First Test	50	87.0
Fused Mullite- Fine	Retest	50	78.2
Fused Zirconia Mullite-Fine	First Test	50	92.4
Fused Zirconia Mullite-Fine	Retest	50	76.0
High Alumina Proppant	First Test	40	27.1
High Alumina Proppant	Retest	40	26.9
Silica Sand	First Test	100	68.0
Silica Sand	Retest	100	70.0

3.5.2 Conclusions

The better candidates for replacing silica sand can be determined by examining chemical composition, thermal properties and pulverization resistance against functionality considerations, as follows.

Moldability:

An ideal molding medium has a hard, round-grain structure that resists crushing, provides ample permeability, and affords good compactability. A low bulk density molding medium will make more cores or molds than an equal weight of silica sand. Low bulk density will also reduce the workload on mixers, conveyors, and muscles.

Against these criteria suitable alternative media are:

- High alumina proppant
- Fused brown aluminum oxide
- Fused white aluminum oxide
- Calcined bauxitic kaolin
- Calcined bauxite

Thermal stability:

An ideal molding medium has thermal conductivity and thermal diffusivity comparable to silica sand and low thermal expansion to minimize molten metal penetration and burn-on. The medium cannot have any crystallographic inversions such as the expansion reaction which silica undergoes.

The media meeting these criteria are:

- Carbon sand
- Zircon
- Aluminum silicate sand
- Calcined bauxitic kaolin
- Calcined kyanite
- Low bulk density proppant
- Fused zirconia mullite.

Chemistry:

An ideal molding medium has high refractoriness to metal oxides and is compatible with binders and their calcined reaction products.

The most suitable alternative media based on composition are:

All of the materials listed, for the casting of aluminum alloys, copper alloys and cast irons.

Reclamation:

An ideal molding medium has rounded grains which present a smaller total surface area and thus carry less bonding material such that less time and scrubbing is required for reclamation. Angular and compound grains require a longer reclamation time and more scrubbing and they have a greater tendency to breakdown into irregular shapes. Rounded grains will be less subject to pulverization than angular or compound sands.

The following media have the best properties for reclamation:

- High alumina proppant
- Low bulk density proppant
- Carbon sand

The alternative media which have the best combination of properties when compared to silica are high alumina proppant, low bulk density proppant and fused brown aluminum oxide. The volumetric cost of these materials ranges from 10 to 24 times that of silica sand. This is not significantly different from the volumetric cost of several species of materials currently used for green sand casting.

The true cost of any molding medium, however, is its total life cycle cost, including all reclamation costs and disposal costs. The total life cycle cost issue is examined in the next section of this report.

4. Economic Model for Alternative Granular Media

The alternative granular media that are manufactured by fusion or sintering processes were shown in the previous section to have significantly higher initial costs than silica sand. The costs that were quoted were current costs. The differential will narrow if one of the alternative materials is made in higher volumes. However, the cost differential will always be a large multiple of silica sand, usually more than an order of magnitude, because the manufacturing processes for the alternative media require significant quantities of energy for sintering or fusion. Silica sands may carry some small energy component in their total cost from washing, sifting and transportation but that energy component is insignificant in comparison to the energy required for heating to sintering or melting temperatures.

The cost for silica sand disposal is not insignificant in comparison with the initial costs for alternative media. If a disposal cost is assumed of $100 per ton for silica sand which will be used only once and a cost for fused brown aluminum oxide of $600 per ton which can be used indefinitely, the initial cost differential is a multiple of six. Six times higher cost is certainly significant but the potential now exists for a lower life cycle cost because disposal costs per ton of castings shipped are significantly reduced. In life cycle cost, all of the costs are included which are incurred in using a given medium to make casting molds - original purchase price, initial processing, dust collector and casting adhesion losses, post-casting cooling and recycling costs and final disposal expenses.

In the analysis which follows, life-cycle costs are compared on an incremental basis. With this approach, only the costs which change are considered. This makes cost comparisons between processes easier to follow and more accurate.

4.1 Alternative processes for media recycling

In his comprehensive discussion of foundry sand reclamation, Good (1983) notes that internal recycling was proposed as early as 1912. His chronology of reclamation systems shows an evolution in process philosophy and equipment design that reflects changes in environmental concerns and in costs for sand purchase and disposal. He concludes that a combination of calcining and mechanical scrubbing is best suited for the clays used in green sand and the organic binders currently used for cores.

Hayes (1993) notes that a sand reclamation system must include eight steps:

1. Remove the casting from the mold.
2. Remove all tramp metal from the sand.
3. Break up all lumps into manageable sizes.
4. Further disintegrate lumps and agglomerates into grain size.
5. Remove the maximum amount of residual binder and carbonaceous material from each grain without fracture.
6. Screen small metallic and non-metallic particles that still contaminate sand.
7. Cool to a temperature where sand can be used immediately in the continuous mixer.
8. Classify the sand to as near the original grain size as possible.

He also notes that thermally reclaimed silica sand may have a more stable grain shape than new sand and may be desirable in certain critical core areas. This confirms the importance of pulverization resistance of silica sand during mechanical scrubbing.

Kunes and Smith (1983) show a flow diagram of a typical green sand system and conclude that waste sand can be generated from:

- Waste return sand from shareout, finishing rooms and spillage,
- Mold and core lumps,
- Waste green sand originating from core sand additions to the green sand system.

Reier and Andrews (1984) describe design approaches and precautions for thermal reclamation systems. This paper is one of the few that presents good design data and rules. The authors note that a closed sand system is necessary for economic feasibility and for sand consistency.

A closed sand system where sand grains or grains of alternative media never leave the foundry is a key consideration in the design of a foundry molding system. A foundry green sand system that does not include reclaiming and that uses new sand for cores will necessarily have to dispose of a portion of the sand that is removed from each mold at shareout. The portion is approximately equal to the weight of cores used for the casting. This can be a substantial amount of sand, estimated by Leidel to be 300 lbs to 500 lbs of sand per ton of castings poured (1988). Baillod et al found that foundries that made ferrous castings disposed of approximately 1000 lbs of silica sand per ton of castings produced (1991). A reclaiming system for any alternative media must thus be a closed system, if this expensive leak to landfills is to be closed. A completely closed system cannot be attained in practice but it should be a goal for operations and a benchmark for engineering studies.

Finally, companies that recycle sand find that it has a quality level that is better than new sand (Philbin, 1994). Good (1983) points out that a reclamation system that is "well designed and operated" can achieve better consistency. Leidel cautions that recycled sand may resist attrition better than new sand but only because weak grains have already been broken into smaller pieces; thermal reclaiming does not develop the stable tridymite phase of silica and, as a result, reclaimed silica sands will continue to be subject to the structural breakdown associated with phase changes that occur on exposure to liquid metals.

4.2 Cost model assumptions

The literature is replete with descriptions of foundry sand reclamation equipment and processes. Many of the papers include capital and operating costs. Some of the cost data presented in the model are preliminary and thus may be optimistically overstated. Other cost data may not be fully described in order to protect proprietary concerns and thus may be understated. A reading across a broad range of papers, however, leads one to conclusions about the cost of reclaiming that are reasonable for comparison studies, such as this one. Several papers will be described that include extensive process and cost descriptions.

Reier (1993) described a thermal reclaiming system which used natural gas to heat spent sand to 1350-1650F and then used a recuperator to transfer heat from calcined sand to incoming sand. A pneumatic scrubber was used to remove dead clay and residual organic materials. Operating cost per ton ranged from \$11 to \$13 per ton for a unit capable of reclaiming 6000 tons per year.

Bex described stacked bed thermal reclaimers that operate by fluidizing a sand bed (1993). The system is capable of heating spent sand to 1250°F to burn off organic binders and breaking lumps down to individual sand grains. Incoming air and water cooled heat exchanger tubes are used to cool the sand, such that reclaimed sand exits at a temperature of 86°F. Operating costs are quoted to be \$3.60 to \$5.00 per ton.

Leidel claimed that dry attrition processes for reclamation of silica sand have an associated dust collector residue that is 85% to 90% silica sand and 10% to 15% residual binder(1988). He separately reports that maintenance costs for sand reclamation systems have been found to be \$2.21 per ton of sand processed in a medium sized gray and ductile iron jobbing foundry (Simmons and Leidel, 1992). The same paper quotes prior work which reports maintenance costs of \$7.14 per ton for a reclamation system in an aluminum foundry. In another paper, he recommends that reclamation be considered if foundries are using 1200-1500 tons of sand per year (Ruzbehi & Leidel, 1983). Reclamation costs were quoted to be \$15 or less per ton for mechanical/thermal systems. Equipment that works on a purely mechanical attrition basis can dry sand and remove loose clay to a residual level of 3.5% or less at a cost of \$4 to \$6 per ton processed (Leidel, 1993) in contrast to gas-fired sand reclamation systems that consume between 200,000 BTU/ton and 2,000,000 BTU/ton of sand processed (Leidel, 1989).

Reclaiming systems in some configurations may not be entirely closed. Leidel found that silica sand losses could be as much as 15% of input tonnage, attributed to:

- thermal breakdown
- spilled sand contaminated with other refuse
- sand adhering to castings which is removed in cleaning
- sand losses due to attrition during reclamation.

This was experimentally confirmed (partially) by making test castings on the same batch of sodium silicate bonded sand (adding 15% new sand per cycle to makeup for losses) which was in turn mechanically reclaimed after each pouring cycle. The yield was 90% on the first cycle and 95% thereafter, the grain shapes became rounded due to attrition, the BET surface area decreased, screen distributions became slightly coarser, and casting quality was unchanged (1985).

Vogel & Campbell discussed a two-stage thermal reclamation system which mixed furane polymer bonded zircon sand previously heated to 450°C with 41% additional sand (1982). A slow burnoff of the organics at bulk temperatures of 300°C to 500°C resulted in a final LOI of 0.03%. Energy requirements were 100 kWh/tonne and sand loss was 0.2% as fines to the dust collector.

Lumsden claimed that a thermal reclamation system using a rotary calcine collected 3% of the input volume of sand in a conventional baghouse as fugitive dust and dead burned clay (1993). The operating cost for the nominal 2000 lb/hr system was $12.99/ton for gas and electricity, $37.50/ton for labor and $2.39 for maintenance. The capital cost was $530,000. The conclusions of the paper regarding annual costs and cost savings are skewed because costs prior to thermal *reclamation included $400/ton for sand disposal due to lead contamination.*

Capital costs for sand reclamation systems are obviously a function of the tonnage to be processed and equipment quotes are always obtained as part of an engineering study for a new system. However, it is useful to understand the magnitude of investment that is required. Leidel stated that the cost of a system that uses calcining ranges from $25,000 to $140,000 per ton of installed capacity, less any equipment required for dust collection (1989). Kucharczyk and Leidel described a mechanical attrition reclaiming system that was installed in a steel jobbing foundry that used about 25 tons of green sand per day (1988). Sand additions were cut from 100 tons per month to 10 tons while clay additions ($150/ton for western bentonite and $200/ton for southern bentonite) increased slightly. The total system cost was $200,000.

4.3 Cost model

The objective of this part of the study was to develop a cost model that would allow comparisons to be made among different granular media, including silica sand, for various operating scenarios. Operating parameters that affect total sand system cost, such as purchase price and tendency for pulverization, change with media type and thus the model must include the capability for visible and easy changes.

In the preceding discussion, cost data were quoted from the literature. They provide an important check for this study, since they are valid case studies. Other studies attempt to be more flexible, such as the report from the AFS Sand Reclamation and Reuse Committee (1985). This is a very useful guide to developing a feasibility study for a specific foundry that includes representative data. Lynch-Caris developed a linear model based on proprietary software and demonstrated its use with data from an operating foundry. The flowchart on which the model is based is a comprehensive snapshot of an operating foundry and thus requires specific cost data for all operations which it includes. These data will vary among different companies and thus the model is best used for a specific operation.

This study took an incremental approach to evaluating the cost impact of substituting alternative granular media for silica sand. Thus, the effect of media purchase price was included with the assumption that molding cost will not change. The sand supplied to the core system may be new sand or recycled media, but the labor and energy cost associated with making cores is the same. This is reasonable, given the objective of providing comparisons among different molding media rather than providing a bottom line cost estimate for castings made under different scenarios.

The model is based on the flow sheet shown in Figure 1. Green sand and cores, in a ratio that is stipulated, are used in a casting line in direct proportion to the tonnage of metal that leaves the foundry as saleable castings. After casting, the green sand and cores are assumed to be completely intermingled. The mixture leaves a shareout/sand cooling unit and is split for reuse through the mullers or reclaiming on a specified ratio. The shareout/sand cooling unit is a significant leak in the "closed" system. Pyrolyzed core binder, dust and moisture leave for landfilling, as would be expected. However, a small fraction of the input sand also leaves by adhering to casting surfaces. The other leak in the system is from the reclaimer. The equipment is not precisely defined and the processing parameters such as calcining temperature are not specified, but there is an underlying assumption that a calcining/mechanical scrubbing process is used. All clay that enters is calcined and removed from the sand surface along with all fines and free moisture. Thus, grains of reclaimed sand (or alternative media) are separated from the dust that is left after calcining. The grains are then used to make cores and the dust leaves for a landfill.

New sand, or granular media, must be added to the system as makeup for the sand that leaves as dust after thermal or mechanical attrition and as makeup for the sand that leaves the system on casting surfaces. These two sources of material loss represent material that leaves the foundry. Any spills from conveyors, tanks or other equipment that occur within the foundry walls are regarded as temporary detours on the flowsheet and not an actual loss to the sand system.

The two material leaks discussed above, however, must be quantified so that a realistic quantity of replacement sand is added to the system. Unfortunately, the thermal and mechanical attrition of silica sand in foundry operations is not discussed in the literature and studies do not exist that could be the basis for modeling. Therefore, the assumption was made for this study that a fraction of the sand, or granular medium, is attritted during each trip through the sand mulling, molding, shareout and cooling and thermal reclamation processes.

The fraction of sand that is attrited during each trip through a foundry sand system is related to the pulverization resistance of the sand or granular medium, but it is probably not directly proportional. For this study, silica sand, a brittle mineral that is also prone to thermal shock from crystallographic inversions, was assigned an attrition rate of 2%. The attrition rate is defined as the percentage of the total mass that is reduced to an unacceptably small size during one trip through the total foundry process and thus must be replaced. Thus, a foundry that has a need for 100 tons of silica sand per hour of operation would lose 2 tons to thermal and mechanical attrition. In contrast, a round, ceramic medium such as oilfield proppant was assumed to have no attrition. The model is constructed so that the effect of different attrition rates can be evaluated.

The quantity of sand lost by adherence to casting surfaces was modeled by assuming that castings leave the shareout/sand cooling unit with their surface partially coated with sand grains. These sand (or granular medium) grains would be removed during blasting and thus lost for reclaiming or reuse. From a modeling standpoint, this means that each ton of iron that is poured will carry sand away from the molding system. The weight of sand that is assumed to be removed was calculated as follows and is based on conditions at a commercial green sand foundry.[1]

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[1]The amount of molding media adhering to castings after shareout is probably a function of many factors including total surface area and surface complexity of castings, and the shape of media particles. Thus, the amount of adherences is unique to each casting. The amount of adhering sand reported here is based on a single commercial casting design and may not be representative of sand mold castings in general.

Weight of sand on One square Inch of Casting surface:

Assumed Particle Dimension, in.	0.0117
Surface Coverage, Percent	30.0%
Specific Gravity of Particles	2.32
Weight per Square Inch, lbs	0.0002941
Surface area of Casting per Unit Volume:	4
Lbs. of adhering Sand per Lb. of Casting:	0.0047
Lbs. of Adhering Sand per Ton of Castings:	9.4099

If the calculation is repeated to consider media with different specific gravity and shape, the value for silica sand is seen to be a typical value.

Media Type	Silica Sand	Zircon Sand	Carbon Sand	Low B.D. Proppant	Alumina Proppant
Particle Shape	Cube	Cube	Cube	Sphere	Sphere
Specific Gravity	2.3	4.6	2.2	2.7	3.4
Lbs. of Adhering Sand per Ton of Casting Poured	9.41	18.6	8.92	5.73	7.22

The factor calculated for silica was thus assumed for all media. It is a low estimate by about 50% for a high density alternative medium such as zircon and it is a high estimate by about 40% for a low-density oilfield proppant. In practice, a spherical alternative medium such as oilfield proppant would not adhere well to casting surfaces and a lower weight loss than calculated here would be expected.

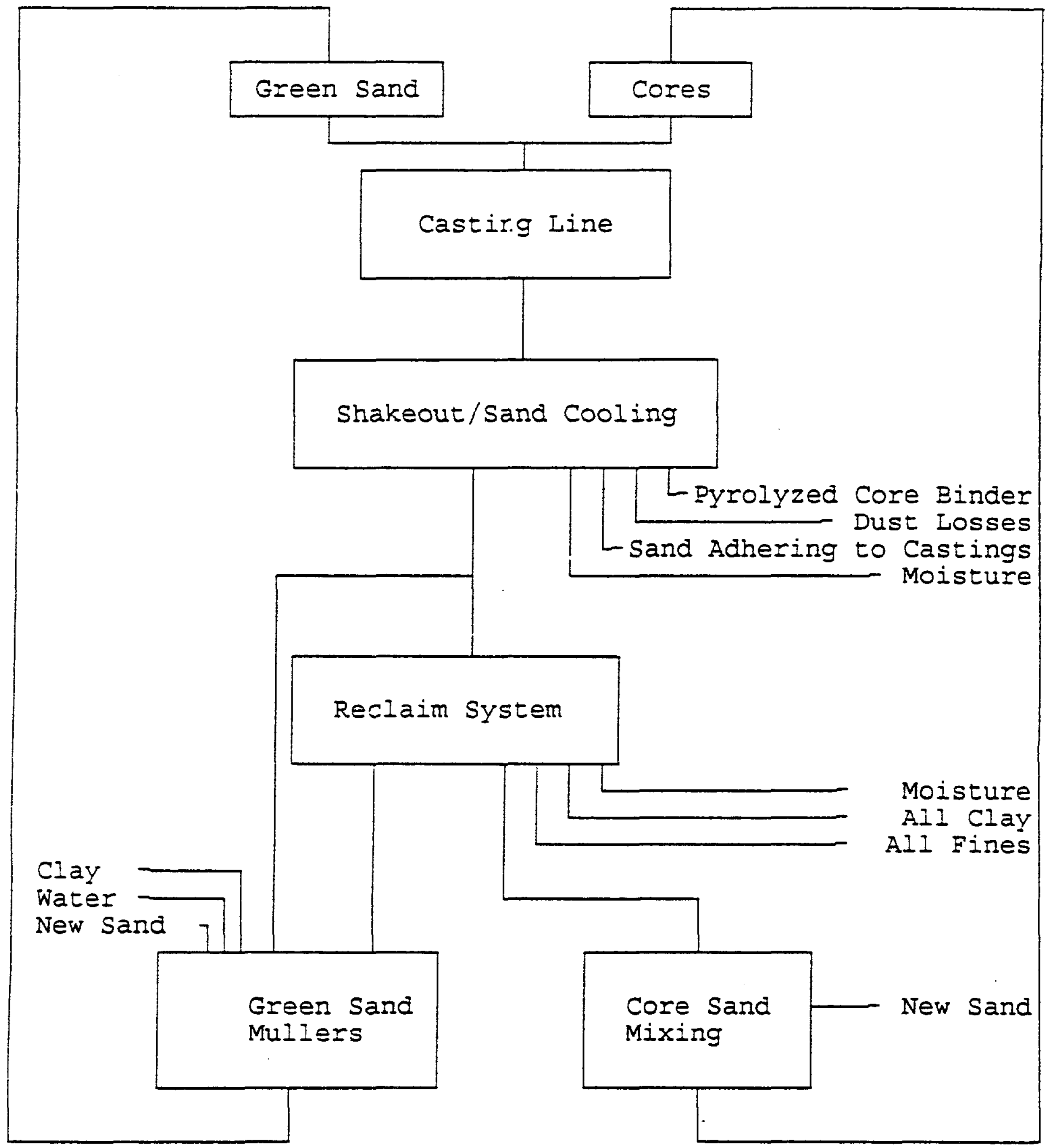

Figure 1. Flowsheet for cost model used to calculate the cost impact of substituting various alternative granular media for silica sand.

The model was written using Quattro Pro® spreadsheet software. Appendix II contains a full listing of the program. The calculation proceeds as follows:

7 Set Base assumptions — Typical Values

		Typical Values
7.1	Casting Production Rate, Tons/Week	1000
7.2	Casting Yield, tons shipped/tons poured, %	70
7.3	Green Sand to Poured Metal Ratio, lbs/lb	4
7.4	Core Sand to Green Sand Ratio, lbs/lb	0.05
7.5	Sand Adhering to Castings & Gating, lbs/Ton	9.4
7.6	Dust Collector Losses at Shareout & Sand Cooling	
7.6.1	Percent of Dead Clay and Fines	33
7.6.2	Percent of Active Clay	10
7.7	Bentonite Binder Content after Mulling, %	6.5
7.7.1	Percent Calcined per Pouring Cycle	5
7.8	Green Sand Moisture Content after Mulling	3.5
7.8.1	After Shareout/Sand Cooling	1.5
7.9	Core Binder in New Cores, %	2
7.9.1	Percent in Core Sand after Shareout/Sand Cooling	0.5
7.10	Sand System Capacity, Hours of Manufacturing	8
7.11	Bentonite Clay Cost, $/Ton	50
7.12	Core Binder Cost, $/Ton	1500
7.13	Reclaimer Operational Cost per Ton	15
7.14	Sand/Binder/Fines Disposal Cost, $/Ton	75

8 Specify Medium Type and its thermal-mechanical attrition rate.

9 Calculate weights of green sand and core sand used per hr.

10 Calculate weights of materials leaving shareout/sand cooling system, per hr.

11 Calculate weights of materials entering muller, per hr.

12 Calculate weights of materials entering core sand mixing system, per hr.

13 Calculate total costs for reclaimer operation, fines disposal and new sand and clay additions

14 Calculate above costs per Ton of Castings.

15 Calculate Costs Without Reclaiming.

The model was reviewed in its developmental stage with operations personnel from two high-volume iron foundries. One foundry operates a sand reclaiming unit and the other foundry does not. The flow sheet was discussed in detail and several modifications were made as a result. The values used in the base assumptions reflect these discussions but they do not represent exact practice at either of the foundries.

In building the model, it was necessary and prudent to account for adhering sand. Physically, this means that as castings leave the shareout/sand cooling unit, their surface is partially coated with sand grains. These grains are removed during blasting and are assumed to be lost for reclaiming or reuse. From a modelling standpoint, this means that each ton of iron that is poured will carry sand away from the molding system. The weight of sand that is assumed to be removed was calculated as follows:

Weight of Sand on One Square Inch of Casting Surface:

Assumed Particle Dimension, in.	0.0117
Surface Coverage, Percent	30.0%
Specific Gravity of Particles	2.32
Weight per Square Inch, lbs	0.0002941
Surface Area of Castings per Unit Volume:	4
Lbs.of Adhering Sand per Lb. of Casting:	0.0047
Lbs.of Adhering Sand per Ton of Casting:	9.41

This factor was calculated for silica and was assumed for all media. It is a low estimate for a high density alternative medium such as zircon and it is a high estimate for a spherical alternative medium such as low-density oilfield proppant that would not adhere well to casting surfaces.

4.4 Analysis of Media Cost and Processing Parameters Effects

The cost model is best discussed with an example. In the calculations that follow, the base assumptions discussed above are applied to the case of silica sand that has a purchase price of $30/ton and an attrition rate for each cycle of 0.5%.

Operational Parameters	**Media Type**
	Silica Sand
Delivered Cost, $/ton	$30
Media Thermal & Mechanical Attrition Rate	0.5%
Percent Shareout Sand Reclaimed	30%
Inputs to Molding:	
Green Sand, Tons/Hour	142.9
Core Sand, Tons/Hour	7.1
Outputs from Shareout/Sand Cooling:	
Sand Adhering to Castings/Gating, Tons/Hr	0.2
Fines and Clay to Dust Collector, Tons/Hr	1.8
Sand from Shareout/Sand Cooling, Tons/Hr	145.1
Shareout Sand to Mullers, Tons/Hr:	101.6
Net Granular Particles, Tons/Hr	93.8
Shareout Sand to Reclaim System, Tons/Hr	43.5
Net Granular Particles, Tons/Hr	39.7
Dust to Landfill, Tons/Hr	3.2
Green Sand Muller Inputs:	
Tons/Hr Shareout Sand	101.6
Tons/Hr Reclaim Sand	34.0
Tons/Hr Active Clay	3.7
Tons/Hr Water	3.5
Core Sand System Inputs:	
Tons/Hr Reclaim Sand	5.7
New Sand, Tons/Hr	1.3
Incremental Costs over Conventional Practice:	
Base Assumptions:	Silica Sand
Delivered Cost, $/ton	$30
Medium Thermal & Mechanical Attrition Rate	0.5%
Percent Shareout Sand Reclaimed	30%
Reclaiming Model - Total Cost per Hour	
Reclaimer Operation	$653
Disposal Cost	$237
Sand Additions	$ 40
Clay Additions	$186
Total	$1,117
Total per Ton of Castings	$ 45

The model also calculates the cost for a conventional operation where a quantity of sand equal to the incoming weight of cores is assumed to be sent to a landfill, with the attendant costs. The example below presents the costs if there is no reclamation of media. The total cost per ton of castings is slightly less than with reclamation.

Comparable Costs if no Reclaiming:

Disposal Costs	- Dust Collector Fines	$ 70
	- Core Sand Equivalent	$536
Sand Additions		$214
Clay Additions		$ 89
Total if no reclamation		$909

Costs - No Reclaiming - per Ton of Castings

Disposal Costs	- Dust Collector Fines	$ 3
	- Core Sand Equivalent	$ 21
Sand Additions		$ 9
Clay Additions		$ 4
Total per Ton of Castings		$ 36

The model also accounts for the buildup of attritted particles, calcined clay and adhering core binder present in the sand that moves from shareout/sand cooling through the muller to become green sand in the next molding cycle. This is done by calculating the number of times that a control volume of sand would move through the system, each time accumulating fines and being diluted by core sand until a defined saturation limit is reached. The saturation limit was set at which ever of the following occurs first. 1) 4% loss on ignition (LOI) from adhering core binder, 2) 6% accumulated calcined bentonite clay or 3) 5% accumulated particles from attrition. Test runs of the model showed that saturation was reached in about 10 cycles. Accordingly, the model sets the analysis of the mixture that is removed for landfilling and the analysis of the sand sent to the mullers to correspond to the tenth cycle analysis.

The model is written as a spreadsheet thus sensitivity analyses can be generated quite easily to determine, for example, the effect of media cost on the sand cost per net ton of castings. Since the order of magnitude of the cost difference between silica sand and the various alternative media is relatively large, that analysis will be presented first. The base assumptions were made with an additional stipulation that no attrition occurs and that 30% of the output from the shareout/sand cooler is reclaimed. After the base case was run the spreadsheet was replicated across 10 columns to reflect media cost from $50/ton (just slightly over the delivered cost of silica sand) to $500/ton, a representative cost for one of the alternative granular medium.

The results of the analysis are shown in Figure 2 and present the unexpected independence of operating costs and media cost.

Media cost, calculated on a per ton of castings shipped basis, is the smallest component of the total cost. Reclaimer cost is the largest component. For a medium such as low bulk density proppant with a nominal price of $300 per ton, the total media cost is about $50 per ton of castings. The cost for disposal of the media fines resulting from sand adhering to castings is small, as is the cost for clay additions to replace the clay lost to calcining in the reclaiming operations. All of the calculations for this scenario and the ones that follow are listed in Appendix III.

The comparable costs for a conventional operation, where excess sand is sent to the landfill and reclaiming is not a part of the sand system, are considerably higher as shown in Figure 3.

As an example, the total sand associated costs for a conventional system operating at a core sand to green sand ratio of 0.3 is \$195 per ton of castings with disposal costs being the largest portion of the total.

In contrast to the above case, the cost model can also be used to determine the costs for a silica sand operation that includes reclaiming. The model assumes that during each trip that sand makes through the casting system, thermal shock and mechanical handling will break down a small fraction of the sand to a smaller size, or attrit it. If attrition is accounted for by removing that fraction and adding back an equivalent weight of new sand, the total sand cost per ton of castings shipped becomes significant, as shown in Figure 4.

For a condition where 2% of the sand is attritted on each trip through the sand system, the total sand cost is \$69 per ton of castings, with the largest cost component being the \$36 cost to operate the reclaimer.

Figure 5 shows how the cost of reclaiming changes as the fraction reclaimed increases. Again the reclaimer operating cost is the largest cost component and the cost for adding new sand to the system is almost insignificant. For a condition where 1% of the sand is attritted and 20% is reclaimed on each trip through the sand system, the total sand cost is \$47 per ton of castings. When the reclaim percentage is changed to 35%, the total sand cost is \$73 per ton of castings.

The effect that different reclaiming rates have on the cost for using alternative media is shown in Figure 6. For a 15% reclaiming rate and an alternative medium that has an initial cost of \$300 per ton, the total sand cost per ton of castings shipped is \$31. The slope of the cost curve is relatively low, a reflection of the cost of operating the reclaimer.

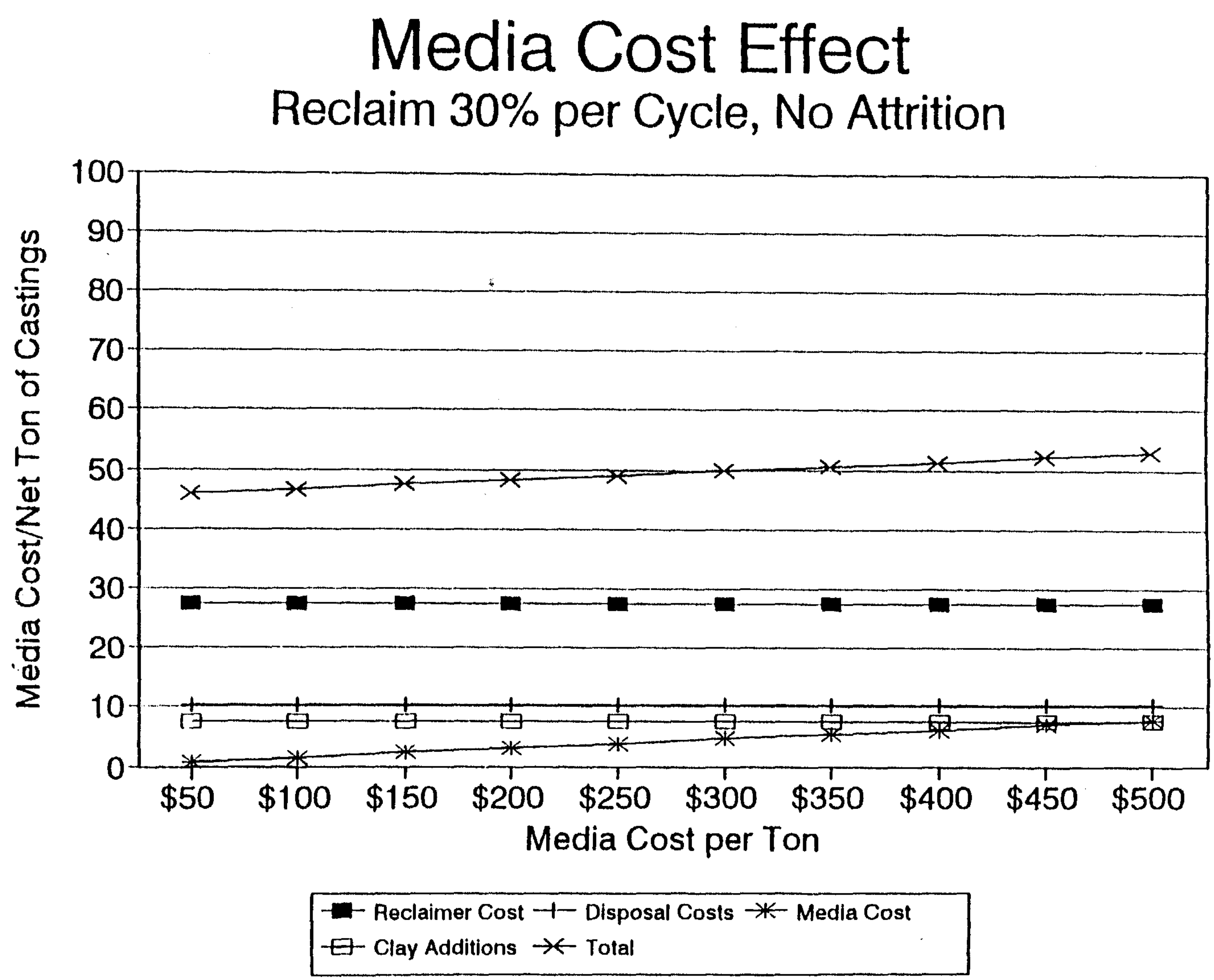

Fig. 2. Cost of media per ton of castings shipped for a range of initial media costs.

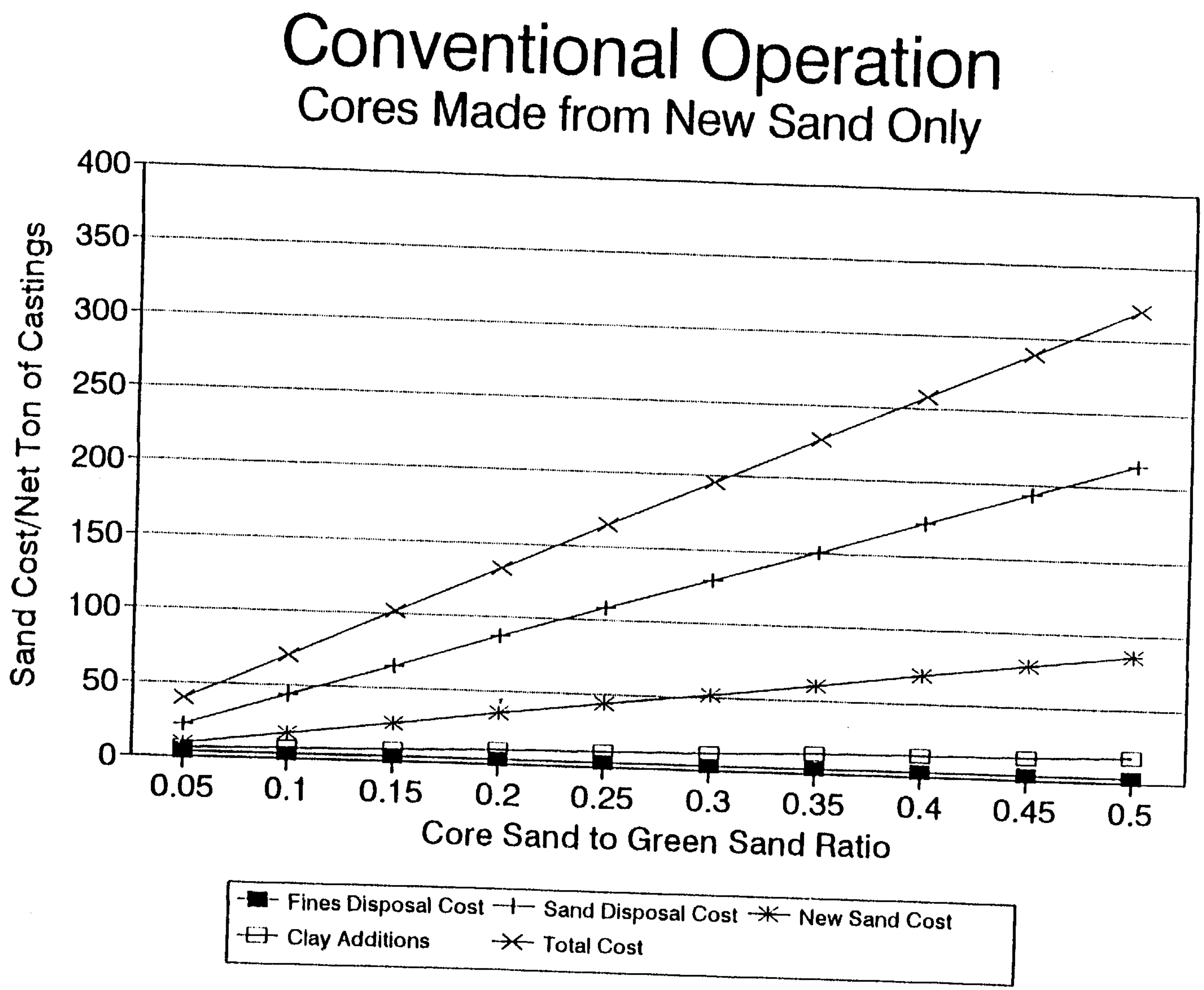

Fig. 3. Media costs for a conventional operation, as calculated by the cost model.

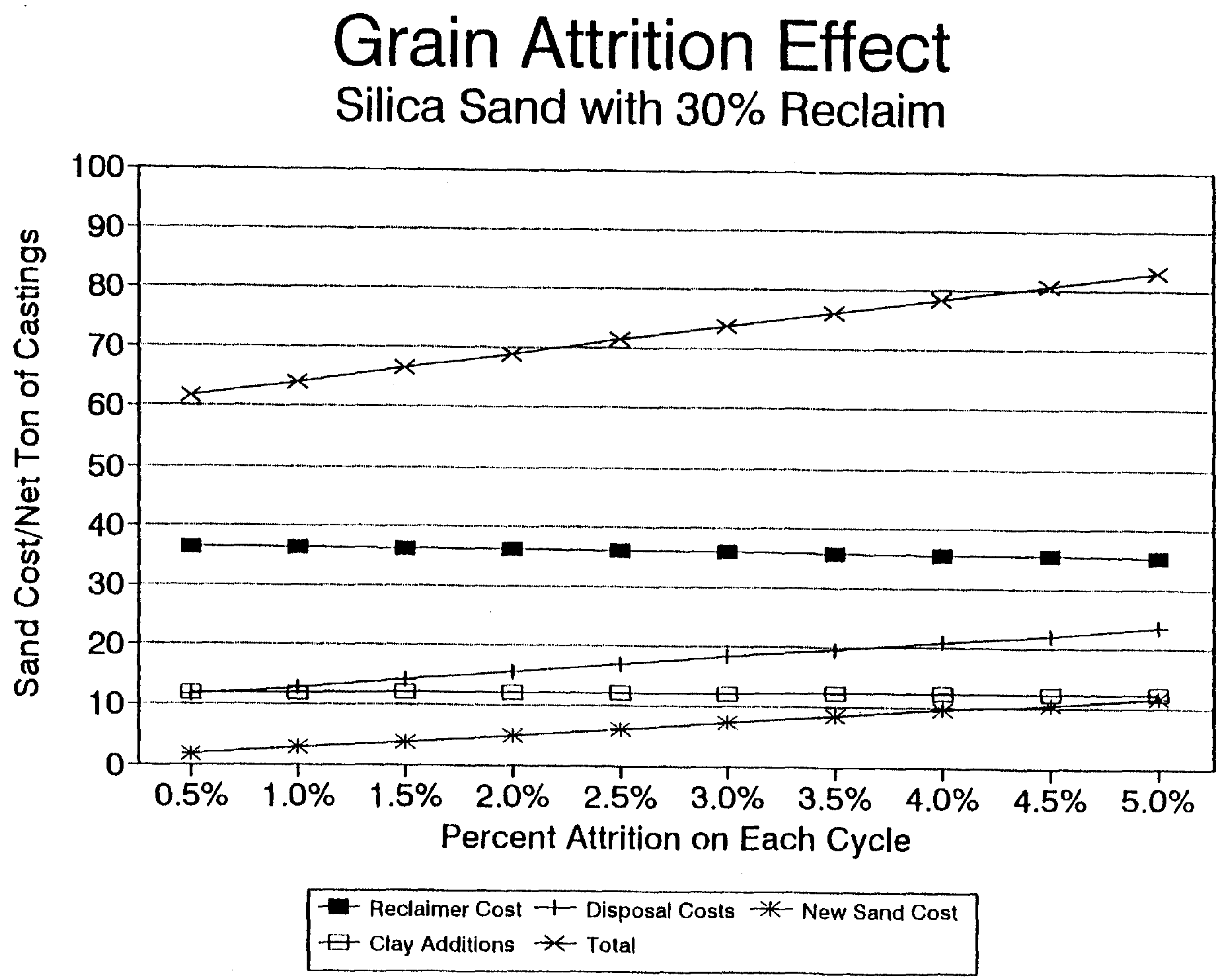

Fig. 4. Sand costs for a foundry that reclaims silica sand.

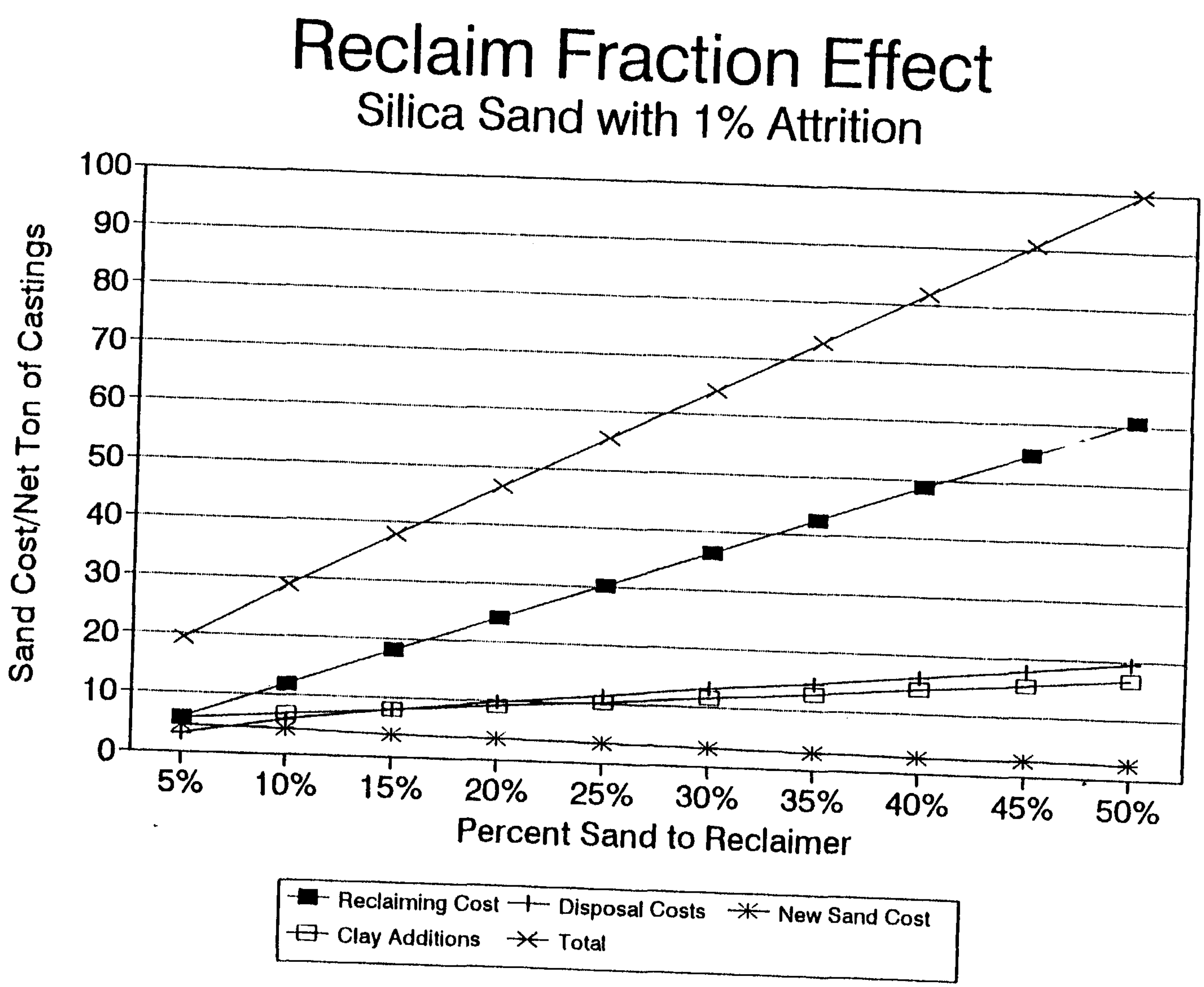

Fig. 5. Sand costs for different percentages of recycled sand.

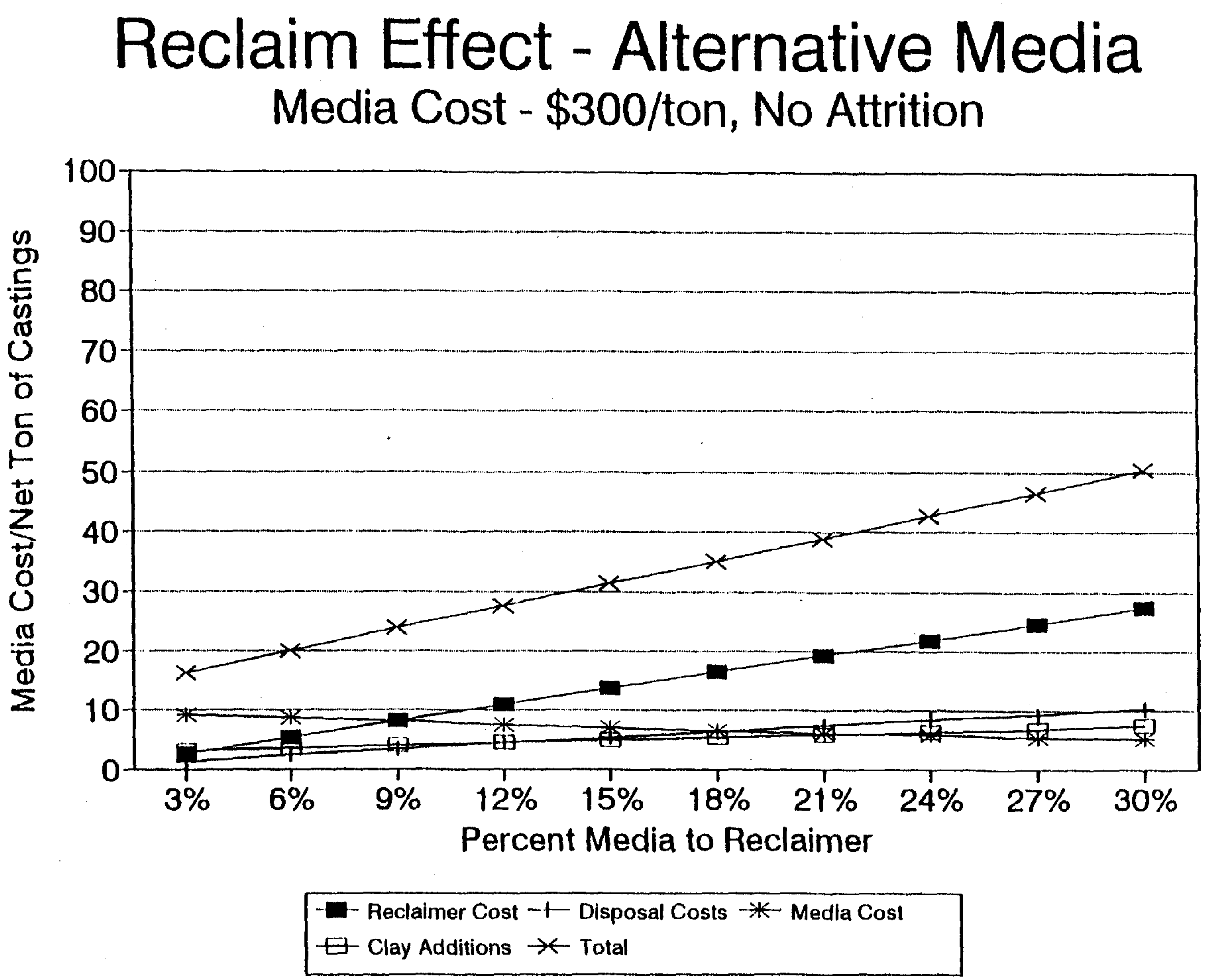

Fig. 6. Reclaim effect on cost per ton of castings when using alternative media.

5. Conclusions

This research project started from a fundamental premise that the attrition experienced by silica sand grains when exposed to the molten metal, sand reclaiming and sand handling systems of a foundry could be eliminated by substituting a pulverizing-resistant granular medium.

Various alternative media were identified and tested for their pulverization resistance. The test used is sensitive to initial grain shape and to intrinsic toughness; it does not reflect resistance to thermal shock. Three of the alternative media had significantly improved resistance to pulverization over silica sand - high alumina proppant, low bulk density proppant and fused brown aluminum oxide. As noted earlier, these media are 10 to 24 times more costly than silica sand on a volumetric basis.

The cost model was developed to determine if the initial cost difference between silica sand and the various alternative media was significant when compared on a total life cycle basis that includes disposal costs. The calculations show that silica sand attrition by itself has very little effect on the cost per ton of castings shipped from a foundry that does not use a reclaiming system; disposal costs are the largest cost factor.

For foundries that operate a reclaimer, that cost is relatively high, the largest component of the sand cost per ton of castings shipped. For all cases, though, reclaiming is less expensive than disposal of excess sand. Attrition of silica sand in a closed, reclaiming system nevertheless affects total costs because it contributes to disposal costs and new sand purchase costs. Further research is needed in this area to determine silica sand attrition rates and to identify the unit operations in sand systems that are responsible for most of the attrition of silica sand. This is an important problem that could have significant impact on operating costs for foundries experiencing high attrition rates. Likewise there is no known method to predict media loss to adherence on casting surfaces during shareout. Research in this area, especially adherence as a function of particle shape, is needed to improve the estimated total costs of using various molding media.

For the initial, and admittedly optimistic, condition of a foundry free from sand leaks, except the grains that adhere to castings, the cost model shows that operating costs are not strongly affected by the initial cost of the particular granular medium used in green sand, whether it be silica sand or one of the alternative media. The cost per ton of castings shipped does not change greatly across the various scenarios shown in Appendix II. Therefore, the application of alternative media into green sand foundries that use sand reclaiming systems is a question of initial cost, not feasibility and not operating cost. For the example studied of a foundry making 1000 tons of castings per week, the cost for an 8 hour inventory of silica sand is about $38,000 and the cost for an equivalent amount of low density proppant is about 10 times more, or $380,000. A more careful analysis of the savings resulting from zero attrition and lower bond addition costs might show operational savings that would justify this large initial investment. As noted in the cost study, the assumptions for media loss on the surface of finished castings is overstated; an experimental analysis is needed to determine the tendency for spherical granular media to adhere to casting surfaces.

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Appendix I

Secondary Glass as a Foundry Medium

Appendix I
Secondary Glass as a Foundry Medium

Introduction

The potential used of secondary glass as a foundry medium was evaluated under a grant from the Solid Waste Alternative Program (SWAP) of the Michigan Department of Natural Resources. In May 1988 the Natural Resources Commission adopted a new policy for resolving the solid waste crisis facing the State. The overall goal of the policy is to promote waste reduction, reuse, composting, recycling, and incineration with energy recovery, while limiting use of landfills.

In November 1988 voters approved proposals that made $150 million available in the form of grants and loans to both private and public entities to help reduce the solid waste burden. Grants and loans made under the SWAP program are intended to implement the State's Solid Waste Policy and avert a solid waste disposal crisis.

In August 1993 a SWAP grant to investigate potential uses of container glass and window glass scrap from manufacturing operations was approved for award to the Institute of Materials Processing at Michigan Technological University. Currently most of this material finds its way to landfills after a single use. One of the alternative uses to be investigated was as a foundry molding material.

Glass can be of various compositions. Soda-lime-silica glass, so named because sodium carbonate, calcium oxide, and silica sand are the main constituents, is the glass made in the largest volume and most is used to manufacture window glass and containers (Bauer 1991). As with the other media evaluated and discussed in the body of this report, secondary glass was first characterized as to its physical characteristics and to its ability to resist the physical forces of reclamation.

Physical Characteristics

Two critical physical properties of glass that govern its use as a foundry molding medium are its softening point and friability. These properties are governed by the fact that glass is a family of compounded materials that do not crystallize upon cooling from the molten state. They are unique since, unlike supercooled liquids in general, the high viscosity of glass prevents its crystallization.

As glass is heated, a change in viscosity is noted at certain discrete points. The first is the working point where glass becomes soft enough to be formed by most methods. The second is the softening point where the glass becomes too fluid for convenient working.
According to Stevens (1991), the softening point of soda-lime-silica glass is approximately 725°C. This is considerably below the 1500-1600°C pouring temperature of iron and would severely restrict the suitability of glass media in foundry operations because molds made from glass particles would tend to distort and fuse to the casting.

The objective of the current research project was to investigate materials having potential for reducing the solid waste stream from foundries. This means an alternative material must not only have the ability to withstand the casting environment but also have the ability to be cleaned and reused. As discussed in Section 3.5.2 of this report, friability is a measure of a molding material's resistance to the mechanical actions of cleaning processes.

A friability index is calculated for a medium based on the ability of medium particles to resist crushing when subjected to standardized ball milling test. The index reflects the size distribution of a single screen size of the medium after being subjected to repeated impact by falling steel balls. Thus, an index of 100 means all of the original mono-sized medium sample is reduced in size during milling and passes through the original screen. Less friable materials have correspondingly lower indices.

Samples of window glass were obtained form Acustar, Inc., a wholly owned Chrysler, Inc. company. Two glass samples were evaluated, one tempered and the other untempered. Precrushing was accomplished by passing sheets of glass first through a hammermill to produce nominal 1/4 inch sized particles. A -30 mesh, +40 mesh fraction for ball milling was produced by passing the hammer milled material through a roller mill.

According to the standard pulverizing test procedure described in Section 3.5.2 of this report, 100 grams of the -30 mesh, +40 mesh material was ball milled for the requisite time and subsequently sieved to determine the resistance to mechanical breakdown. In duplicating tests, the glass samples consistently sieved in excess of 94% through the 40 mesh screen. Therefore, the pulverizing index was greater than 94.

Conclusion

With an extremely high pulverizing index and a softening point much lower than the pouring temperature of iron, it is unlikely that glass is suitable for wide use in foundry operations. It might find application as a backup medium but this would introduce yet another material to the sand system that would have to be removed to prevent contamination at the mold face. For the purpose of the present study, glass is not recommended for further study. This does not mean, however, that it should be excluded from foundry use altogether. At least one company that prefers anonymity, is using ground glass as a sand additive to control veining in 316 stainless steel castings (Geoffrey 1993).

References:

Bauer, W.C. and Bailey, J.E., 1991, "Ceramics and Glass", Engineered Materials Handbook Volume 4, ASM International, 378-385.

Stevens, H.J., 1991, "Ceramics and Glass", Engineered Materials Handbook Volume 4, ASM International, 394-401.

Geoffrey, M.M., 1993, "Effects of Sand and Sand Additives on Veining in Stainless Steel", AFS Transactions, 66, 531-539.

Appendix II

Cost Model - Listing of cell statements

A26: [W38] 'Operational Parameters:
B26: [W10] "Media Type:
B27: [W10] "Silica Sand
A28: [W38] 'Delivered Cost, $/ton
B28: (C0) [W10] 30
A29: [W38] 'Media Thermal & Mechanical Attrition Rate
B29: (P1) [W10] 0.005
A31: [W38] 'Inputs to Molding:
A32: [W38] '   Green Sand, Tons/Hour
B32: (F1) [W10] +$B$5*$B$7/($B$6*40)
A33: [W38] '   Core Sand, Tons/Hour
B33: (F1) [W10] +B32*B$8
A35: [W38] 'Outputs from Shakeout/Sand Cooling:
A36: [W38] 'Sand Adhering to Castings/Gating, Tons/Hr
B36: (F2) [W10] ($B$5/($B$6*40))*($B$9/2000)
A37: [W38] 'Fines and Clay to Dust Collector, Tons/Hr
B37: (F2) [W10] +B32*$B$13*$B$12+B189*$B$11+B193*$B$11
A38: [W38] 'Sand from Shakeout/Sand Cooling, Tons/Hr
B38: (F1) [W10] +B32*(1-($B$15-$B$16))+B33*(1-($B$17-$B$18))-B36-B37
A39: [W38] 'Percent Shakeout Sand Reclaimed
B39: (P0) [W10] 0.3
A41: [W38] 'Shakeout Sand to Mullers, Tons
B41: (F1) [W10] +B38*(1-B39)
A42: [W38] '   Net Granular Particles, Tons
B42: (F1) [W10] (B41*(B32/(B32+B33)*(1-($B$16+$B$13))))+(B41*(B33/(B32+B33)*(1-$B$18)))
A43: [W38] 'Shakeout Sand to Reclaim System, Tons
B43: (F1) [W10] +B38*B39
A44: [W38] '   Net Granular Particles, Tons
B44: (F1) [W10] +B43*(1-B196-B197-B198-B199-B200)
A45: [W38] '   Dust to Landfill, Tons
B45: (F1) [W10] +B43-B44-(B32*B39*B$16)
A47: [W38] 'Green Sand Muller Inputs:
A48: [W38] ' Tons Shakeout Sand
B48: (F1) [W10] +B41
A49: [W38] ' Tons Reclaim Sand
B49: (F1) [W10] +B32-B48-B50-B51
A50: [W38] ' Tons Active Clay
B50: (F1) [W10] +B32*($B$13)-B48*B199
A51: [W38] ' Tons Water
B51: (F1) [W10] +B32*$B$15-B48*B198
A53: [W38] 'Core Sand System Inputs:
A54: [W38] ' Tons Reclaim Sand
B54: (F1) [W10] +B44-B49
A55: [W38] ' New Sand, Tons
B55: (F1) [W10] +B33*(1-$B$17)-B54

A56: [W38] |::
A57: [W38] 'Incremental Costs over Conventional Practice:
A58: [W38] 'Base Assumptions:
B58: [W10] "Silica Sand
A59: [W38] 'Delivered Cost, $/ton
B59: (C0) [W10] 30
A60: [W38] 'Media Thermal & Mechanical Attrition Rate
B60: (P1) [W10] 0.005
A61: [W38] 'Percent Shakeout Sand Reclaimed
B61: (P0) [W10] 0.3
A63: [W38] 'Reclaiming Model - Total Cost per Hour
A64: [W38] '   Reclaimer Operation
B64: (C0) [W10] +$B$22*B43
A65: [W38] '   Disposal Cost
B65: (C0) [W10] +$B$23*B45
A66: [W38] '   Sand Additions
B66: (C0) [W10] +B$28*B55
A67: [W38] '   Clay Additions
B67: (C0) [W10] +$B$20*B50
A68: [W38] '   Total
B68: (C0) [W10] @SUM(B64..B67)
A69: [W38] '   Total per Ton of Castings
B69: (C0) [W10] +B68*40/$B$5
A71: [W38] 'Comparable Costs if no Reclaiming:
A72: [W38] '   Disposal Costs - Dust Collector Fines
B72: (C0) [W10] +B32*$B$13*$B$12*$B$23
A73: [W38] '   - Core Sand Equivalent
B73: (C0) [W10] (B33)*$B$23
A74: [W38] '   Sand Additions
B74: (C0) [W10] +B33*B28
A75: [W38] '   Clay Additions
B75: (C0) [W10] ((B32-B33)*$B$13*($B$12+$B$14)+B33*(1-$B$17)*$B$13)*$B$20
A76: [W38] '   Total
B76: (C0) [W10] @SUM(B72..B75)
A78: [W38] '   Costs - No Reclaiming - per Ton of Castings
A79: [W38] '   Disposal Costs - Dust Collector Fines
B79: (C0) [W10] +B72*40/$B$5
A80: [W38] '   - Core Sand Equivalent
B80: (C0) [W10] +B73*40/$B$5
A81: [W38] '   Sand Additions
B81: (C0) [W10] +B74*40/$B$5
A82: [W38] '   Clay Additions
B82: (C0) [W10] +B75*40/$B$5
A83: [W38] '   Total per Ton of Castings
B83: (C0) [W10] +B76*40/$B$5

A84: [W38] |::
A85: [W38] 'Sand Adhering to Casting Surfaces:
A86: [W38] 'Weight of Sand on One Square Inch of Casting Surface:
A87: [W38] '   Assumed Particle Dimension, in.
B87: (F4) [W10] 0.0117
A88: [W38] '   Surface Coverage, Percent
B88: (P1) [W10] 0.3
A89: [W38] '   Specific Gravity of Particles
B89: [W10] 2.32
A90: [W38] '   Weight per Square Inch, lbs
B90: [W10] +B87*B89*(62.4/1728)*B88
A91: [W38] 'Surface Area of Castings per Unit Volume:
B91: [W10] 4
A92: [W38] 'Lbs.ofAdhering Sand per Lb. of Casting:
B92: (F4) [W10] +B90*B91/0.25
A93: [W38] 'Lbs.of Adhering Sand per Ton of Casting:
B93: (F4) [W10] +B92*2000
A96: [W38] 'Surface Area of Castings per Unit Volume:
A97: [W38] '   Thin Walls - 1/4"
B97: [W10] (1*1*2)/(1*1*0.25)
A98: [W38] '   Moderate Walls - 1/2"
B98: [W10] (1*1*2)/(1*1*0.5)
A99: [W38] '   Runners - 1 in. square
B99: [W10] (1*1*4)/(1*1*1)
A100: [W38] '   Bulky Runner - 4 in. Square
B100: [W10] (4*1*4)/(4*4*1)
A101: [W38] '   Cube - 2" Sides
B101: [W10] 6/2
A102: [W38] '   Value Assumed
B102: [W10] 4
A104: [W38] |::
A106: [W38] 'Media Contamination Limits:
A107: [W38] ' Maximum Allowable Fines, %
B107: (P1) [W10] 0.05
A108: [W38] ' Maximum Allowable LOI, %
B108: (P1) [W10] 0.04
A109: [W38] ' Maximum Allowable Burned Clay, %
B109: (P1) [W10] 0.06
A111: [W38] ' Number of Reclaim Loops for:
A112: [W38] '   Max. Allowable Fines
B112: (F2) [W10] ((B$107*B38-B$119)/(B133-B$119))
A113: [W38] '   Max. LOI
B113: (F2) [W10] ((B$108*B38-B120)/(B127-B120))
A114: [W38] '   Max. Burned Clay
B114: (F2) [W10] ((B$109*B38-B123)/(B130-B123))

A116: [W38] 'Cumulative Sand Fines & LOI after Casting
A117: [W38] 'Shakeout and Sand Cooling:
A118: [W38] ' First Loop Formulation:
A119: [W38] ' Attritted Particles, Tons
B119: (F2) [W10] (B$32*(1-$B$13-$B$15)*B$29+B$33*(1-$B$17)*B$29)*(1-$B$11)
A120: [W38] ' Core Binder, Tons
B120: (F2) [W10] +B$33*($B$18)
A121: [W38] ' Moisture, Tons
B121: (F2) [W10] +B$32*$B$16
A122: [W38] ' Active Clay, Tons
B122: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A123: [W38] ' Burned Clay, Tons
B123: (F2) [W10] +B$32*$B$13*$B$14*(1-$B$11)
A125: [W38] ' Iterative Loop Number
B125: [W10] 1
A126: [W38] ' Attritted Particles, Tons
B126: (F2) [W10] +B$119*(1+(1-B$39))
A127: [W38] ' Core Binder, Tons
B127: (F2) [W10] +B$120*(1+(1-B$39))
A128: [W38] ' Moisture, Tons
B128: (F2) [W10] +B$32*$B$16
A129: [W38] ' Active Clay, Tons
B129: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A130: [W38] ' Burned Clay, Tons
B130: (F2) [W10] +B$123*(1+(1-B$39))
A132: [W38] ' Iterative Loop Number
B132: [W10] 2
A133: [W38] ' Attritted Particles, Tons
B133: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2)
A134: [W38] ' Core Binder, Tons
B134: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2)
A135: [W38] ' Moisture, Tons
B135: (F2) [W10] +B$32*$B$16
A136: [W38] ' Active Clay, Tons
B136: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A137: [W38] ' Burned Clay, Tons
B137: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2)
A139: [W38] ' Iterative Loop Number
B139: [W10] 3
A140: [W38] ' Attritted Particles, Tons
B140: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3)
A141: [W38] ' Core Binder, Tons
B141: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3)
A142: [W38] ' Moisture, Tons
B142: (F2) [W10] +B$32*$B$16

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A143: [W38] '    Active Clay, Tons
B143: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A144: [W38] '    Burned Clay, Tons
B144: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3)
A146: [W38] ' Iterative Loop Number
B146: [W10] 4
A147: [W38] '    Attritted Particles, Tons
B147: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4)
A148: [W38] '    Core Binder, Tons
B148: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4)
A149: [W38] '    Moisture, Tons
B149: (F2) [W10] +B$32*$B$16
A150: [W38] '    Active Clay, Tons
B150: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A151: [W38] '    Burned Clay, Tons
B151: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4)
A153: [W38] ' Iterative Loop Number
B153: [W10] 5
A154: [W38] '    Attritted Particles, Tons
B154: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5)
A155: [W38] '    Core Binder, Tons
B155: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5)
A156: [W38] '    Moisture, Tons
B156: (F2) [W10] +B$32*$B$16
A157: [W38] '    Active Clay, Tons
B157: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A158: [W38] '    Burned Clay, Tons
B158: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5)
A160: [W38] ' Iterative Loop Number
B160: [W10] 6
A161: [W38] '    Attritted Particles, Tons
B161: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A162: [W38] '    Core Binder, Tons
B162: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A163: [W38] '    Moisture, Tons
B163: (F2) [W10] +B$32*$B$16
A164: [W38] '    Active Clay, Tons
B164: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A165: [W38] '    Burned Clay, Tons
B165: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A167: [W38] ' Iterative Loop Number
B167: [W10] 7
A168: [W38] '    Attritted Particles, Tons
B168: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A169: [W38] '    Core Binder, Tons
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B169: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A170: [W38] ' Moisture, Tons
B170: (F2) [W10] +B$32*$B$16
A171: [W38] ' Active Clay, Tons
B171: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A172: [W38] ' Burned Clay, Tons
B172: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A174: [W38] ' Iterative Loop Number
B174: [W10] 8
A175: [W38] ' Attritted Particles, Tons
B175: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A176: [W38] ' Core Binder, Tons
B176: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A177: [W38] ' Moisture, Tons
B177: (F2) [W10] +B$32*$B$16
A178: [W38] ' Active Clay, Tons
B178: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A179: [W38] ' Burned Clay, Tons
B179: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A181: [W38] ' Iterative Loop Number
B181: [W10] 9
A182: [W38] ' Attritted Particles, Tons
B182: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A183: [W38] ' Core Binder, Tons
B183: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A184: [W38] ' Moisture, Tons
B184: (F2) [W10] +B$32*$B$16
A185: [W38] ' Active Clay, Tons
B185: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A186: [W38] ' Burned Clay, Tons
B186: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A188: [W38] ' Iterative Loop Number
B188: [W10] 10
A189: [W38] ' Attritted Particles, Tons
B189: (F2) [W10] +B$119*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A190: [W38] ' Core Binder, Tons
B190: (F2) [W10] +B$120*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A191: [W38] ' Moisture, Tons
B191: (F2) [W10] +B$32*$B$16
A192: [W38] ' Active Clay, Tons
B192: (F2) [W10] +B$32*$B$13*(1-$B$14)*(1-$B$12)
A193: [W38] ' Burned Clay, Tons
B193: (F2) [W10] +B$123*(1+(1-B$39)+(1-B$39)^2+(1-B$39)^3+(1-B$39)^4+(1-B$39)^5+(1-
A195: [W38] ' For Loop Number 10, Amount in Sand Leaving Cooler:
A196: [W38] ' Attritted Particles, %

B196: (P1) [W10] +B189/$B$38
A197: [W38] '   Core Binder, %
B197: (P1) [W10] +B190/$B$38
A198: [W38] '   Moisture, %
B198: (P1) [W10] +B191/$B$38
A199: [W38] '   Active Clay, %
B199: (P1) [W10] +B192/$B$38
A200: [W38] '   Burned Clay, %
B200: (P1) [W10] +B193/$B$38

Appendix III

Cost Model - Calculated Values for Different Scenarios

Alternative Granular Media Project

Media Cost Comparison Study - Effect of Media Cost

Base Assumptions:

Casting Production Rate, Tons/Wk	1000
Casting Yield	70%
Green Sand to Poured Metal Ratio	4
Core Sand to Green Sand Ratio	0.1
Sand Adhering to Castings/Gating, Lb./Ton:	9.4
Dust Collector Losses at Shakeout/Cooling	
Percent of Dead Clay and Fines	33.0%
Percent of Active Clay	10.0%
Bentonite Binder Content - New	6.5%
- Percent Calcined per Pouring Cycle	5.0%
Green Sand Moisture Content - New	3.5%
- After Cooling	1.5%
Core Binder Percent - New	2.0%
- At Shakeout	0.5%
Sand System Capacity, Hrs of Mfg.	8
Bentonite Clay Cost, $/Ton	$50
Core Binder Cost, $/Ton	$1,500
Reclaimer Operational Cost per Ton	$15
Sand/Binder/Fines Disposal Cost, $/Ton	$75

Operational Parameters:	Media Type: Alternative Granular Media									
Delivered Cost, $/ton	$50	$100	$150	$200	$250	$300	$350	$400	$450	$500
Media Thermal & Mechanical Attrition Rate	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Inputs to Molding:										
Green Sand, Tons/Hour	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9
Core Sand, Tons/Hour	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
Outputs from Shakeout/Sand Cooling:										
Sand Adhering to Castings/Gating, Tons/Hr	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fines and Clay to Dust Collector, Tons/Hr	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26
Sand from Shakeout/Sand Cooling, Tons/Hr	152.6	152.6	152.6	152.6	152.6	152.6	152.6	152.6	152.6	152.6
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Shakeout Sand to Mullers, Tons	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8
Net Granular Particles, Tons	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0
Shakeout Sand to Reclaim System, Tons	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8
Net Granular Particles, Tons	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4
Dust to Landfill, Tons	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Green Sand Muller Inputs:										
Tons Shakeout Sand	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8	106.8
Tons Reclaim Sand	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
Tons Active Clay	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Tons Water	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Core Sand System Inputs:										
Tons Reclaim Sand	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6
New Sand, Tons	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Incremental Costs over Conventional Practice:

Base Assumptions:	Alternative Granular Media									
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Reclaiming Model - Total Cost per Hour										
Reclaimer Operation	$687	$687	$687	$687	$687	$687	$687	$687	$687	$687
Disposal Cost	$255	$255	$255	$255	$255	$255	$255	$255	$255	$255
Sand Additions	$19	$39	$58	$78	$97	$116	$136	$155	$175	$194
Clay Additions	$186	$186	$186	$186	$186	$186	$186	$186	$186	$186
Total	$1,148	$1,167	$1,186	$1,206	$1,225	$1,245	$1,264	$1,283	$1,303	$1,322
Reclaiming Model - Costs per Ton of Castings:										
Reclaimer Operation	$27	$27	$27	$27	$27	$27	$27	$27	$27	$27
Disposal Cost	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10
Sand Additions	$1	$2	$2	$3	$4	$5	$5	$6	$7	$8
Clay Additions	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7
Total per Ton of Castings	$46	$47	$47	$48	$49	$50	$51	$51	$52	$53
Comparable Costs if no Reclaiming:										
Disposal Costs - Dust Collector Fines	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70
- Core Sand Equivalent	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084
Sand Additions	$714	$1,429	$2,143	$2,857	$3,571	$4,286	$5,000	$5,714	$6,429	$7,143
Clay Additions	$108	$108	$108	$108	$108	$108	$108	$108	$108	$108
Total	$1,976	$2,690	$3,405	$4,119	$4,833	$5,548	$6,262	$6,976	$7,690	$8,405
Total per Ton of Castings	$79	$108	$136	$165	$193	$222	$250	$279	$308	$336

Alternative Granular Media Project

Media Cost Comparison Study - Conventional Operation with No Reclaiming

Base Assumptions:

Casting Production Rate, Tons/Wk	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Casting Yield	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Green Sand to Poured Metal Ratio	4	4	4	4	4	4	4	4	4	4
Core Sand to Green Sand Ratio	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
Sand Adhering to Castings/Gating, Lb./Ton:	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Dust Collector Losses at Shakeout/Cooling										
Percent of Dead Clay and Fines	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%
Percent of Active Clay	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Bentonite Binder Content - New	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
- Percent Calcined per Pouring Cycle	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Green Sand Moisture Content - New	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
- After Cooling	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Core Binder Percent - New	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
- At Shakeout	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Sand System Capacity, Hrs of Mfg.	8	8	8	8	8	8	8	8	8	8
Bentonite Clay Cost, $/Ton	$80	$80	$80	$80	$80	$80	$80	$80	$80	$80
Core Binder Cost, $/Ton	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500
Reclaimer Operational Cost per Ton	$20	$20	$20	$20	$20	$20	$20	$20	$20	$20
Sand/Binder/Fines Disposal Cost, $/Ton	$75	$75	$75	$75	$75	$75	$75	$75	$75	$75

Operational Parameters:	Media Type:									
	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Inputs to Molding:										
Green Sand, Tons/Hour	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9
Core Sand, Tons/Hour	7.1	14.3	21.4	28.6	35.7	42.9	50.0	57.1	64.3	71.4
Outputs from Shakeout/Sand Cooling:										
Sand Adhering to Castings/Gating, Tons/Hr	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fines and Clay to Dust Collector, Tons/Hr	2.24	2.29	2.34	2.40	2.45	2.50	2.55	2.60	2.65	2.70
Sand from Shakeout/Sand Cooling, Tons/Hr	144.6	151.6	158.6	165.6	172.6	179.6	186.5	193.5	200.5	207.5
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Shakeout Sand to Mullers, Tons	101.2	106.1	111.0	115.9	120.8	125.7	130.6	135.5	140.4	145.2
Net Granular Particles, Tons	93.5	98.4	103.2	108.1	112.9	117.8	122.7	127.5	132.4	137.3
Shakeout Sand to Reclaim System, Tons	43.4	45.5	47.6	49.7	51.8	53.9	56.0	58.1	60.2	62.2
Net Granular Particles, Tons	39.1	40.9	42.7	44.5	46.3	48.1	49.8	51.6	53.4	55.1
Dust to Landfill, Tons	4.3	4.5	4.8	5.1	5.5	5.8	6.1	6.4	6.8	7.1
Green Sand Muller Inputs:										
Tons Shakeout Sand	101.2	106.1	111.0	115.9	120.8	125.7	130.6	135.5	140.4	145.2
Tons Reclaim Sand	34.4	29.8	25.3	20.7	16.2	11.6	7.1	2.6	-2.0	-6.5
Tons Active Clay	3.7	3.5	3.2	2.9	2.7	2.4	2.1	1.8	1.6	1.3
Tons Water	3.5	3.4	3.4	3.3	3.2	3.1	3.1	3.0	2.9	2.8
Core Sand System Inputs:										
Tons Reclaim Sand	4.7	11.1	17.4	23.8	30.1	36.4	42.8	49.1	55.4	61.8
New Sand, Tons	2.3	2.9	3.6	4.2	4.9	5.6	6.2	6.9	7.6	8.4

Incremental Costs over Conventional Practice:	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Base Assumptions:										
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$10	$30
Media Thermal & Mechanical Attrition Rate	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Reclaiming Model - Total Cost per Hour										
Reclaimer Operation	$868	$910	$952	$993	$1,035	$1,077	$1,119	$1,161	$1,203	$1,245
Disposal Cost	$319	$341	$363	$386	$410	$434	$458	$484	$509	$536
Sand Additions	$68	$87	$107	$127	$147	$167	$187	$208	$229	$251
Clay Additions	$298	$277	$255	$234	$212	$191	$169	$148	$126	$105
Total	$1,553	$1,614	$1,677	$1,740	$1,804	$1,869	$1,934	$2,001	$2,068	$2,136
Comparable Costs if no Reclaiming:										
Disposal Costs - Dust Collector Fines	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70
- Core Sand Equivalent	$546	$1,084	$1,620	$2,155	$2,691	$3,227	$3,763	$4,298	$4,834	$5,370
Sand Additions	$214	$429	$643	$857	$1,071	$1,288	$1,500	$1,714	$1,929	$2,143
Clay Additions	$142	$173	$204	$235	$266	$298	$327	$358	$389	$420
Total	$975	$1,755	$2,538	$3,317	$4,098	$4,879	$5,659	$6,440	$7,221	$8,002
Costs - No Reclaiming - per Ton of Castings										
Disposal Costs - Dust Collector Fines	$3	$3	$3	$3	$3	$3	$3	$3	$3	$3
- Core Sand Equivalent	$22	$43	$65	$86	$108	$129	$151	$172	$193	$215
Sand Additions	$9	$17	$26	$34	$43	$51	$60	$69	$77	$86
Clay Additions	$6	$7	$8	$9	$11	$12	$13	$14	$16	$17
Total per Ton of Castings	$39	$70	$101	$133	$164	$195	$226	$258	$289	$320

Alternative Granular Media Project

Media Cost Comparison Study - Effect of Mechanical and Thermal Attrition

Base Assumptions:

Casting Production Rate, Tons/Wk	1000
Casting Yield	70%
Green Sand to Poured Metal Ratio	4
Core Sand to Green Sand Ratio	0.1
Sand Adhering to Castings/Gating, Lb /Ton:	9.4
Dust Collector Losses at Shakeout/Cooling	
Percent of Dead Clay and Fines	33.0%
Percent of Active Clay	10.0%
Bentonite Binder Content - New	6.5%
- Percent Calcined per Pouring Cycle	5.0%
Green Sand Moisture Content - New	3.5%
- After Cooling	1.5%
Core Binder Percent - New	2.0%
- At Shakeout	0.5%
Sand System Capacity, Hrs of Mfg.	8
Bentonite Clay Cost, $/Ton	$80
Core Binder Cost, $/Ton	$1,500
Reclaimer Operational Cost per Ton	$20
Sand/Binder/Fines Disposal Cost, $/Ton	$75

Operational Parameters:	Media Type:									
	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
Inputs to Molding:										
Green Sand, Tons/Hour	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9
Core Sand, Tons/Hour	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
Outputs from Shakeout/Sand Cooling:										
Sand Adhering to Castings/Gating, Tons/Hr	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fines and Clay to Dust Collector, Tons/Hr	1.78	2.29	2.81	3.32	3.84	4.35	4.87	5.38	5.90	6.41
Sand from Shakeout/Sand Cooling, Tons/Hr	152.1	151.6	151.1	150.6	150.1	149.5	149.0	148.5	148.0	147.5
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Shakeout Sand to Mullers, Tons	106.5	106.1	105.8	105.4	105.0	104.7	104.3	104.0	103.6	103.2
Net Granular Particles, Tons	98.7	98.4	98.0	97.7	97.4	97.0	96.7	96.4	96.0	95.7
Shakeout Sand to Reclaim System, Tons	45.6	45.5	45.3	45.2	45.0	44.9	44.7	44.6	44.4	44.2
Net Granular Particles, Tons	41.8	41.2	40.6	40.0	39.4	38.8	38.2	37.6	37.0	36.4
Dust to Landfill, Tons	3.9	4.3	4.8	5.2	5.7	6.1	6.5	7.0	7.4	7.8
Green Sand Muller Inputs:										
Tons Shakeout Sand	106.5	106.1	105.8	105.4	105.0	104.7	104.3	104.0	103.6	103.2
Tons Reclaim Sand	29.1	29.5	29.8	30.2	30.5	30.8	31.2	31.5	31.8	32.2
Tons Active Clay	3.7	3.7	3.8	3.8	3.8	3.8	3.8	3.9	3.9	3.9
Tons Water	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Core Sand System Inputs:										
Tons Reclaim Sand	12.6	11.7	10.7	9.8	8.9	7.9	7.0	6.1	5.2	4.2
New Sand, Tons	1.4	2.3	3.3	4.2	5.1	6.1	7.0	7.9	8.8	9.8

Incremental Costs over Conventional Practice:

Base Assumptions:	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
Percent Shakeout Sand Reclaimed	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Reclaiming Model - Total Cost per Hour										
Reclaimer Operation	$913	$910	$907	$903	$900	$897	$894	$891	$888	$885
Disposal Cost	$290	$324	$358	$391	$425	$458	$491	$523	$555	$586
Sand Additions	$41	$69	$98	$126	$154	$182	$210	$238	$265	$293
Clay Additions	$298	$300	$301	$303	$304	$306	$307	$309	$310	$312
Total	$1,542	$1,603	$1,663	$1,723	$1,783	$1,843	$1,902	$1,961	$2,019	$2,077
Reclaiming Model - Costs per Ton of Castings:										
Reclaimer Operation	$37	$36	$36	$36	$36	$36	$36	$36	$36	$35
Disposal Cost	$12	$13	$14	$16	$17	$18	$20	$21	$22	$24
Sand Additions	$2	$3	$4	$5	$6	$7	$8	$10	$11	$12
Clay Additions	$12	$12	$12	$12	$12	$12	$12	$12	$12	$12
Total per Ton of Castings	$62	$64	$67	$69	$71	$74	$76	$78	$81	$83
Comparable Costs if no Reclaiming:										
Disposal Costs - Dust Collector Fines	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70
- Core Sand Equivalent	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084
Sand Additions	$429	$429	$429	$429	$429	$429	$429	$429	$429	$429
Clay Additions	$173	$173	$173	$173	$173	$173	$173	$173	$173	$173
Total	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755
Total per Ton of Castings	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70

Alternative Granular Media Project

Media Cost Comparison Study - Effect of Percentage Sand Reclaimed per Cycle

Base Assumptions:

Casting Production Rate, Tons/Wk	1000
Casting Yield	70%
Green Sand to Poured Metal Ratio	4
Core Sand to Green Sand Ratio	0.1
Sand Adhering to Castings/Gating, Lb./Ton:	9.4
Dust Collector Losses at Shakeout/Cooling	
Percent of Dead Clay and Fines	33.0%
Percent of Active Clay	10.0%
Bentonite Binder Content - New	8.5%
- Percent Calcined per Pouring Cycle	5.0%
Green Sand Moisture Content - New	3.5%
- After Cooling	1.5%
Core Binder Percent - New	2.0%
- At Shakeout	0.5%
Sand System Capacity, Hrs of Mfg.	8
Bentonite Clay Cost, $/Ton	$80
Core Binder Cost, $/Ton	$1,500
Reclaimer Operational Cost per Ton	$20
Sand/Binder/Fines Disposal Cost, $/Ton	$75

Operational Parameters:	Media Type:									
	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Inputs to Molding:										
Green Sand, Tons/Hour	142.9	142.9	142.9	142.9	142 9	142.9	142.9	142.9	142 9	142.9
Core Sand, Tons/Hour	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
Outputs from Shakeout/Sand Cooling:										
Sand Adhering to Castings/Gating, Tons/Hr	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0 17
Fines and Clay to Dust Collector, Tons/Hr	4.53	3.80	3.25	2.84	2.53	2.29	2.11	1.97	1.86	1.76
Sand from Shakeout/Sand Cooling, Tons/Hr	149.4	150.1	150.7	151.1	151.4	151.6	151.8	151.9	152.0	152.1
Percent Shakeout Sand Reclaimed	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Shakeout Sand to Mullers, Tons	141.9	135.1	128.1	120.9	113.5	106.1	98.7	91.2	83.6	76.1
Net Granular Particles, Tons	131.5	125.2	118.7	112.0	105 2	98.4	91.4	84.5	77.5	70.5
Shakeout Sand to Reclaim System, Tons	7.5	15 0	22.8	30.2	37.8	45.5	53.1	60.8	68.4	76.1
Net Granular Particles, Tons	6.4	13.1	20.0	26.9	34.0	41.1	48 2	55.3	62.4	69.6
Dust to Landfill, Tons	1.1	1.9	2.6	3.3	3.9	4.4	4.9	5.5	6.0	6 5
Green Sand Muller Inputs:										
Tons Shakeout Sand	141.9	135.1	128.1	120.9	·113.5	106.1	98.7	91.2	83.6	76 1
Tons Reclaim Sand	-3.8	2.8	9.2	15.9	22.7	29.8	36.8	43.8	50.6	57 6
Tons Active Clay	1.7	2.1	2.5	2.9	3.3	3.6	4.0	4.4	4.8	5 2
Tons Water	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3 9
Core Sand System Inputs:										
Tons Reclaim Sand	10.1	10.5	10.8	11.1	11 3	11.5	11.6	11.8	11.9	11 9
New Sand, Tons	3.9	3.5	3.2	2.9	2.7	2.5	2.4	2.2	2.1	2 1

Incremental Costs over Conventional Practice:

Base Assumptions:	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical Attrition Rate	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Percent Shakeout Sand Reclaimed	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Reclaiming Model - Total Cost per Hour										
Reclaimer Operation	$149	$300	$452	$604	$757	$910	$1,063	$1,215	$1,368	$1,521
Disposal Cost	$81	$145	$198	$246	$289	$330	$370	$409	$448	$487
Sand Additions	$116	$105	$96	$88	$81	$76	$71	$67	$64	$62
Clay Additions	$139	$168	$198	$229	$260	$292	$323	$355	$387	$419
Total	$485	$719	$945	$1,167	$1,387	$1,607	$1,827	$2,047	$2,268	$2,490
Reclaiming Model - Costs per Ton of Castings:										
Reclaimer Operation	$6	$12	$18	$24	$30	$36	$43	$49	$55	$61
Disposal Cost	$3	$6	$8	$10	$12	$13	$15	$16	$18	$19
Sand Additions	$5	$4	$4	$4	$3	$3	$3	$3	$3	$2
Clay Additions	$6	$7	$8	$9	$10	$12	$13	$14	$15	$17
Total per Ton of Castings	$19	$29	$38	$47	$55	$64	$73	$82	$91	$100
Comparable Costs if no Reclaiming:										
Disposal Costs - Dust Collector Fines	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70
- Core Sand Equivalent	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084
Sand Additions	$429	$429	$429	$429	$429	$429	$429	$429	$429	$429
Clay Additions	$173	$173	$173	$173	$173	$173	$173	$173	$173	$173
Total	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755	$1,755
Total per Ton of Castings	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70

Operational Parameters:	Media Type: Alternative Granular Media									
Delivered Cost, $/ton	$300	$300	$300	$300	$300	$300	$300	$300	$300	$300
Media Thermal & Mechanical	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Inputs to Molding:										
Green Sand, Tons/Hour	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9
Core Sand, Tons/Hour	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
Outputs from Shakeout/Sand Cooling:										
Sand Adhering to Castings/Ga	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fines and Clay to Dust Collect	1.90	1.77	1.66	1.57	1.50	1.43	1.38	1.34	1.30	1.26
Sand from Shakeout/Sand Co	152.0	152.1	152.2	152.3	152.4	152.5	152.5	152.6	152.6	152.6
Percent Shakeout Sand Reclai	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%
Shakeout Sand to Mullers, To	147.4	143.0	138.5	134.0	129.5	125.0	120.5	116.0	111.4	106.8
Net Granular Particles, Ton	136.7	132.5	128.4	124.2	120.1	115.9	111.7	107.5	103.3	99.0
Shakeout Sand to Reclaim Sy	4.6	9.1	13.7	18.3	22.9	27.4	32.0	36.6	41.2	45.8
Net Granular Particles, Ton	4.2	8.3	12.5	16.8	21.0	25.3	29.6	33.8	38.1	42.4
Dust to Landfill, Tons	0.4	0.8	1.2	1.5	1.8	2.2	2.5	2.8	3.1	3.4
Green Sand Muller Inputs:										
Tons Shakeout Sand	147.4	143.0	138.5	134.0	129.5	125.0	120.5	116.0	111.4	106.8
Tons Reclaim Sand	-9.1	-4.9	-0.8	3.4	7.6	11.8	16.1	20.3	24.6	28.8
Tons Active Clay	1.6	1.8	2.0	2.3	2.5	2.8	3.0	3.2	3.5	3.7
Tons Water	2.9	3.0	3.0	3.1	3.2	3.2	3.3	3.4	3.4	3.5
Core Sand System Inputs:										
Tons Reclaim Sand	13.2	13.3	13.3	13.4	13.4	13.4	13.5	13.5	13.5	13.6
New Sand, Tons	0.8	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.4

Incremental Costs over Conventional Practice:										
Base Assumptions:	Alternative Granular Media									
Delivered Cost, $/ton	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30
Media Thermal & Mechanical	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.0%	4.0%
Percent Shakeout Sand Reclai	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%
Reclaiming Model - Total Cost per Hour										
Reclaimer Operation	$68	$137	$206	$274	$343	$412	$480	$549	$618	$687
Disposal Cost	$31	$59	$87	$112	$137	$162	$186	$209	$233	$256
Sand Additions	$228	$216	$203	$190	$178	$166	$156	$146	$137	$130
Clay Additions	$79	$91	$102	$114	$126	$138	$150	$161	$173	$185
Total	$406	$503	$597	$691	$784	$878	$972	$1,066	$1,162	$1,258
Reclaiming Model - Costs per Ton of Castings:										
Reclaimer Operation	$3	$5	$8	$11	$14	$16	$19	$22	$25	$27
Disposal Cost	$1	$2	$3	$4	$5	$6	$7	$8	$9	$10
Sand Additions	$9	$9	$8	$8	$7	$7	$6	$6	$5	$5
Clay Additions	$3	$4	$4	$5	$5	$6	$6	$6	$7	$7
Total per Ton of Castings	$16	$20	$24	$28	$31	$35	$39	$43	$46	$50
Comparable Costs if no Reclaiming:										
Disposal Costs - Dust Colle	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70
- Core Sand Equiv	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084	$1,084
Sand Additions	$4,286	$4,286	$4,286	$4,286	$4,286	$4,286	$4,286	$4,286	$4,286	$4,286
Clay Additions	$108	$108	$108	$108	$108	$108	$108	$108	$108	$108
Total	$5,548	$5,548	$5,548	$5,548	$5,548	$5,548	$5,548	$5,548	$5,548	$5,548
Total per Ton of Castings	$222	$222	$222	$222	$222	$222	$222	$222	$222	$222

Alternative Granular Media Project

Media Cost Comparison Study - Effect of Reclaim Rate for $300 Medium

Base Assumptions:	
Casting Production Rate, Tons	1000
Casting Yield	70%
Green Sand to Poured Metal R	4
Core Sand to Green Sand Rati	0.1
Sand Adhering to Castings/Ga	9.4
Dust Collector Losses at Shakeout/Cooling	
Percent of Dead Clay and F	33.0%
Percent of Active Clay	10.0%
Bentonite Binder Content - Ne	6.5%
- Percent Calcined per Pourin	5.0%
Green Sand Moisture Content	3.5%
- After Cooling	1.5%
Core Binder Percent - Ne	2.0%
- At Shakeout	0.5%
Sand System Capacity, Hrs of	8
Bentonite Clay Cost, $/Ton	$50
Core Binder Cost, $/Ton	$1,500
Reclaimer Operational Cost p	$15
Sand/Binder/Fines Disposal C	$75