Casting

2.810

T. Gutowski
Casting since about 3200 BCE…

Etruscan casting with runners circa 500 BCE

China circa 3000BCE

Lost wax jewelry from Greece circa 300 BCE
Bronze age to iron age

Ancient Greece; bronze statue casting circa 450BCE

Iron works in early Europe, e.g. cast iron cannons from England circa 1543
Cast Parts
Outline

1. **Review**: Sand Casting, Investment Casting, Die Casting
2. **Basics**: Phase Change, Shrinkage, Heat Transfer
3. **Pattern Design and New Technologies**
4. **Environmental Issues**
Casting

Readings:
1. Kalpakjian, Chapters 10, 11, 12
2. Boothroyd, “Design for Die Casting”
3. Flemings “Heat Flow in Solidification”
4. Dalquist “LCA of Casting”

Note: a good heat transfer reference can be found by Profs John Lienhard online http://web.mit.edu/lienhard/www/ahtt.html
Casting Methods

- **Sand Casting**
  - High Temperature Alloy,
  - Complex Geometry,
  - Rough Surface Finish

- **Investment Casting**
  - High Temperature Alloy,
  - Complex Geometry,
  - Moderately Smooth Surface Finish

- **Die Casting**
  - High Temperature Alloy,
  - Moderate Geometry,
  - Smooth Surface
Sand Casting

(a) Mechanical drawing of part

(b) Cope pattern plate

(c) Gate

Drag pattern plate

(d) Core boxes

(e) Core halves pasted together

(f) Risers

Sprue

(g) Flask

(f) Cope ready for sand

(h) Drag ready for sand

(i) Drag after removing pattern

(j) Drag with core set in place

(k) Cope

Drag

Closing pins

(l) Cope and drag assembled ready for pouring

(m) Casting as removed from mold heat treated

(n) Casting ready for shipment
Sand Casting

Description: Tempered sand is packed into wood or metal pattern halves, removed from the pattern, and assembled with or without cores, and metal is poured into resultant cavities. Various core materials can be used. Molds are broken to remove castings. Specialized binders now in use can improve tolerances and surface finish.

Metals: Most castable metals.

Size Range: Limitation depends on foundry capabilities. Ounces to many tons.

Tolerances:

- Non-Ferrous: ± 1/32” to 6”
- Add ± .003” to 3”, ± 3/64” from 3” to 6”.
- Across parting line add ± .020” to ± .090” depending on size. (Assumes metal patterns)

Surface Finish:

- Non-Ferrous: 150-350 RMS
- Ferrous: 300-700 RMS

Minimum Draft Requirements:

- 1° to 5°
- Cores: 1° to 1 1/2°

Normal Minimum Section Thickness:

- Non-Ferrous: 1/8” - 1/4”
- Ferrous: 1/4” - 3/8”

Ordering Quantities: All quantities

Normal Lead Time:

- Samples: 2-10 weeks
- Production 2-4 weeks A.S.A.
Sand Casting Mold Features

**FIGURE 10.7**  Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification. See also Fig. 11.4. Source: American Foundrymen’s Society.

**FIGURE 11.4**  Schematic illustration of a sand mold, showing various features.

*Vents*, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the molds and core. They also exhaust air from the mold cavity as the molten metal flows into the mold.
Videos from Mass & Burlington Foundries
Production sand casting

FIGURE 11.8
(a) Schematic illustration of a jolt-type mold-making machine. (b) Schematic illustration of a mold-making machine which combines jolting and squeezing.
Description: Metal mold makes wax or plastic replica. There are sprued, then surrounded with investment material, baked out, and metal is poured in the resultant cavity. Molds are broken to remove the castings.

Metals: Most castable metals.

Size Range: fraction of an ounce to 150 lbs..

Tolerances:

- ± .003” to 1/4”
- ± .004” to 1/2”
- ± .005” per inch to 3”
- ± .003” for each additional inch

Surface Finish:
63-125RMS

Minimum Draft Requirements: None

Normal Minimum Section Thickness:
- .030” (Small Areas)
- .060” (Large Areas)

Ordering Quantities:
- Aluminum: usually under 1,000
- Other metals: all quantities

Normal Lead Time:
- Samples: 5-16 weeks (depending on complexity)
- Production 4-12 weeks A.S.A. (depending on subsequent operations).

Talbot Associates Inc.
The **investment-casting process**, also called the *lost-wax* process, was first used during the period 4000-3500 B.C. The pattern is made of wax or a plastic such as polystyrene. The sequences involved in investment casting are shown in Figure 11.18. The pattern is made by injecting molten wax or plastic into a metal die in the shape of the object.
Die Casting

Description: Molten metal is injected, under pressure, into hardened steel dies, often water cooled. Dies are opened, and castings are ejected.

Metals: Aluminum, Zinc, Magnesium, and limited Brass.

Size Range: Not normally over 2 feet square. Some foundries capable of larger sizes.

Tolerances:
- Al and Mg ± .002"/in.
- Zinc ± .0015"/in.
- Brass ± .001"/in.
- Add ± .001” to ± .015” across parting line depending on size

Surface Finish: 32-63RMS

Minimum Draft Requirements:
- Al & Mg: 1° to 3°
- Zinc: 1/2° to 2°
- Brass: 2° to 5°

Normal Minimum Section Thickness:
- Al & Mg: .03” Small Parts: .06” Medium Parts
- Zinc: .03” Small Parts: .045” Medium Parts
- Brass: .025” Small Parts: .040” Medium Parts

Ordering Quantities:
- Usually 2,500 and up.

Normal Lead Time:
- Samples: 12-20 weeks
- Production: ASAP after approval.
Die cast parts & runners
High Melt Temperature

• Reactivity
  • with air, mold mat’ ls,

• Gas solubility
  • $H_2$ gas in Al

• Safety
  • Metal fires, e.g. Mg

3000° C
- Tungsten Carbide, WC
- Silicon Carbide, SiC
- Cubic Zirconia, ZrO$_2$
- Molybdenum

2000° C
- Alumina Al$_2$O$_3$
- Platinum, Pt
- Titanium, Ti
- Iron, Plain Carbon Steels, low alloy, stainless
- Nickel, Ni
- Nickel Alloy
- Silicon, Si

1000° C
- Copper, Cu, Bronze, Brass
- Aluminum
- Magnesium
- Zinc, Zn
- PTFE (Teflon)
- Tin, Sn
- HDPE
- Nylon
- Acetal
Mold Filling

Bernoulli’s Equation:
\[ h + \frac{p}{pg} + \frac{v^2}{2g} = \text{Const.} \]

Reynold’s Number:
\[ \text{Re} = \frac{vDP}{\mu} \]

• Short filling times
• Potential Turbulence

(see Kalpakjian..Ch 10)
Mold Filling Example

Mold Filling Example (order of magnitude)

from Bernoulli’s Eq’n

the inlet velocity can be estimated as:

\[ v = \sqrt{2gh} \]

\[ = \sqrt{2 \times 10 \frac{m}{s^2} \times 10^{-1} m} = 1.4 \frac{m}{s} \]

estimate Reynolds Number

\[ Re = \frac{\nu D \rho}{\mu} = 1.4 \frac{m}{s} \cdot 0.5 \text{cm} \cdot 2.7 \frac{g}{cm^3} = 18,900 \]

\[ \mu \cdot 10^{-3} \frac{N \cdot m}{s} \cdot \frac{m^2}{s} \]

Mold filling issues: oxidation, turbulence, mold erosion, soluble gases, safety
Phase Change & Shrinkage

TABLE 10.1

<table>
<thead>
<tr>
<th>Volumetric Solidification Contraction or Expansion for Various Cast Metals</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contraction (%)</strong></td>
<td><strong>Expansion (%)</strong></td>
</tr>
<tr>
<td>Aluminum</td>
<td>7.1</td>
</tr>
<tr>
<td>Zinc</td>
<td>6.5</td>
</tr>
<tr>
<td>Al-4.5% Cu</td>
<td>6.3</td>
</tr>
<tr>
<td>Gold</td>
<td>5.5</td>
</tr>
<tr>
<td>White iron</td>
<td>4-5.5</td>
</tr>
<tr>
<td>Copper</td>
<td>4.9</td>
</tr>
<tr>
<td>Brass (70-30)</td>
<td>4.5</td>
</tr>
<tr>
<td>Magnesium</td>
<td>4.2</td>
</tr>
<tr>
<td>90% Cu-10% Al</td>
<td>4</td>
</tr>
<tr>
<td>Carbon steels</td>
<td>2.5-4</td>
</tr>
<tr>
<td>Al-12% Si</td>
<td>3.8</td>
</tr>
<tr>
<td>Lead</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Solidification of a binary alloy

FIGURE 12.5 (a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.
Composition change during solidification

**FIGURE 4.5** Phase diagram for nickel-copper alloy system obtained at a slow rate of solidification. Note that pure nickel and pure copper each have one freezing or melting temperature. The top circle on the right depicts the nucleation of crystals. The second circle shows the formation of dendrites (see Section 10.2). The bottom circle shows the solidified alloy, with grain boundaries.
FIGURE 4.7 The lead–tin phase diagram. Note that the composition of the eutectic point for this alloy is 61.9% Sn–38.1% Pb. A composition either lower or higher than this ratio will have a higher liquidus temperature.
Solidification

Dendrite growth in metals- lower surface energy crystallographic planes are favored, producing tree like structures if not disturbed.

http://www.itc.caltech.edu/~atomic/knowcrystals/
Cast structures

Schematic illustration of three cast structures solidified in a square mold: (a) pure metals; (b) solid solution alloys; and c) structure obtained by using nucleating agents. Source: G. W. Form, J. F. Wallace, and A. Cibula
Properties of castings

e.g. Compare elongation of carbon steels (4-36%) Table 5.3, with cast irons (0-18%) Table 12.3 (Kalpakjian & Schmid 7th)
How long does it take to solidify?

Thickness ~ 30 cm

Thickness ~ 0.5 cm
Heat Transfer – Sand Casting

\[ t_s \approx \left( \frac{V}{A} \right)^2 \]

**FIGURE 1-6**
Approximate temperature profile in solidification of a pure metal poured at its melting point against a flat, smooth mold wall.

Ref: Mert Flemings “Solidification Processing”
Thermal Conductivity “k” (W/m·K)

\[ q = -k \frac{dT}{dx} \]

Copper 394
Aluminum 222
Iron 29
Sand 0.61
PMMA 0.20
PVC 0.16
Transient Heat Transfer

\[ q \rightarrow \frac{\rho C_p \partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \]

\[ k \neq k(x) \]

\[ \alpha = \frac{k}{\rho C_p} \]

Materials:
- Metals
- Glass
- Polymers
- Gases

\[ \alpha \left[ \frac{cm^2}{sec} \right] \]

Alu: \[ 10^1 \]
Sand 3X10^{-3}: \[ 10^{-3} \]
Sand Casting (see Flemings)

Define new variable

\[ \zeta = x / \sqrt{\alpha t} \]

Use

\[ \theta = \frac{T - T_M}{T_o - T_M} \]

We seek the transient temperature profile in the sand.
Sand Casting (see Flemings)

Ordinary differential eq'us

\[ \frac{d^2 \theta}{d\zeta^2} = -\frac{\zeta}{2} \frac{d\theta}{d\zeta} \]

i.c. \( \theta = 1 \) at \( \zeta = \infty \) \quad \text{At } t=0, T=T_o \text{ everywhere}

b.c. \( \theta = 0 \) at \( \zeta = 0 \) \quad \text{At } x=0, T=T_m \text{ always}

\[ \theta = \text{erf} \left( -\frac{\zeta}{2} \right) \]

This will allow us to calculate the heat lost by the metal at the boundary with the sand tooling.
Solidification Time

Heat required to solidify to distance "s"

\[ = A \cdot s \cdot \rho \cdot H \]

Rate eq'n (per unit area)

\[ \rho H \frac{ds}{dt} = -q = k \left( \frac{dT}{dx} \right)_{x=0} \]
Solidification Time (cont.)

This leads to

\[ s = \frac{2}{\sqrt{\pi}} \left( \frac{T_M - T_o}{\rho M H_M} \right) \sqrt{K_S \rho_S C_p S t} \]

let \( s = \frac{V}{A} \)

\[ t = C \left( \frac{V}{A} \right)^2 \]

Chvorinov’s rule

The constant “C” (in this case not heat capacity) is determined by experiment.

Several references suggest that values range:

\( C \sim 2 \text{ to } 4 \text{ min/cm}^2 \) (with most data for iron and steel)
How long does it take to solidify?

Order of magnitude estimate using half thickness, & $C = 3.3 \text{ min/cm}^2$

Thickness $\sim 30 \text{ cm}$
Solidification time $= 3.3 \left(\frac{30}{2}\right)^2 \text{ [min]} \sim 12 \text{ hrs}$

Thickness $\sim 0.5 \text{ cm}$
$t = 3.3 \left(\frac{0.5}{2}\right)^2 \text{ [min]} \sim 12 \text{ sec}$
What happened?
Can you explain these Solidification features?

Picture taken from the Chipman Room
Pattern Design suggestions

Figure 7.2.24 Identifying hot spots in castings by using outward projecting arrows of length half the casting thickness. Where arrows overlap, hot spots may develop. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.25 Examples of relative cooling times. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.26 Fill all sharp angles. (Courtesy of Meehanite Metal Corp.)
More Pattern Design suggestions

Figure 7.2.28 Avoid abrupt section changes. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.29 Design for uniform thickness in sections. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.30 More intersection details. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.31 Design for bolting or bearing bosses. (Courtesy of Meehanite Metal Corp.)
Heat Transfer – Die Casting

\[ t_s \approx \left( \frac{V}{A} \right) \]

**FIGURE 1-9**
Temperature profile during solidification against a large flat mold wall with mold-metal interface resistance controlling.
Film Coefficients $h$ W/m$^2$·K

$$q = -hA(\Delta T)$$

- Typical die casting: 1,000 - 10,000
- Natural convection: 1 - 10
- Flowing air: 10 - 50
- Carbon coating: high pressure, low pressure polished die
Die casting contact resistance

Die Casting
Solidification
Time

Time to form solid part

\[ q = -hA(T_M - T_o) = \rho_M H_M A \frac{ds}{dt} \]

\[ t = \frac{\rho_M H_M V}{h(T_M - T_o) A} \]

Also need to cool casting to below \( T_M \) to eject \( T_{eject} \)

and will inject at \( T_{inject} > T_M \).
Time to **cool part to the ejection temperature.** (lumped parameter model)

\[
mc \frac{dT}{dt} = -Ah(T - T_o)
\]

Let, \[ \theta = T - T_o \]

\[
\int_{\theta_i}^{\theta_f} \left( \frac{d\theta}{\theta} \right) = -\frac{Ah}{mC_p} \int_{t_i}^{t_f} dt
\]

Integration yields...

\[ t = \frac{-mC}{Ah} \ln \frac{\Delta \theta_f}{\Delta \theta_i} \]

Note \( C = \) heat capacity, \( h = \) enthalpy
Time to cool part to the ejection temperature. (lumped parameter model)

For thin sheets of thickness “w”, including phase change

\[ \Delta \theta_i = T_i + \Delta T_{sp} - T_{mold} \]
\[ \Delta T_{sp} = \frac{h}{C} \]
\[ \Delta \theta_f = T_{eject} - T_{mold} \]

"sp" means superheat
C is heat capacity
h is enthalpy of phase change

Approximations,
\[ t \approx 0.42 \text{ sec/mm} \times w_{\text{max}} \text{ (Zn)} \]
\[ t \approx 0.47 \text{ sec/mm} \times w_{\text{max}} \text{ (Al)} \]
\[ t \approx 0.63 \text{ sec/mm} \times w_{\text{max}} \text{ (Cu)} \]
\[ t \approx 0.31 \text{ sec/mm} \times w_{\text{max}} \text{ (Mg)} \]

Ref Boothroyd, Dewhurst, Knight p 447
Pattern Design Issues (Alum)

- Shrinkage Allowance: 1.3%
- Machining Allowance: \(1/16” = 1.6 \text{ mm}\)
- Minimum thickness: \(3/16” = 5 \text{ mm}\)
- Parting Line: even
- Draft Angle: 3 to 5%
- Thickness: even
Table 12.1
Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

<table>
<thead>
<tr>
<th>Metal</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray cast iron</td>
<td>0.83 – 1.3</td>
</tr>
<tr>
<td>White cast iron</td>
<td>2.1</td>
</tr>
<tr>
<td>Malleable cast iron</td>
<td>0.78 – 1.0</td>
</tr>
<tr>
<td><strong>Aluminum alloys</strong></td>
<td><strong>1.3</strong></td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>1.3</td>
</tr>
<tr>
<td>Yellow brass</td>
<td>1.3 – 1.6</td>
</tr>
<tr>
<td>Phosphor bronze</td>
<td>1.0 – 1.6</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>2.1</td>
</tr>
<tr>
<td>High-manganese steel</td>
<td>2.6</td>
</tr>
</tbody>
</table>

FIGURE 12.5 Redesign of a casting by making the parting line straight to avoid defects. Source: Steel Casting Handbook, 5th ed. Steel Founders’ Society of America, 1980. Used with permission.

FIGURE 11.7 Taper on patterns for ease of removal from the sand mold.
Pattern materials
Digital Sand Casting: Print molds or parts?

1. Print
   - Selectively disperse binder using Injet printing technology

2. New layer
   - The build platform is lowered by a set increment.

3. Spread
   - Spreads a new layer of pre-mixed molding sand.

4. Repeat
   - Repeat steps 1-3, until the molds or cores are built.

5. Finishing
   - Unbound sand is removed. Metal parts can be cast.

Start from the Computer Model

Add gating system and risers

Design mold and core package, without draft angles and regardless of undercuts

Print sand molds and cores

Casting is poured & ready

Casting is inspected

Parts are ready to be dispatched
Early Versions of 3-D printing

Printed mold and cast part
Ely Sachs, MIT

Liquid metal droplets
Jung-Hoon Chun, MIT

Liquid metal droplets
CMU
Printed steel & aluminum tools
**Additive Steps to produce tooling**

1. **CAD file**
2. **Support structure generation**
3. **Printing: EOS M280**
4. **Sawing (or wire EDM) and hand tool removal of support structure**
5. **Printed part on plate, stress relieve**
Laser melting of powders

Common laser power:
Polymers ~ 50 W (CO$_2$ 10.6$\mu$m)
Metals ~ 200 W (Nd:YAG 1.06$\mu$m)
Absorption ~ 0.7

Laser scan speeds
~ 0.1 to 1 m/s

“max” build rate:
30mm$^3$/s
= 108 cm$^3$/hr

$w \sim 0.3 \text{ mm}$  $d \sim 0.1 \text{ mm}$
Actual Build
Sand casting; Environmental Issues

- Energy
- Emissions
- Sand
- Waste water

Input:
- Vapor waste
- Aquous waste
- Solid waste

Included in analysis:
- PM, NOx, HC, CO, SO2

Not included in analysis:
- PM, abrasives
- Scrap metal

S. Dalquist
## Cast Iron Example (Cupola)

<table>
<thead>
<tr>
<th>Stage</th>
<th>MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold preparation</td>
<td>3.0</td>
</tr>
<tr>
<td>Metal preparation</td>
<td>6.7</td>
</tr>
<tr>
<td>Casting</td>
<td>0.7</td>
</tr>
<tr>
<td>Finishing</td>
<td>1.2</td>
</tr>
<tr>
<td>Total at foundry</td>
<td>11.6</td>
</tr>
<tr>
<td>Electricity losses</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>~12 MJ/kg</td>
</tr>
</tbody>
</table>


Melting Energy

- pour : part size Ratio $\sim 1.1$ to $3$

- thermal energy
  \[ \Delta H = mC_p\Delta T + m\Delta H_f \Rightarrow 0.95 \text{ (aluminum)}, \ 1.3 \text{ MJ/kg (cast iron)} \]

- melting and holding efficiency,

- *Losses at the utilities for electric furnaces*

  - *National statistics (including elect losses)*
    
    13 – 17 MJ/kg (total)
Improving sand casting

\[ \eta = \frac{C_p \Delta T + \Delta h}{15 \frac{MJ}{kg}} \approx \frac{1}{15} \approx 7\% \]

- reduce runners, risers
- recycle metal & sand
- improve furnace efficiency
- use waste heat
- use fuel Vs electricity
Metals & sand used in Casting

- Iron accounts for 3/4 of US sand cast metals
  - Similar distribution in the UK
  - Share of aluminum expected to increase with lightweighting of automotive parts
- Sand used to castings out– about 5.5:1 by mass
- Sand lost about 0.5:1 in US; 0.25:1 in UK

Aggregate TRI data (toxic releases)

kg released per tonne cast

goes to 2

- Zinc compounds
- Manganese compounds
- Methyl alcohol
- Tin (acetate or dust)
- Aluminum (aluminum or dust)
- Chromium compounds
- Xylene (mixed isomers)
- Phenol
- Copper
- Toluene
- Ammonia
- Lead
- Naphthalene
- Chromium
- Trichlorofluoromethane
- Phosphoric acid
- Benzene
- Lead compounds
- Certain glycol ethers
- Barium
- Nickel
- Formaldehyde
- Ethylene glycol
- Dichloromethane
- Styrene
- N-methyl-2-pyrrolidone
- Copper compounds
- Dichloroethylene
- Butadiene
- N,N-dichloro-1,1-difluoroethylene
- Methyl isobutyl ketone
- Cresol (mixed isomers)
- N-butyl alcohol
- Sulfonic acid
- Nitrate compounds
Sandcasting Emissions Factors

- Emissions factors are useful because it is often too time consuming or expensive to monitor emissions from individual sources.
- They are often the only way to estimate emissions if you do not have test data.
- However, they can not account for variations in processing conditions.

<table>
<thead>
<tr>
<th>Iron Melting Furnace Emissions Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg/Mg of iron produced)</td>
</tr>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Cupola</td>
</tr>
<tr>
<td>Uncontrolled</td>
</tr>
<tr>
<td>Baghouse</td>
</tr>
<tr>
<td>Electric Induction</td>
</tr>
<tr>
<td>Uncontrolled</td>
</tr>
<tr>
<td>Baghouse</td>
</tr>
</tbody>
</table>

*S = % of sulfur in the coke. Assumes 30% conversion of sulfur into SO₂.

Source: EPA AP-42 Series 12.10 Iron Foundries

<table>
<thead>
<tr>
<th>Pouring, Cooling Shakeout Organic HAP Emissions Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>for Cored Greensand Molds</td>
</tr>
<tr>
<td>(lbs/ton of iron produced)</td>
</tr>
<tr>
<td>Core Loading</td>
</tr>
<tr>
<td>AFS heavily cored</td>
</tr>
<tr>
<td>AFS average core</td>
</tr>
<tr>
<td>EPA average core</td>
</tr>
</tbody>
</table>

Source: AFS Organic HAP Emissions Factors for Iron Foundries
www.afsinc.org/pdfs/OrganicHAPemissionfactors.pdf
<table>
<thead>
<tr>
<th>Chemical</th>
<th>Total Air Emissions (lbs)</th>
<th>Surface Water Discharge (lbs)</th>
<th>Total on-site Release (lbs)</th>
<th>Total transfers off site for waste Management (lbs)</th>
<th>Total waste Managed (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COPPER</td>
<td>69</td>
<td>9</td>
<td>78</td>
<td>74,701</td>
<td>74,778</td>
</tr>
<tr>
<td>DIISOCYANATES</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>LEAD</td>
<td>127</td>
<td>40</td>
<td>167</td>
<td>39,525</td>
<td>39,692</td>
</tr>
<tr>
<td>MANGANESE</td>
<td>274</td>
<td>48</td>
<td>322</td>
<td>768,387</td>
<td>768,709</td>
</tr>
<tr>
<td>MERCURY</td>
<td>14.35</td>
<td>0</td>
<td>14.35</td>
<td>0.25</td>
<td>14.6</td>
</tr>
<tr>
<td>PHENOL</td>
<td>6,640</td>
<td>5</td>
<td>6,645</td>
<td>835</td>
<td>7,484</td>
</tr>
<tr>
<td>ZINC (FUME OR DUST)</td>
<td>74</td>
<td>0</td>
<td>74</td>
<td>262,117</td>
<td>262,191</td>
</tr>
<tr>
<td>TOTALS</td>
<td></td>
<td></td>
<td>7,300</td>
<td>1,145,585</td>
<td>1,152,889</td>
</tr>
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Input Metals for Casting