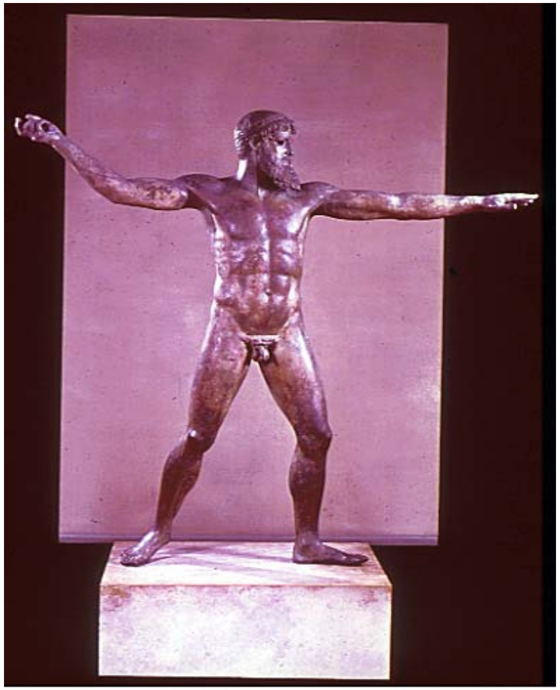


Bronze statue of Zeus from Artemision, ca. 460 BC

Casting

2.810

Prof. Timothy Gutowski

Casting since about 4000 BC…

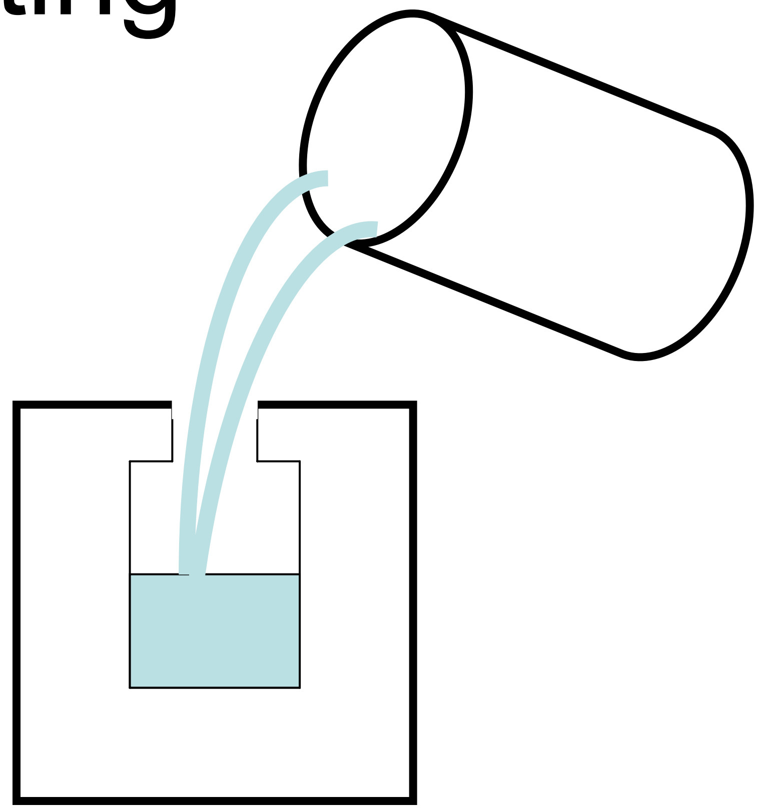
Ancient Greece; bronze statue casting circa 450BC

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

Outline

- Sand Casting, Investment Casting, Die Casting
- Basics and countermeasures
- Phase Change, Shrinkage
- Heat Transfer
- Pattern Design
- Variations & Developments
- Environmental Issues

Casting

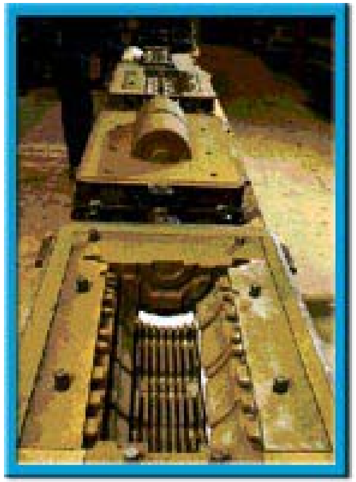


Readings;

1. *Kalpakjian, Chapters 10, 11, 12*
2. *Booothroyd, "Design for Die Casting"*
3. *Flemings "Heat Flow in Solidification"*

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

Casting Methods

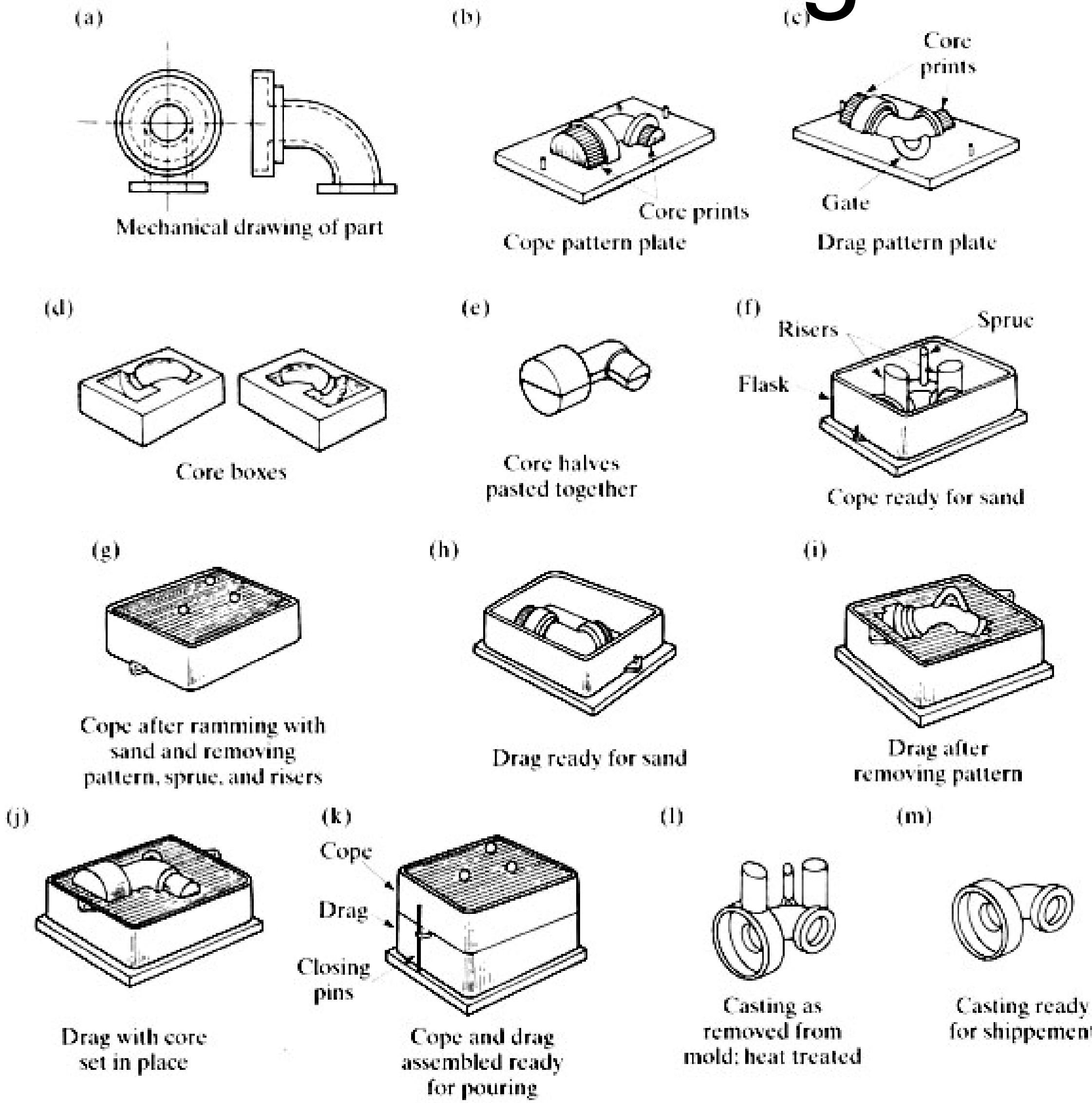


• Sand Casting
High Temperature Alloy,
Complex Geometry,
Rough Surface Finish

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

• Die Casting
High Temperature Alloy,
Moderate Geometry,
Smooth Surface

Sand Casting



Sand Casting

Description: Tempered sand is packed into wood or metal pattern halves, removed form 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)

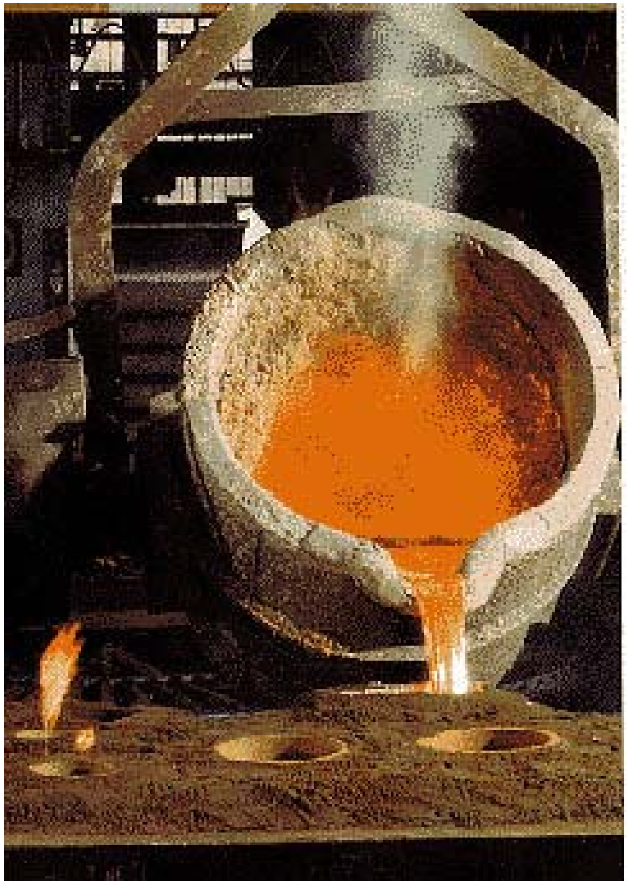
Surface Finish:
- Non-Ferrous: 150-350 RMS
- Ferrous: 300-700RMS

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

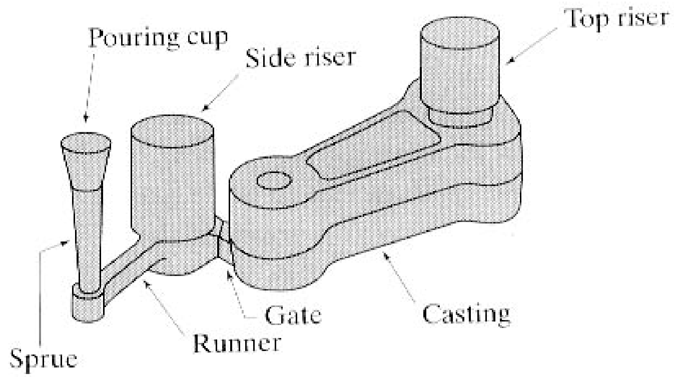


FIGURE 10.7 Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification. See also Fig. 11.4. *Source*: American Foundrymen's Society.

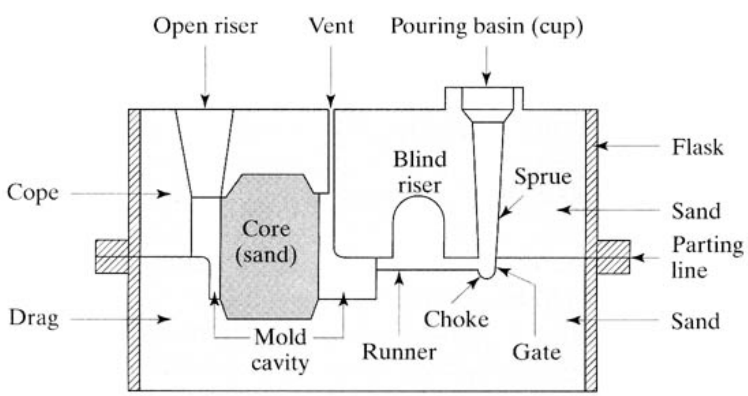


FIGURE 11.4 Schematic illustration of a sand mold, showing various features.

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.

See Video from Mass Foundry

Production sand casting

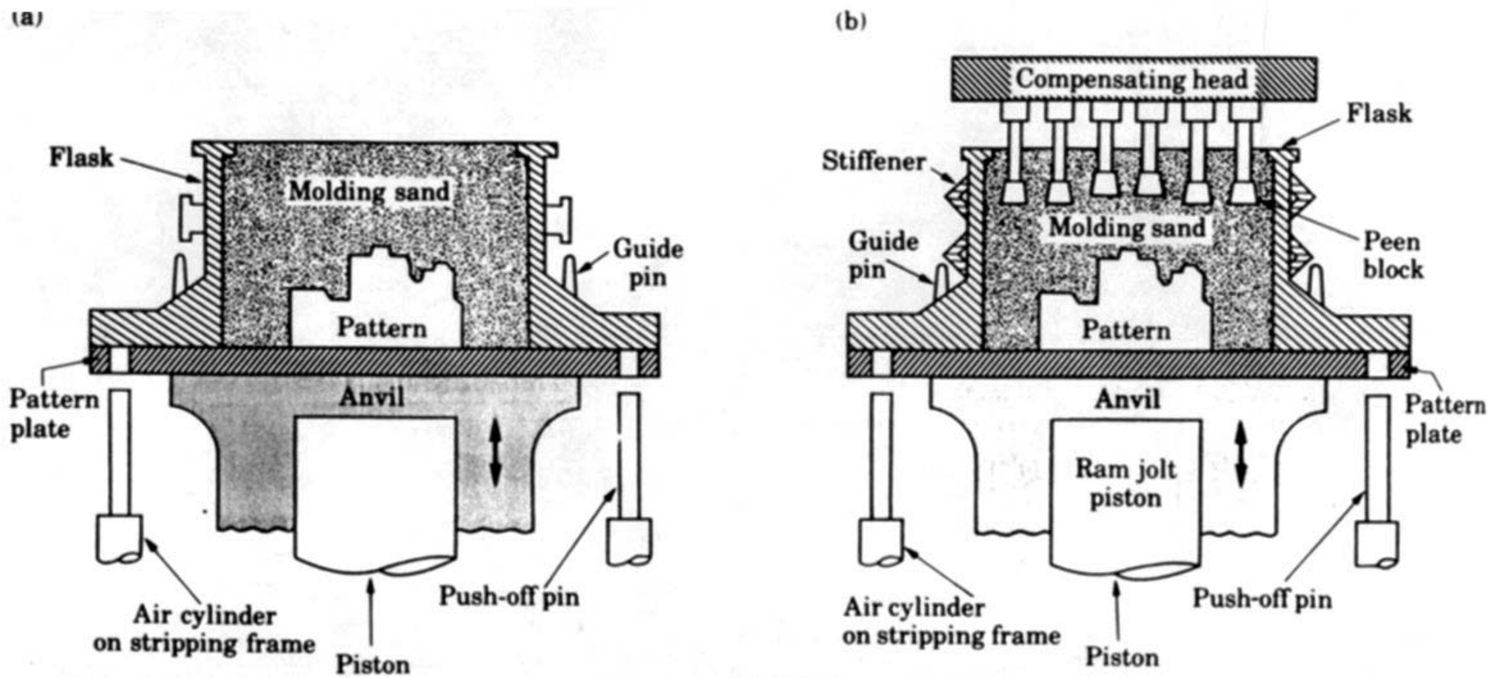


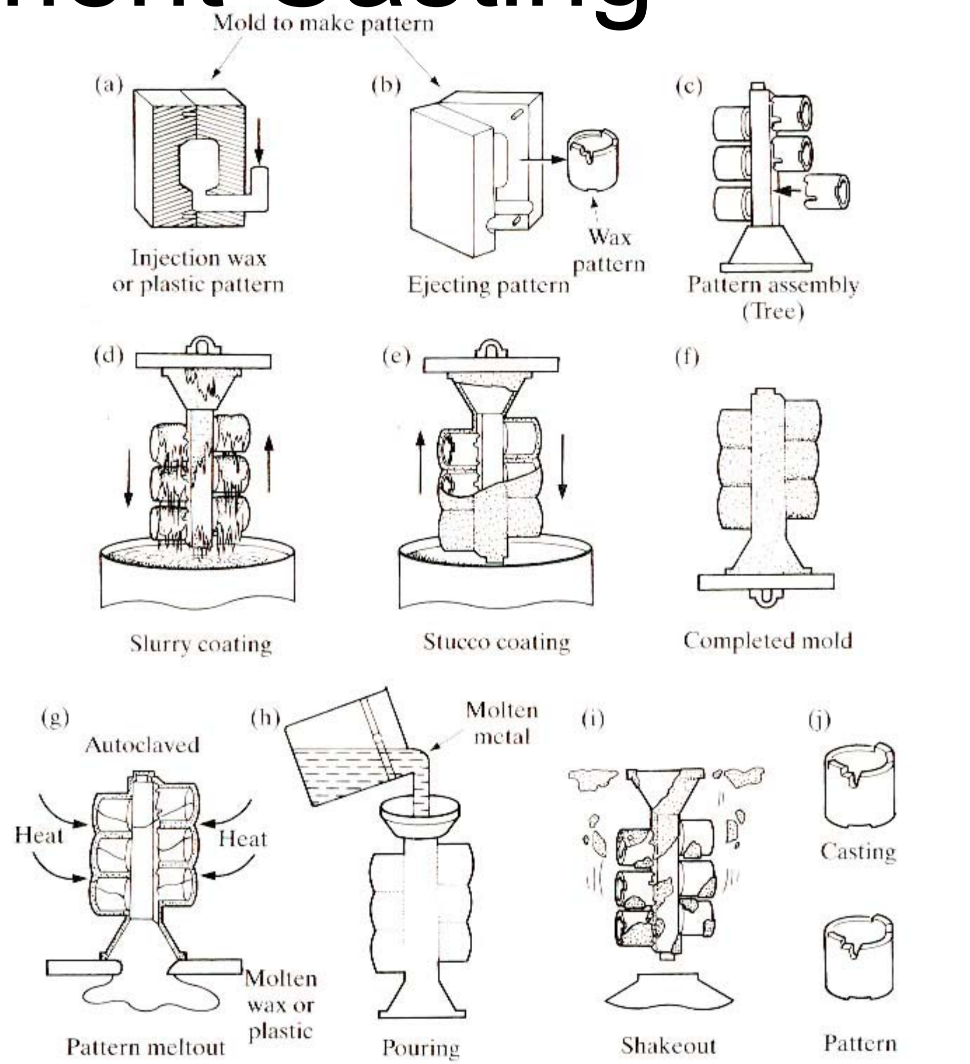
FIGURE 11.8

(a) Schematic illustration of a jolt-type mold-making machine. (b) Schematic illustration of a mold-making machine which combines jolting and squeezing.

Investment Casting

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.

FIGURE 11.18 Schematic illustration of investment casting (lost-wax process). Castings by this method can be made with very fine detail and from a variety of metals. Source: Steel Founders' Society of America.



Investment Casting

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

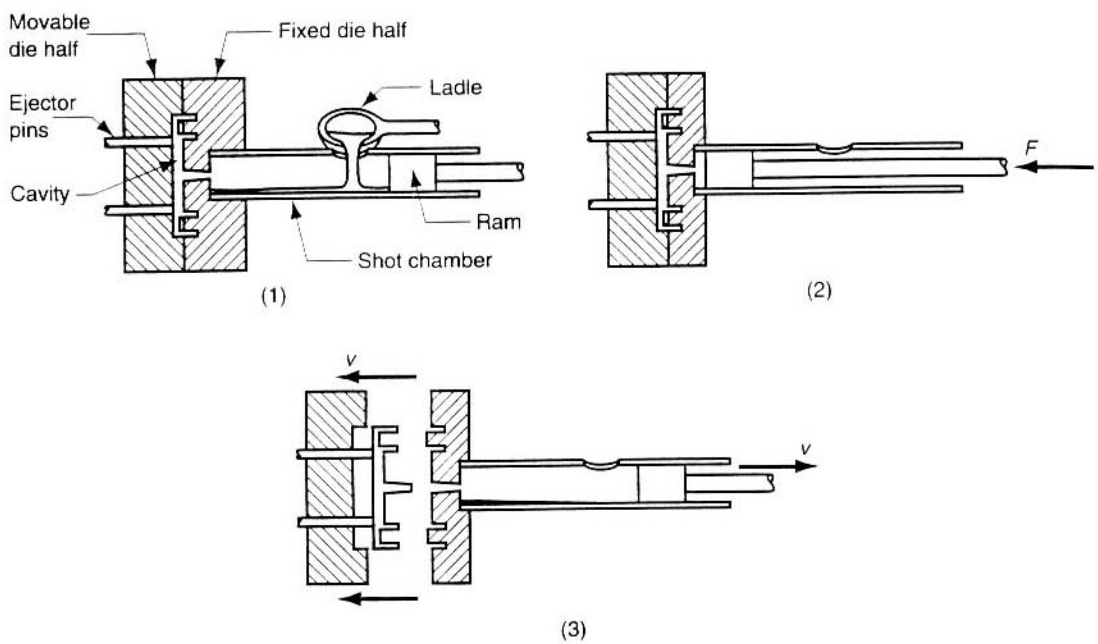
Normal Minimum Section Thickness:
- .030″ (Small Areas)
- .060″ (Large Areas)

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.

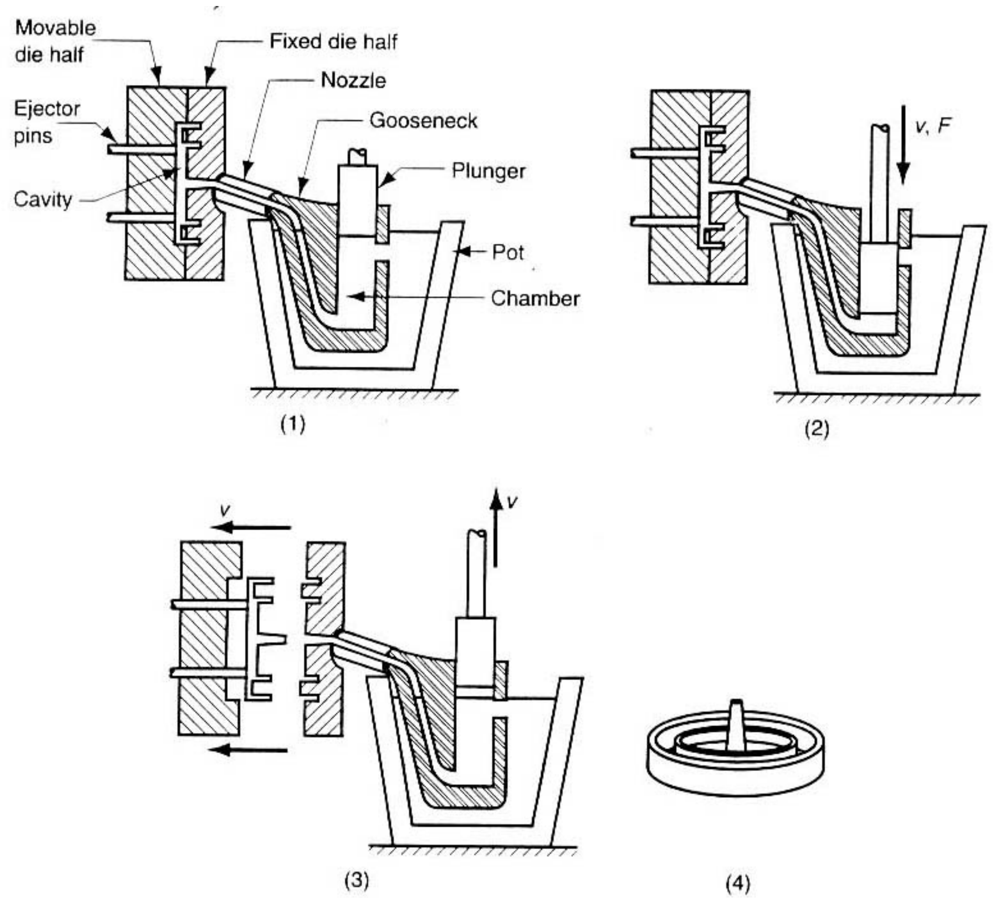
Die Casting – Cold-Chamber Casting



Cycle in cold-chamber casting: (1) with die closed and ram withdrawn, molten metal is poured into the chamber; (2) ram forces metal to flow into die, maintaining pressure during the cooling and solidification; and (3) ram is withdrawn, die is opened, and part is ejected. Used for higher temperature metals eg Aluminum, Copper and alloys

Die Casting – Hot-Chamber Casting

Cycle in hot-chamber casting: (1) with die closed and plunger withdrawn, molten metal flows into the chamber; (2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification; and (3) plunger is withdrawn, die is opened, and solidified part is ejected. Finished part is shown in (4).



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

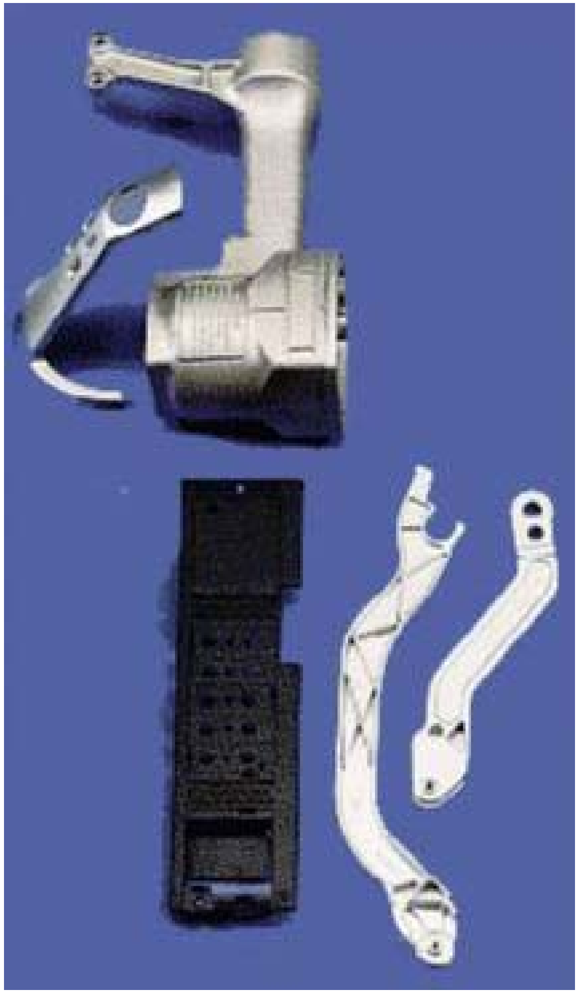
Surface Finish: 32-63RMS

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

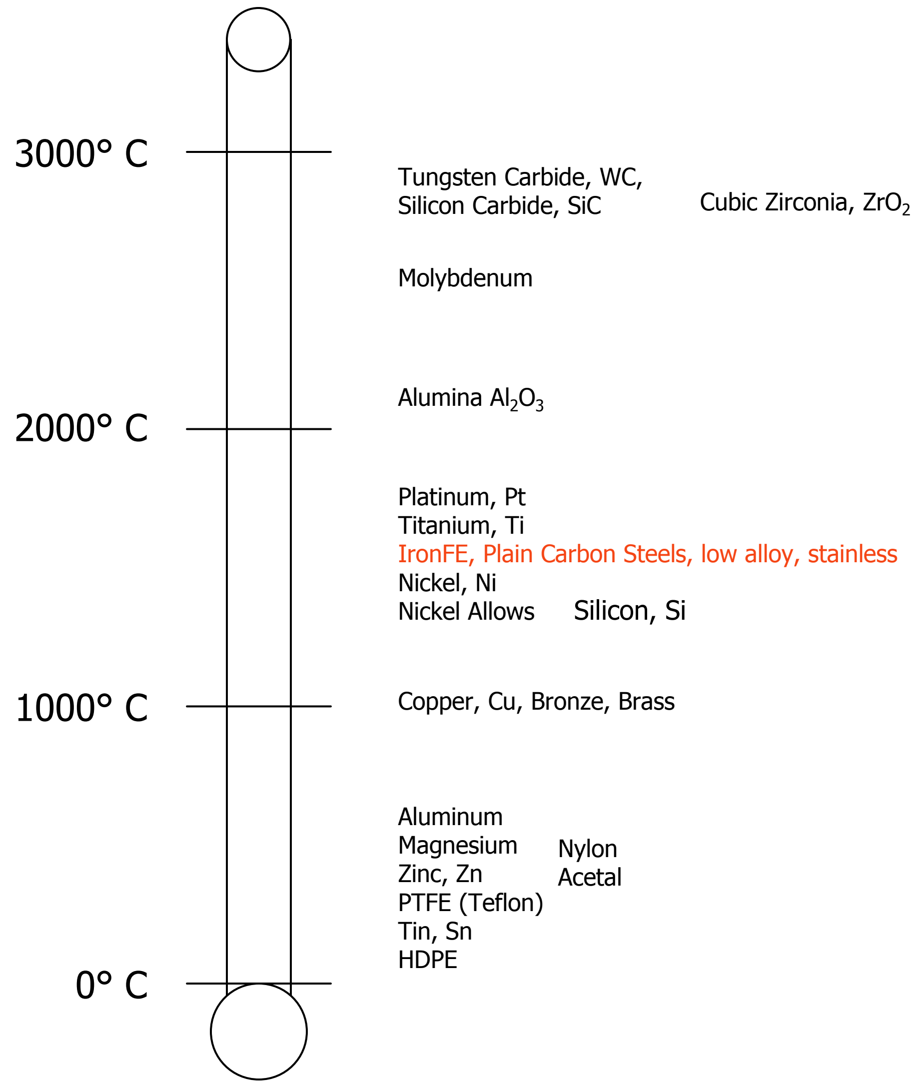
Ordering Quantities:
- Usually 2,500 and up.

Normal Lead Time:
- Samples: 12-20 weeks
- Production: ASAP after approval.



High Melt Temperature

- Chemical Activity
- High Latent Heat
- Handling
- Off-gassing



Mold Filling

Bernouli's Equation:

$$h + \frac{p}{pg} + \frac{v^2}{2g} = Const.$$

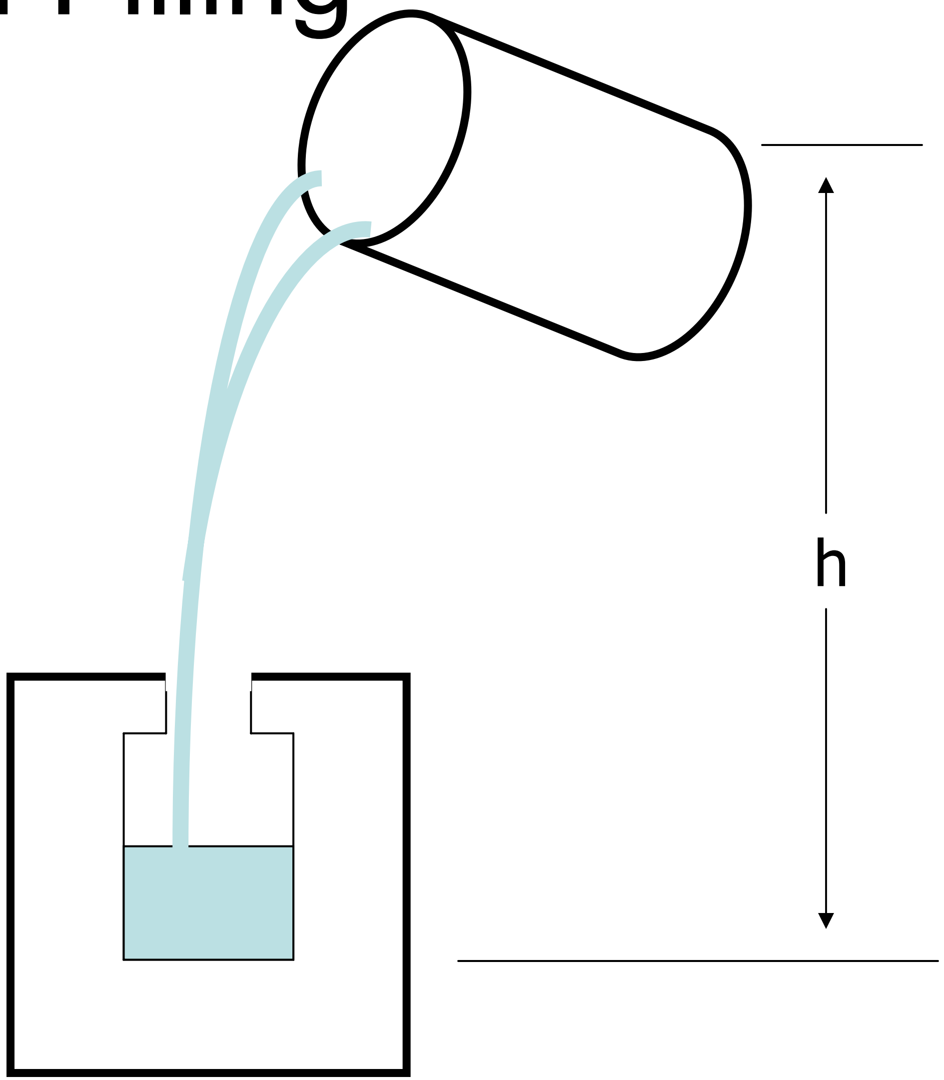
Reynold's Number:

$$\mathrm{Re} = \frac{vDP}{\mu}$$

•Short filling times

•Potential Turbulence

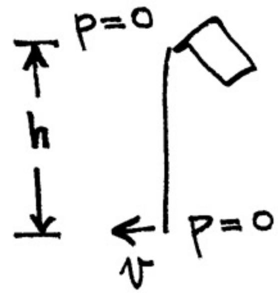
(see p. 273 … Kalpakjian



Mold Filling Example (1 of 2)

Mold Filling Example (order of magnitude)

from Bernoulli's Eq'n the inlet velocity can be estimated as:



$$v \cong \sqrt{2gh}$$

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

Mold Filling Example (2 of 2)

Calculate Reynold's Number

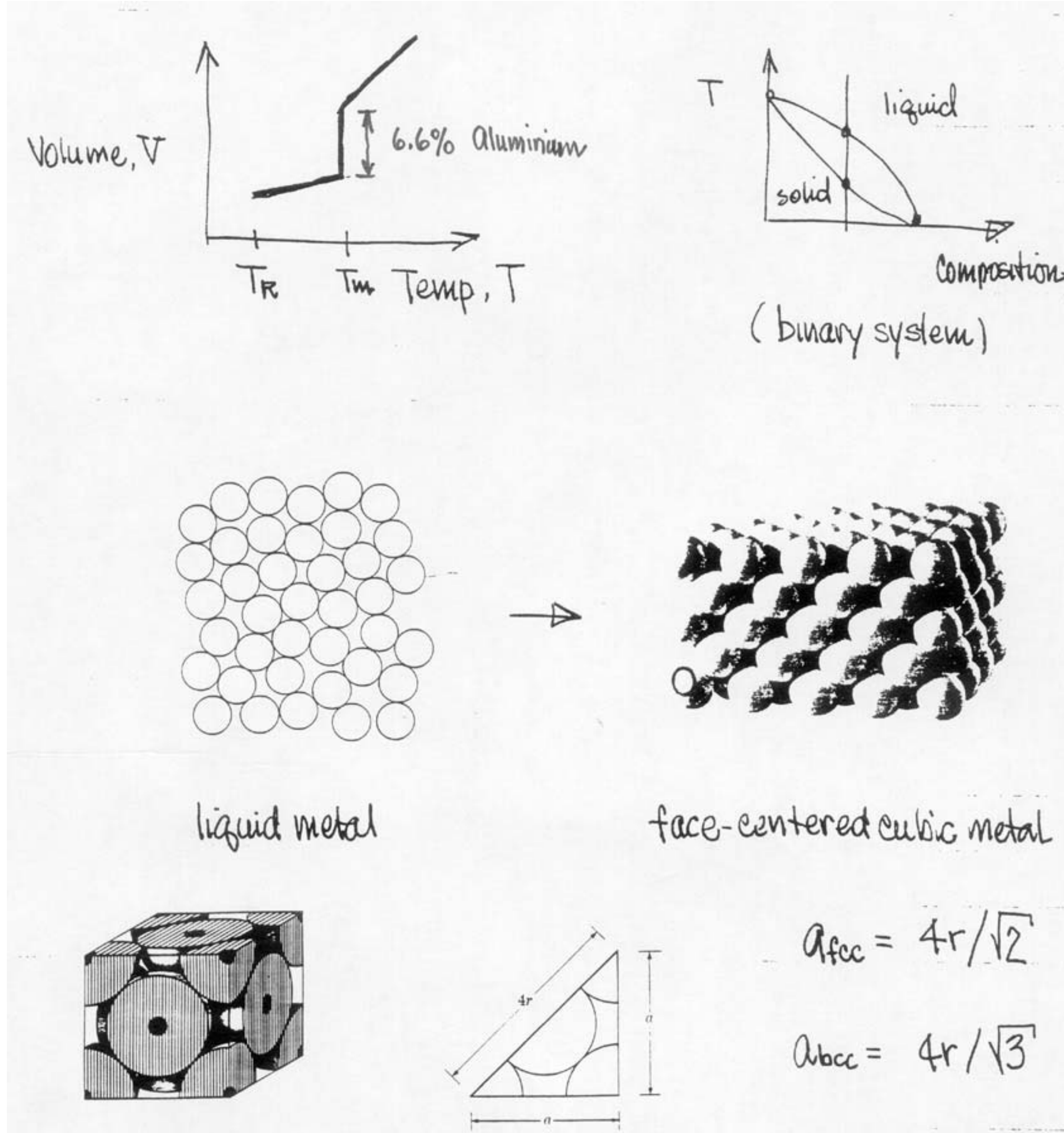
$$Re = \frac{v D \rho}{\mu} = \frac{1.4 \frac{m}{s} \times .5\,cm \times 3 \frac{gr}{cm^3}}{10^{-3} \frac{N}{m^2} \cdot s}$$ (like H_2O)

Re = 21,000 turbulence!

air entrainment, reaction with air – oxides, "dross"…. BAD!

Runner system design (Sprue, Runner, Gate, …) + Filters

Phase Change & Shrinkage



Solidification of a binary alloy

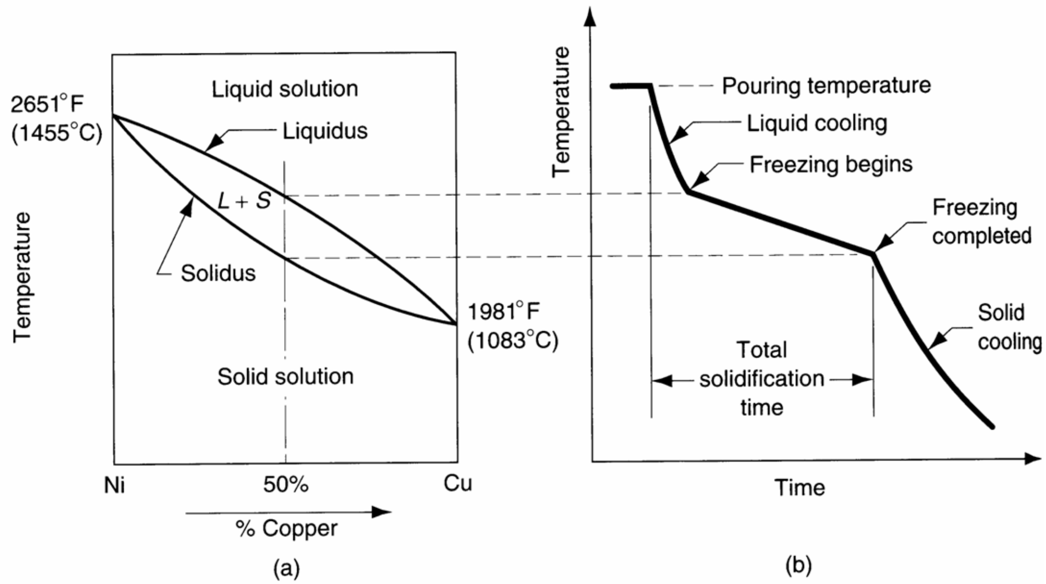


FIGURE 12.5 (a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.

Composition change during solidification

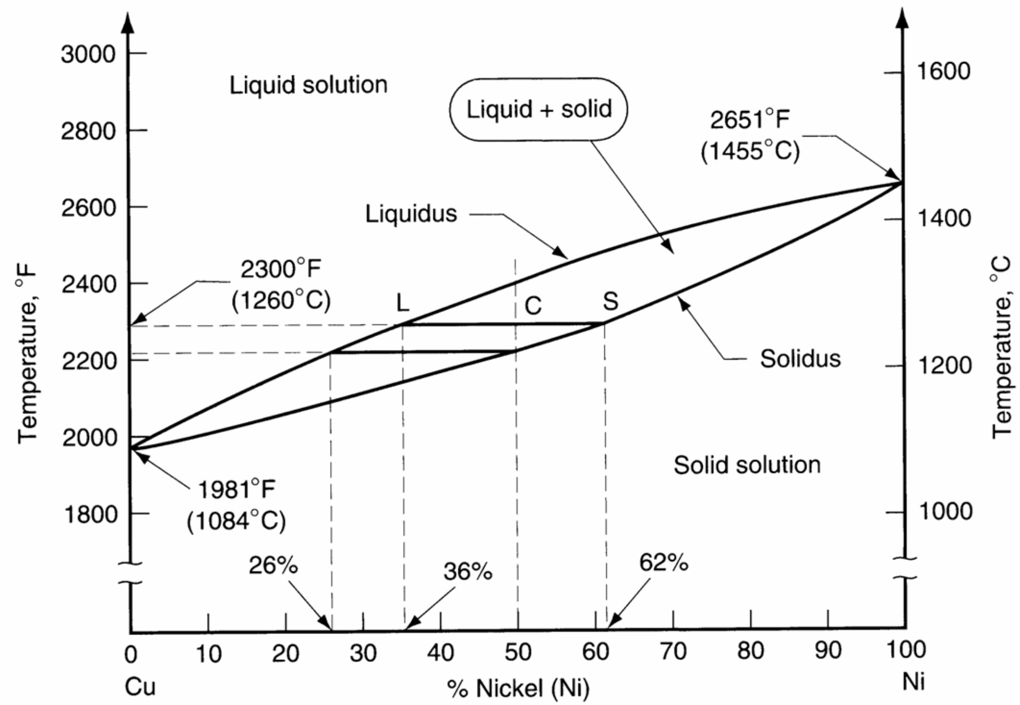


FIGURE 7.2 Phase diagram for the copper–nickel alloy system.

Solidification

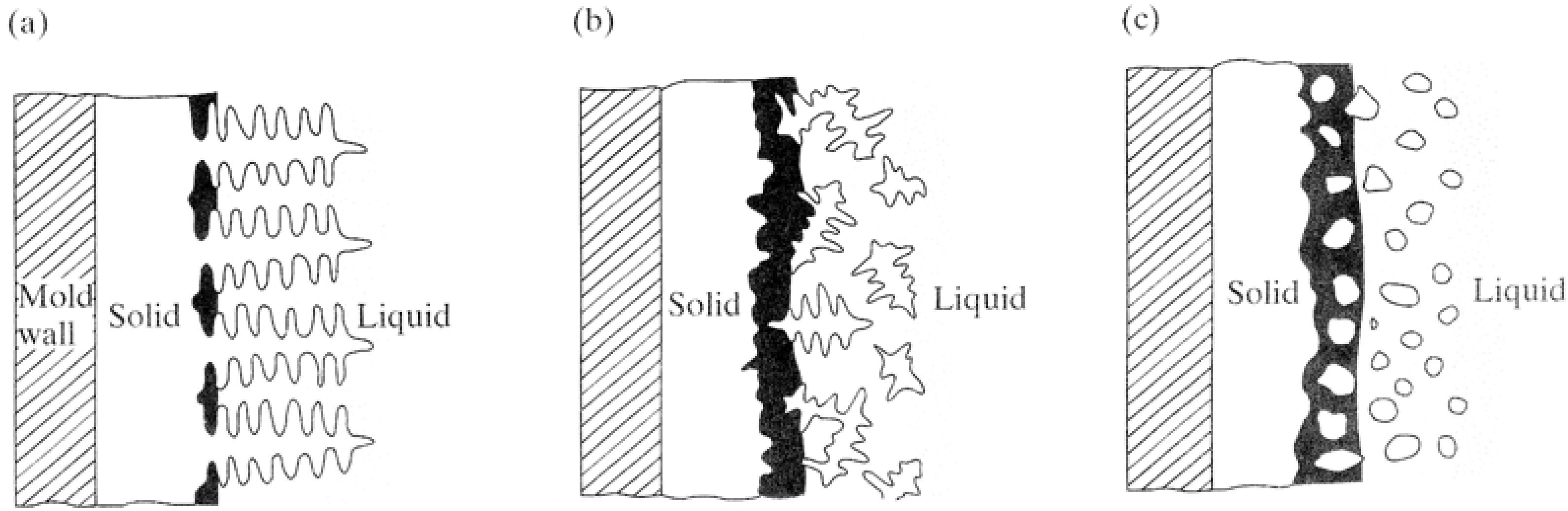
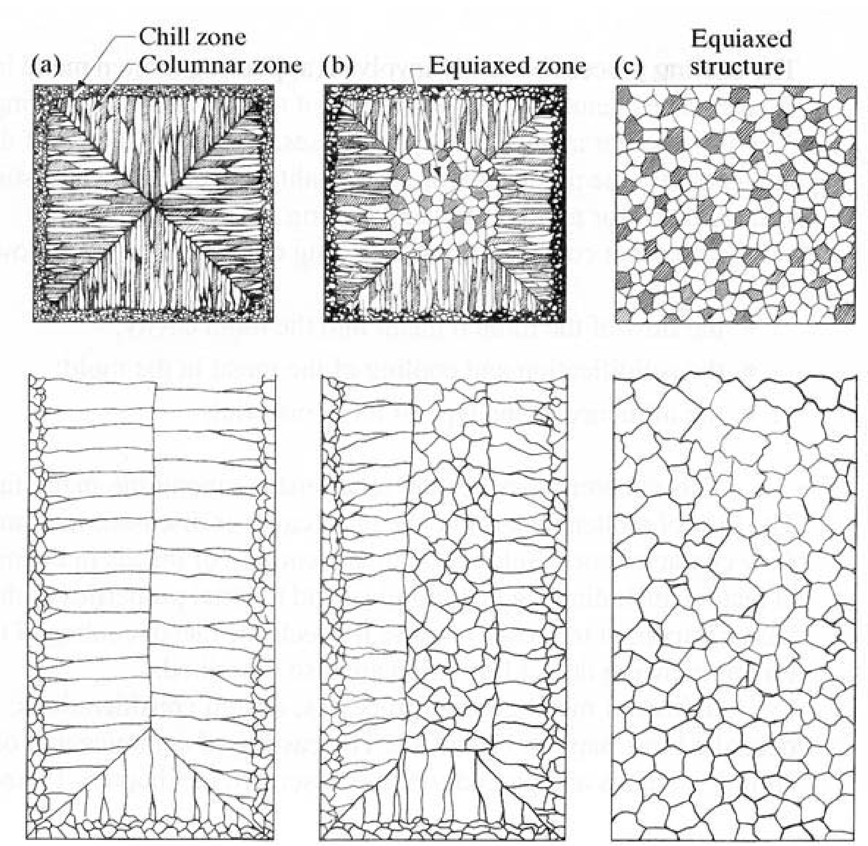


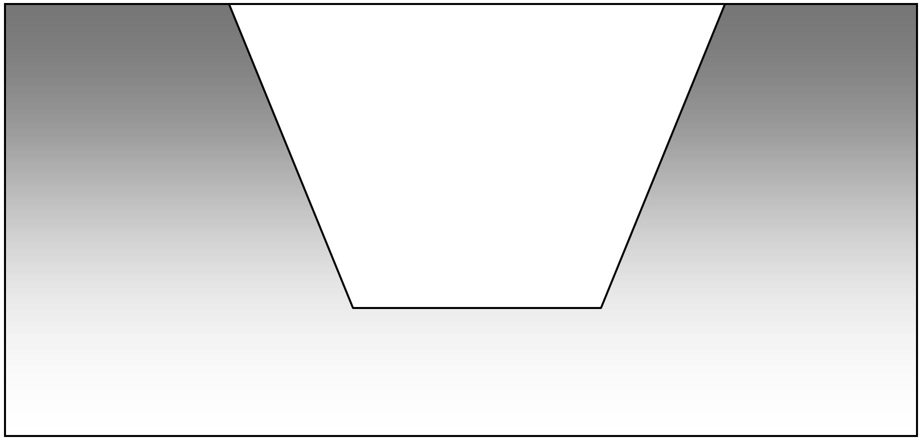
FIGURE 10.5 Schematic illustration of three basic types of cast structures:(a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source*: D. Apelian.

Cast structures

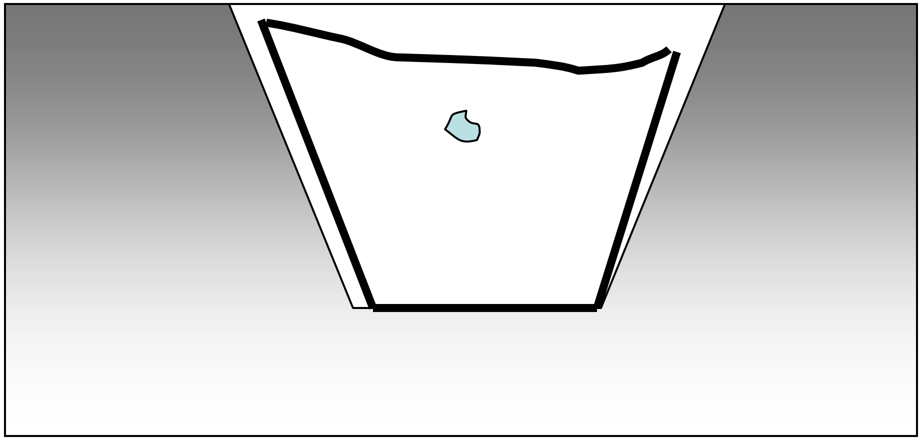


Schematic illustration of three cast structures solidified in a square mold: (a) pure metals; (b) solid solution alloys; and © structure obtained by using nucleating agents. *Source*: G. W. Form, J. F. Wallace, and A. Cibula

Pop quiz; If you top fill the mold below, what will the part look like after solidification?



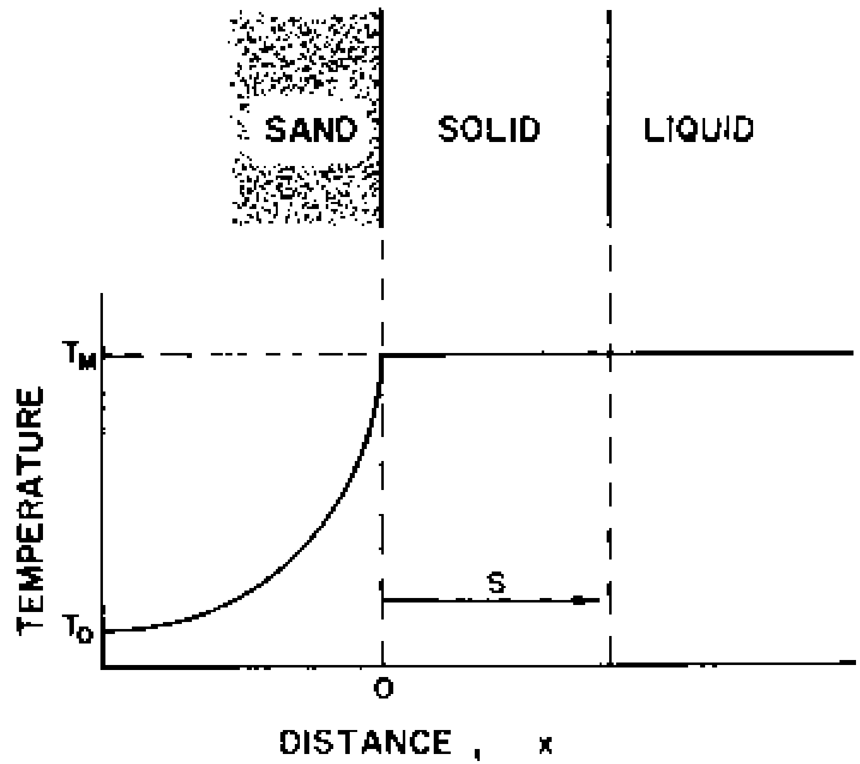
Can you explain these features?



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.



Heat Transfer – Die Casting

$$t_s \approx \left(\frac{V}{A}\right)^1$$

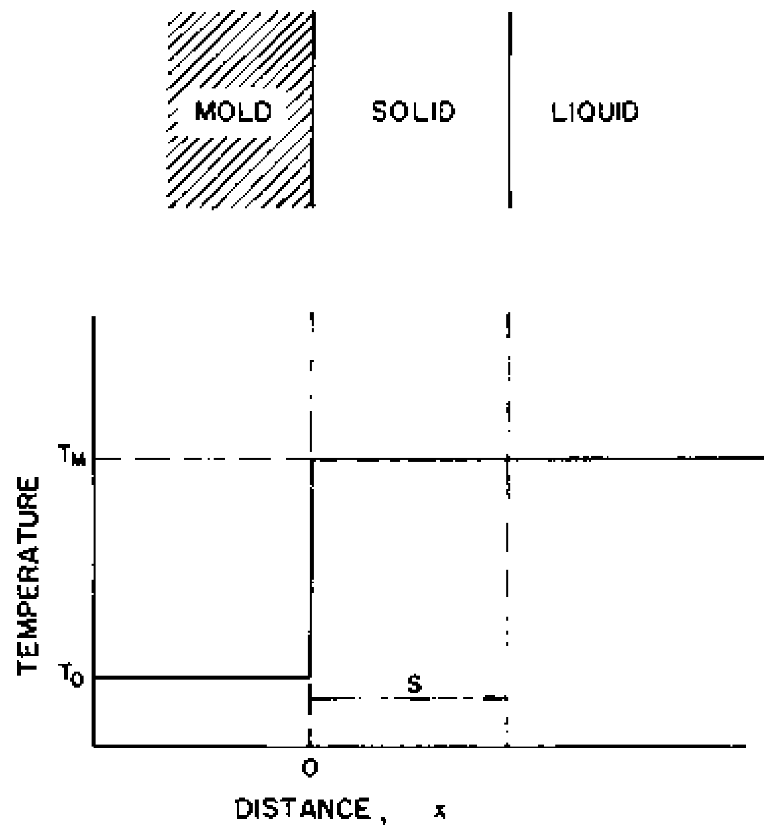
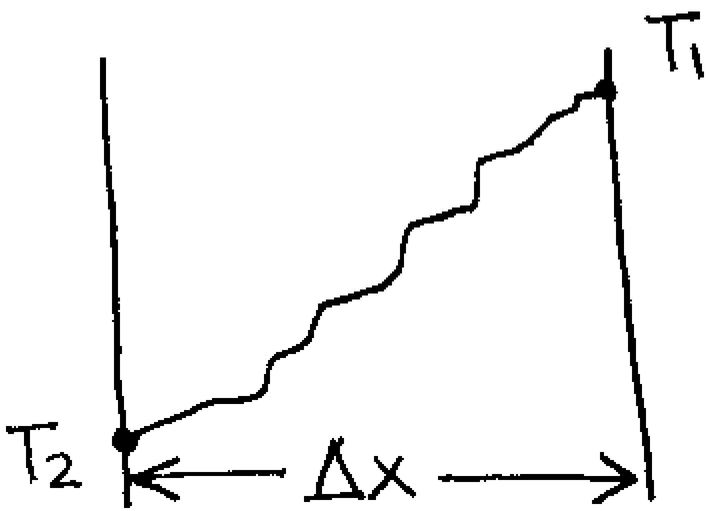


FIGURE 1-9
Temperature profile during solidification against a large flat mold wall with mold-metal interface resistance controlling.

Steady State Conduction Heat Transfer

Figure 1

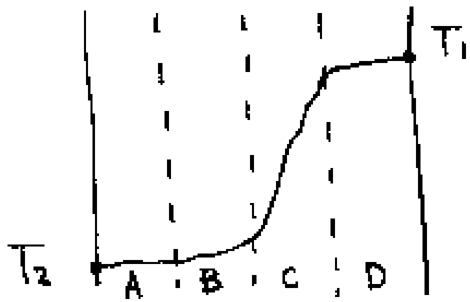


$$q = -k \frac{T_1 - T_2}{\Delta x}$$

Fourier's Law

Steady State Conduction Heat Transfer

Figure 2



Define thermal resistance

$$R_i = \frac{\Delta x_i}{k_i}$$

In steady-state $q_A = q_B = q_C = q_D = q$,

hence for each layer (large ΔT_i implies a large ΔR_i and vice versa)

$$\frac{\Delta T_i}{R_i} = q = \text{Constant}$$

Since $\Delta T = \sum \Delta T_i \Rightarrow$ Requivalent $\doteq$ $R_{eq} = \sum R_i$

i.e. $q = \Delta T / R_{eq}$.

Hence, refering to Fig 2 $R_{eq} \simeq R_c \Rightarrow$

$$q \simeq \frac{\Delta T}{R_c}.$$

Thermal Conductivity "k" of Various Materials for Parts and Molds (W/m °K)

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

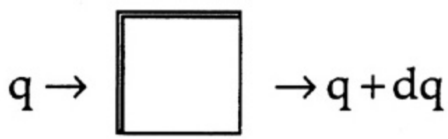
$$q = -k \frac{dT}{dx}$$

Film Coefficients W/m²°K

Typical die casting	5,000
Natural convection	1 - 10
Flowing air	10 - 50

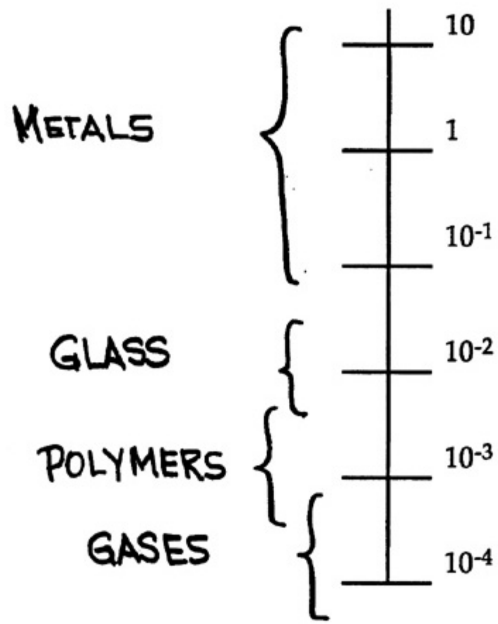
$$q = -h(\Delta T)$$

Transient Heat Transfer



$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

$$k \neq k(x)$$



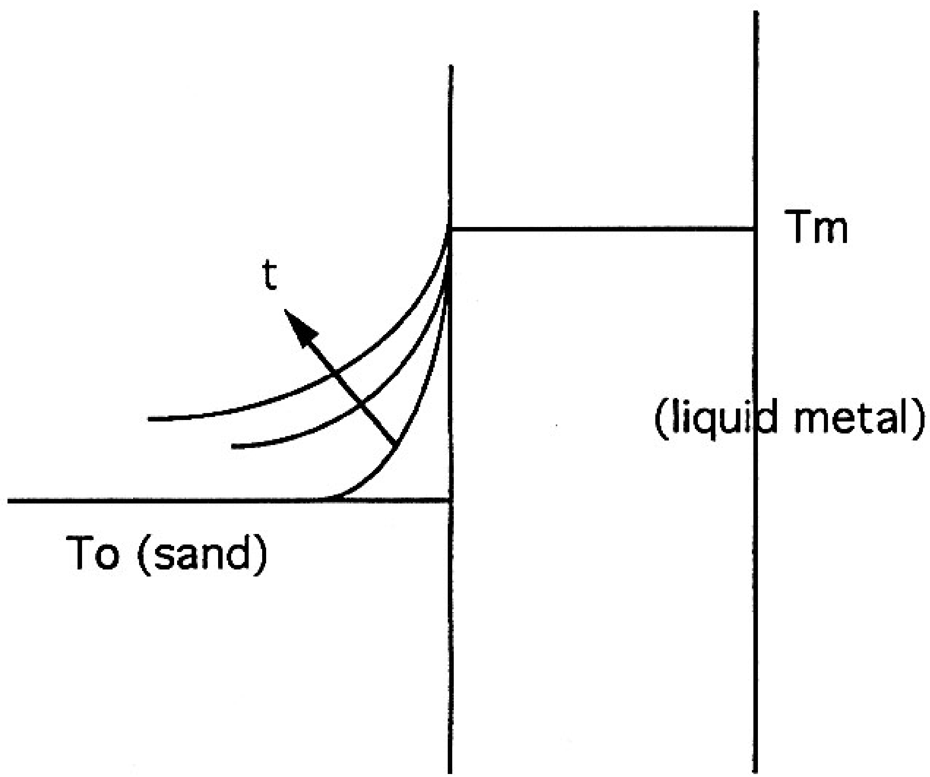
$$\alpha \left[\frac{cm^2}{sec}\right]$$

$$\alpha = \frac{k}{\rho C_p}$$

Sand Casting (see Flemings)

Define new variable $\zeta = x / \sqrt{\alpha t}$

Use $\theta = \dfrac{T - T_M}{T_o - T_M}$



Sand Casting (see Flemings)

Ordinary differential eq'u

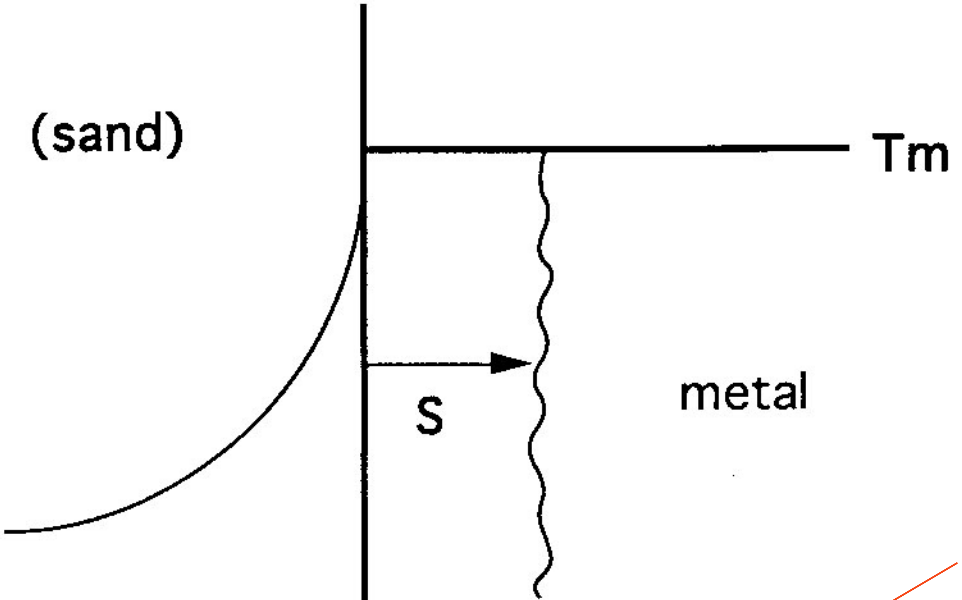
$$\frac{d^2\theta}{d\zeta^2} = -\frac{\zeta}{2}\frac{d\theta}{d\zeta}$$

i.c. $\theta = 1$ at $\zeta = \infty$

b.c. $\theta = 0$ at $\zeta = 0$

$$\boxed{\theta = \operatorname{erf}\left(-\frac{\zeta}{2}\right)}$$

Solidification Time



enthapy

Heat required to solidify to distance "s"

$$= A \cdot s \cdot \rho \cdot H$$

Use Flemings result here

Rate eq'n (per unit area)

$$\rho H \frac{ds}{dt} = -\dot{q} = k\left(\frac{\partial T}{\partial x}\right)_{x=0}$$

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 $s = \frac{V}{A}$

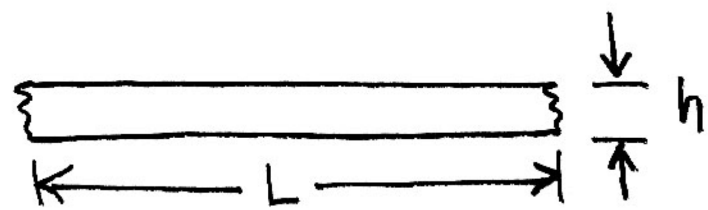
$$\boxed{t = C\left(\frac{V}{A}\right)^2}$$

Chvorinov's rule

Cooling Time; thin slab

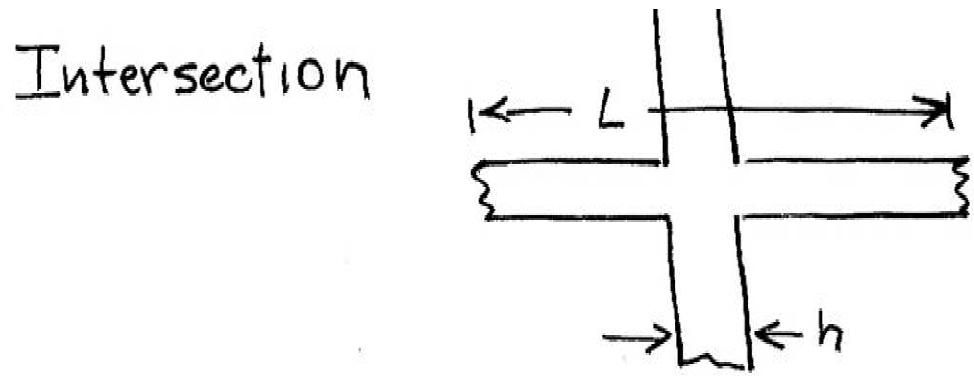
$$\text{Cooling Time} = f\left(\frac{V}{A}\right)$$

Slab



$$\frac{V}{A} = \frac{L \times h \times 1}{2 \times L \times 1} = \frac{h}{2}$$

Cooling time;intersection



$$\frac{V}{A}=\frac{h}{2}\left[1+\frac{1}{2}\left(\frac{1}{\frac{L}{h}-1}\right)\right]$$

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.)

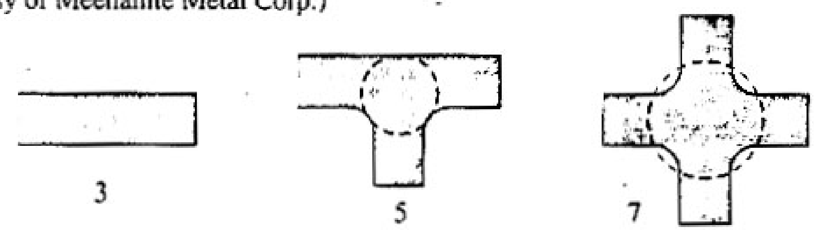


Figure 7.2.25 Examples of relative cooling times. (Courtesy of Meehanite Metal Corp.)

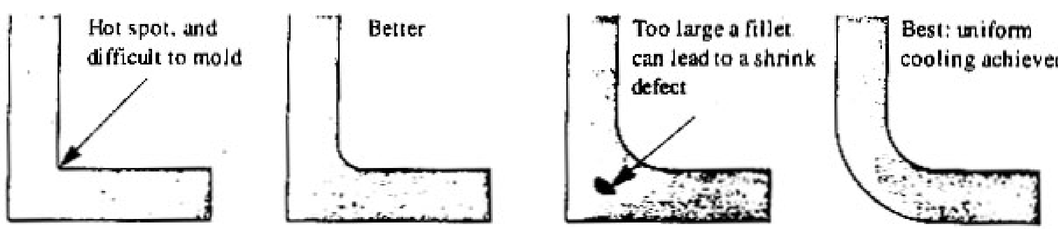


Figure 7.2.26 Fillet all sharp angles. (Courtesy of Meehanite Metal Corp.)

More Pattern Design suggestions

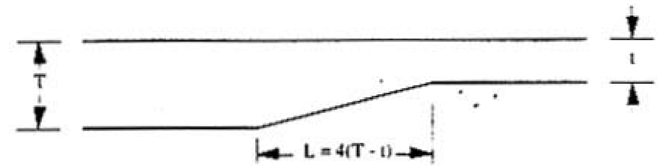


Figure 7.2.28 Avoid abrupt section changes. (Courtesy of Meehanite Metal Corp.)

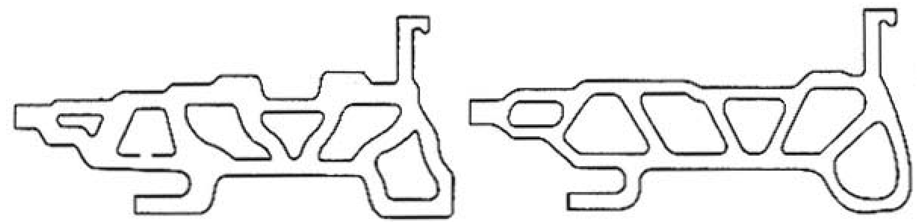


Figure 7.2.29 Design for uniform thickness in sections. (Courtesy of Meehanite Metal Corp.)

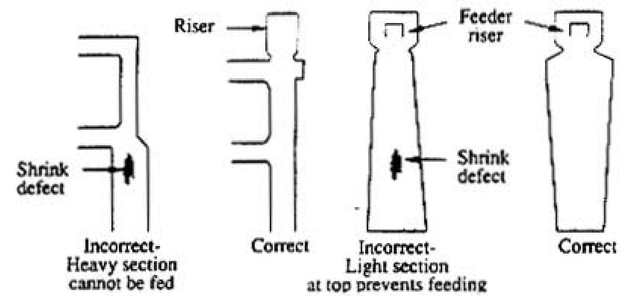


Figure 7.2.30 More intersection details. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.31 Design for bolting or bearing bosses. (Courtesy of Meehanite Metal Corp.)

And more…

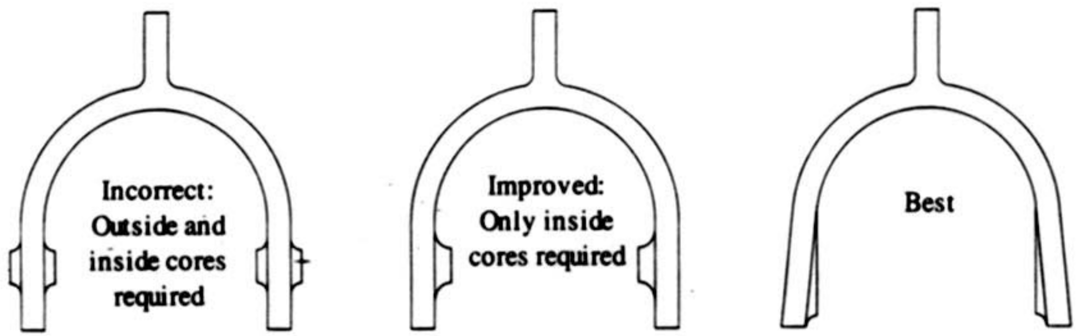


Figure 7.2.32
Omit outside bosses and the need for cores. (Courtesy of Meehanite Metal Corp.)

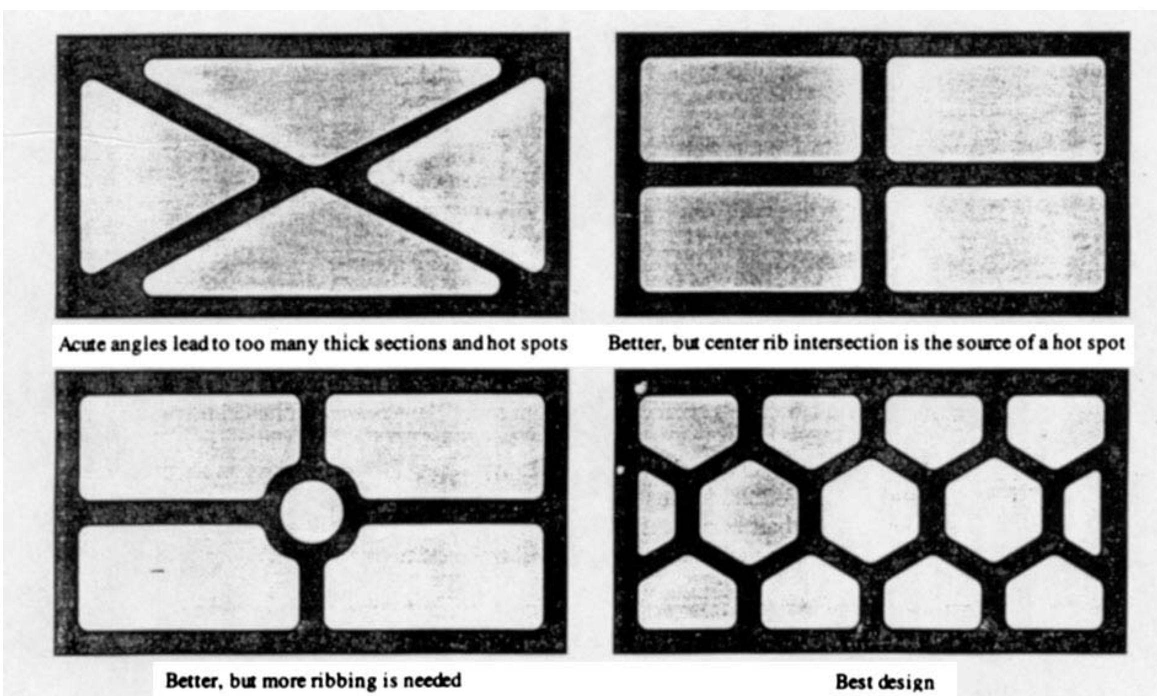
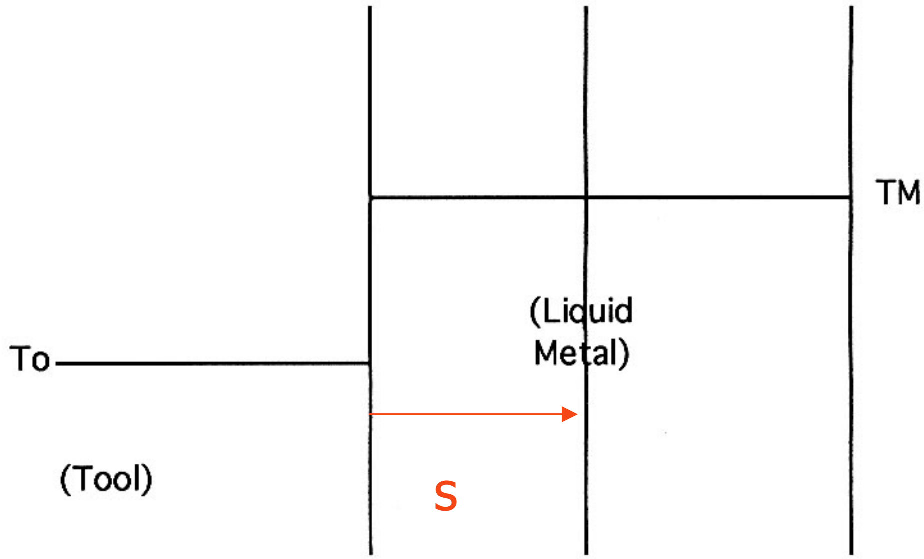


Figure 7.2.35
Avoid using ribs which meet at acute angles. (Courtesy of Meehanite Metal Corp.)

Die Casting Solidification Time



Time to form solid part

$$\dot{q} = -\bar{h}A(T_M - T_o) = \rho_M H_M A \frac{ds}{dt}$$

$$\boxed{t = \frac{\rho_M H_M}{\bar{h}(T_M - T_o)} \frac{V}{A}}$$

Also need to cool casting to below T_M

to eject $\rightarrow T_{eject}$

and will inject at $T_{inject} > T_M$.

Time to cool part to the ejection temperature. (lumped parameter model)

$$mC_p \frac{dT}{dt} = -Ah\left(T - T_o\right)$$

let $\theta = T - T_o$

$$\int_{\theta_f}^{\theta_i} \left(\frac{d\theta}{\theta}\right) = -\int_{ti}^{tf} \frac{Ah}{mC_p} dt$$

$\Delta\theta_i = T_i + \Delta T_{sp} - T_{mold}$

$\Delta T_{sp} = H/Cp$

$\Delta\theta_f = T_{eject} - T_{mold}$

Integration yields…

$$t = \frac{-mC_p}{Ah} \ln \frac{\Delta\theta_f}{\Delta\theta_i}$$

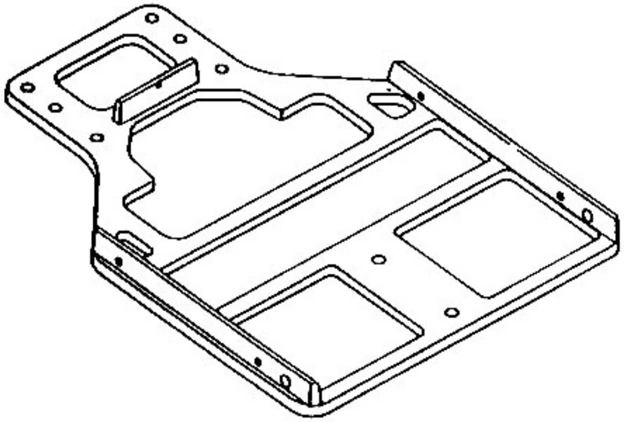
Or for thin sheets of thickness "w",

$$t = \frac{w\rho C_p}{2h} \ln\left(\frac{T_{inject} + \Delta T_{sp} - T_{mold}}{T_{eject} - T_{mold}}\right)$$

"sp" means superheat

Pattern Design Issues (Alum)

- Shrinkage Allowance .013/1
- Machining Allowance 1/16”
- Minimum thickness 3/16”
- Parting Line
- Draft Angle 3 to 5%
- Uniform Thickness



Pattern Design

Table 12.1

Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Metal	Percent
Gray cast iron	0.83 – 1.3
White cast iron	2.1
Malleable cast iron	0.78 – 1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Yellow brass	1.3 – 1.6
Phosphor bronze	1.0 – 1.6
Aluminum bronze	2.1
High-manganese steel	2.6

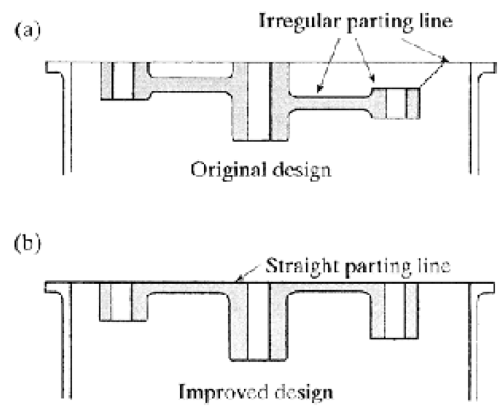
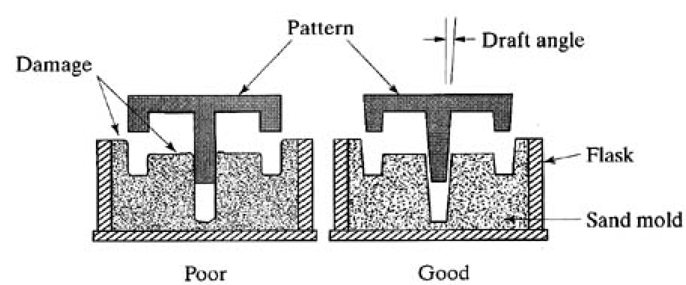


FIGURE 12.5 Redesign of a casting by making the parting line straight to avoid defects. *Source: Steel Casting Handbook*, 5th ed. Steel Founders' Society of America, 1980. Used with permission.

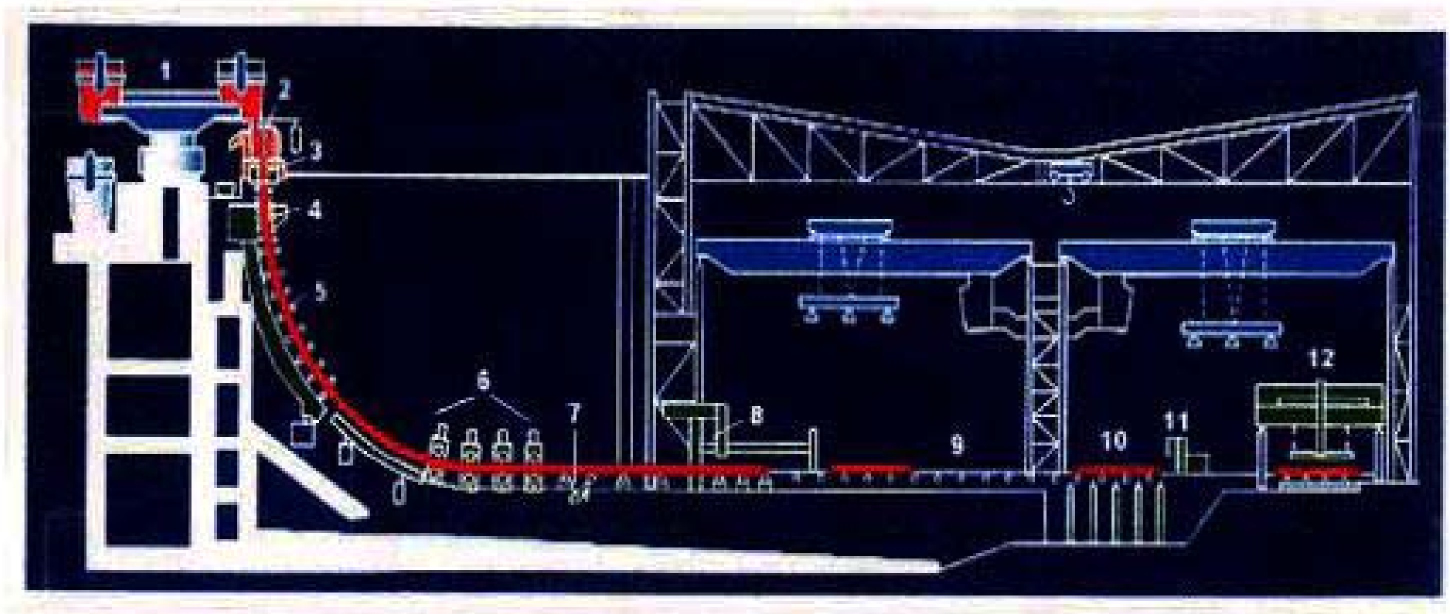
FIGURE 11.7 Taper on patterns for ease of removal from the sand mold.



Variations and Developments

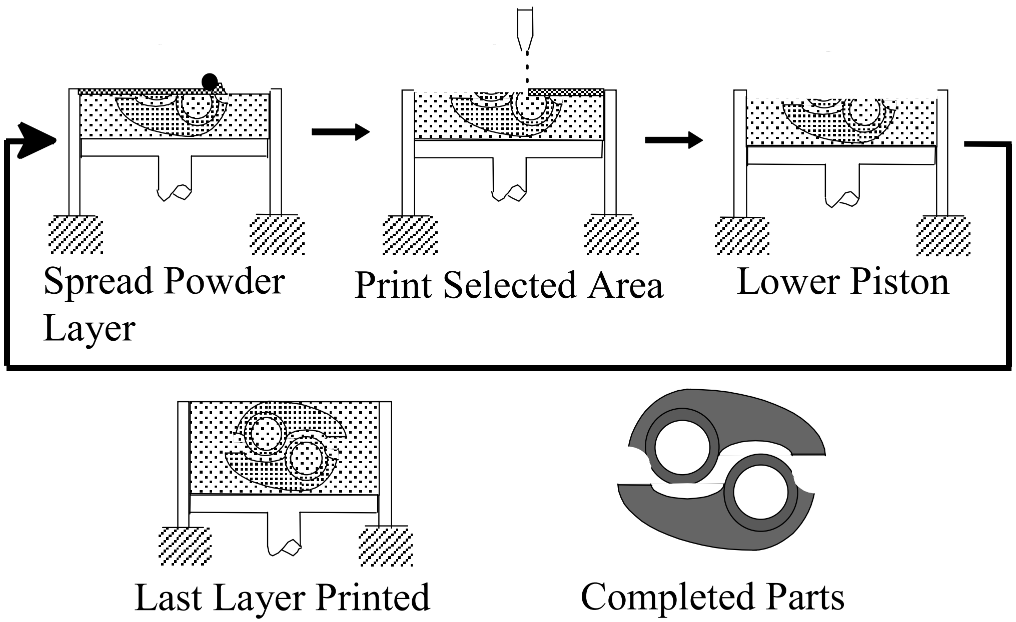
- Continuous casting
- Lost foam molding
- 3D Printing of Investment tooling
- Direct printing with metal droplets
- Uniform metal spray

Continuous casting ref AISI

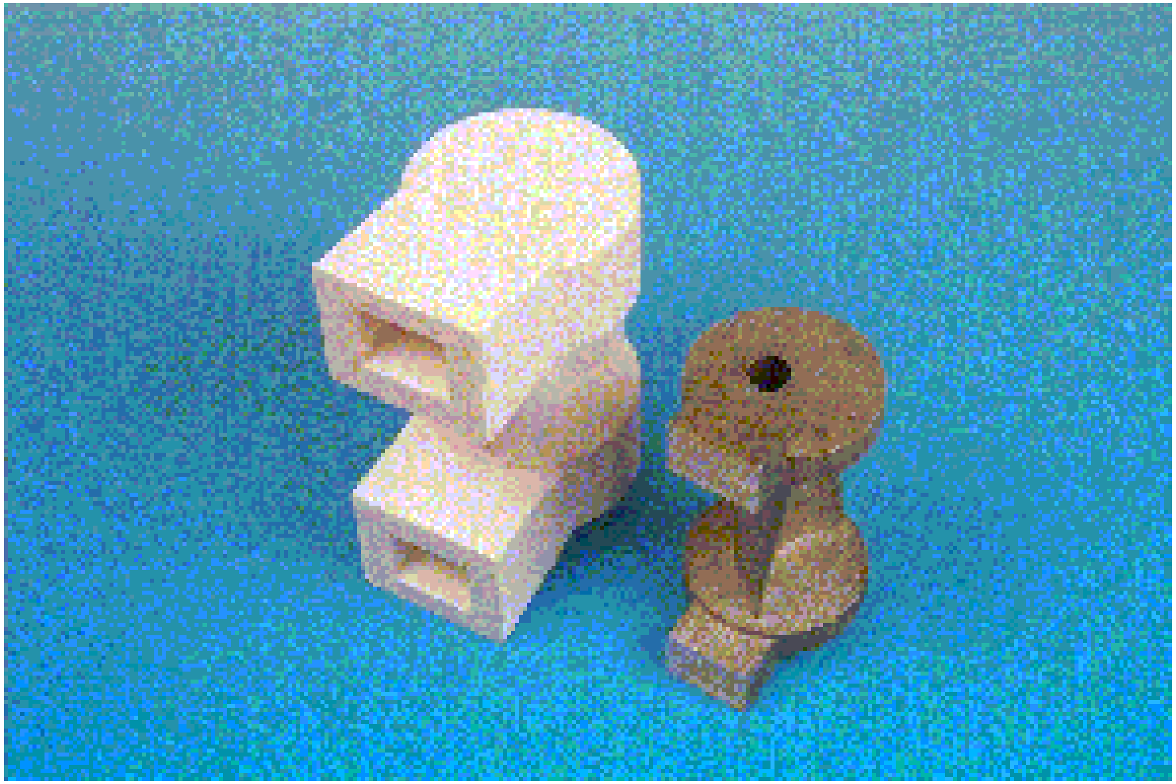


Steel from the electric or basic oxygen furnace is tapped into a ladle and taken to the continuous casting machine. The ladle is raised onto a turret that rotates the ladle into the casting position above the tundish. Referring to Figure 2, liquid steel flows out of the ladle (1) into the tundish (2), and then into a water-cooled copper mold (3). Solidification begins in the mold, and continues through the First Zone (4) and Strand Guide (5). In this configuration, the strand is straightened (6), torch-cut (8), then discharged (12) for intermediate storage or hot charged for finished rolling.

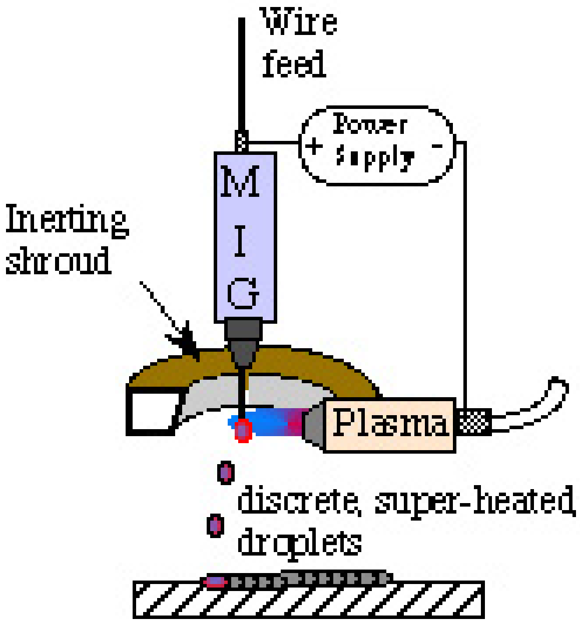
3D Printing of Investment cast tooling



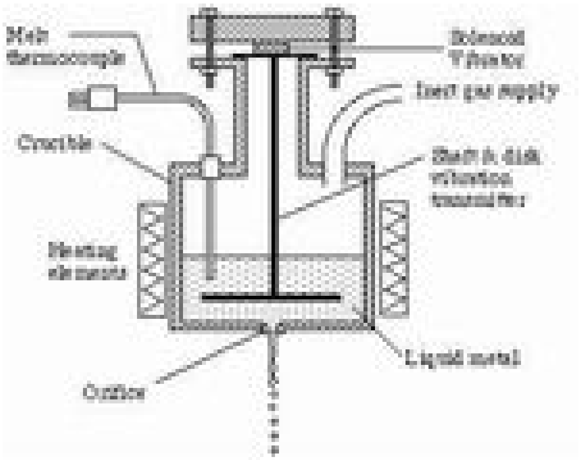
Shell and part (Turbine blade)



Microcasting of droplets



CMU



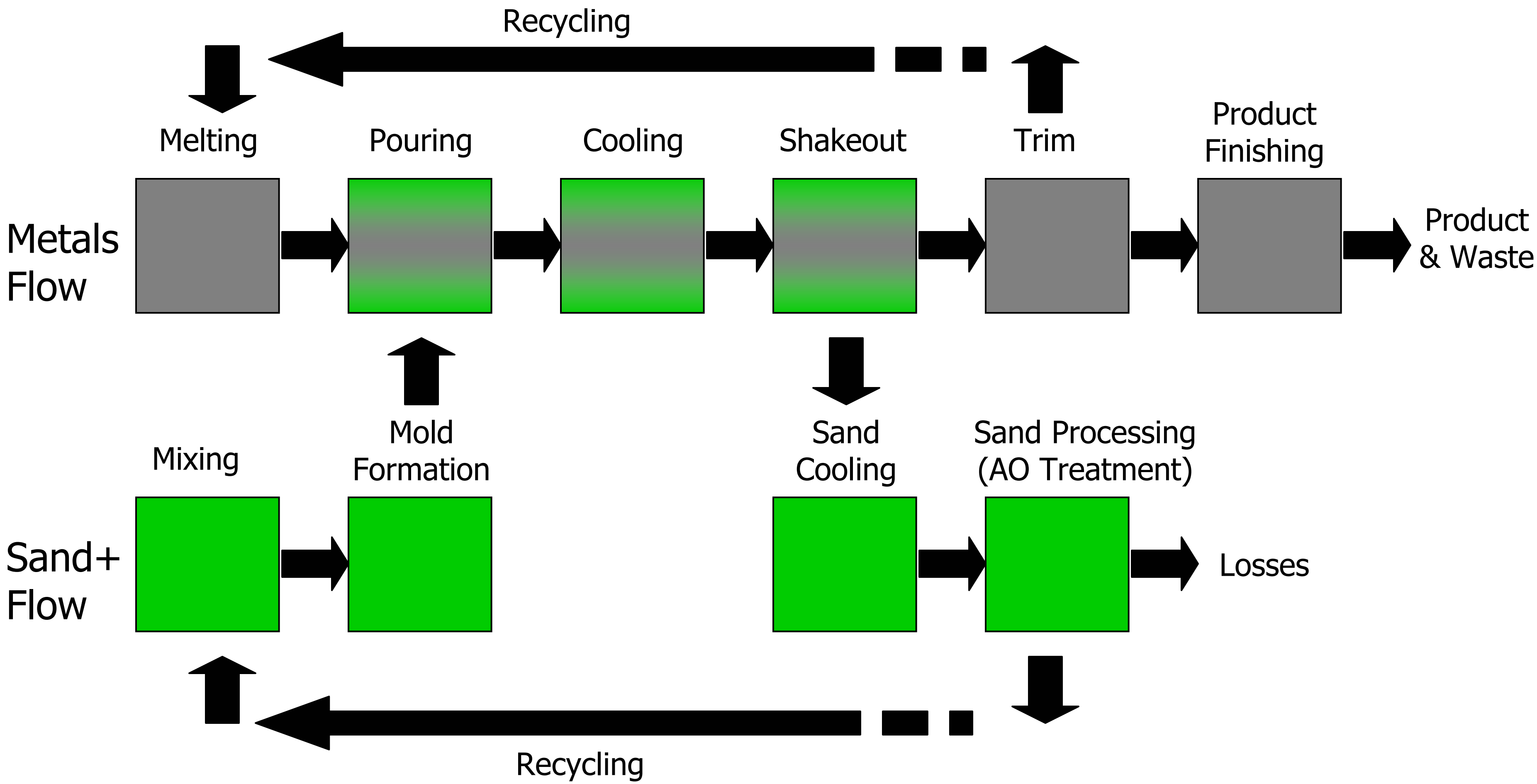
Crucible Assembly

MIT

Environmental Issues

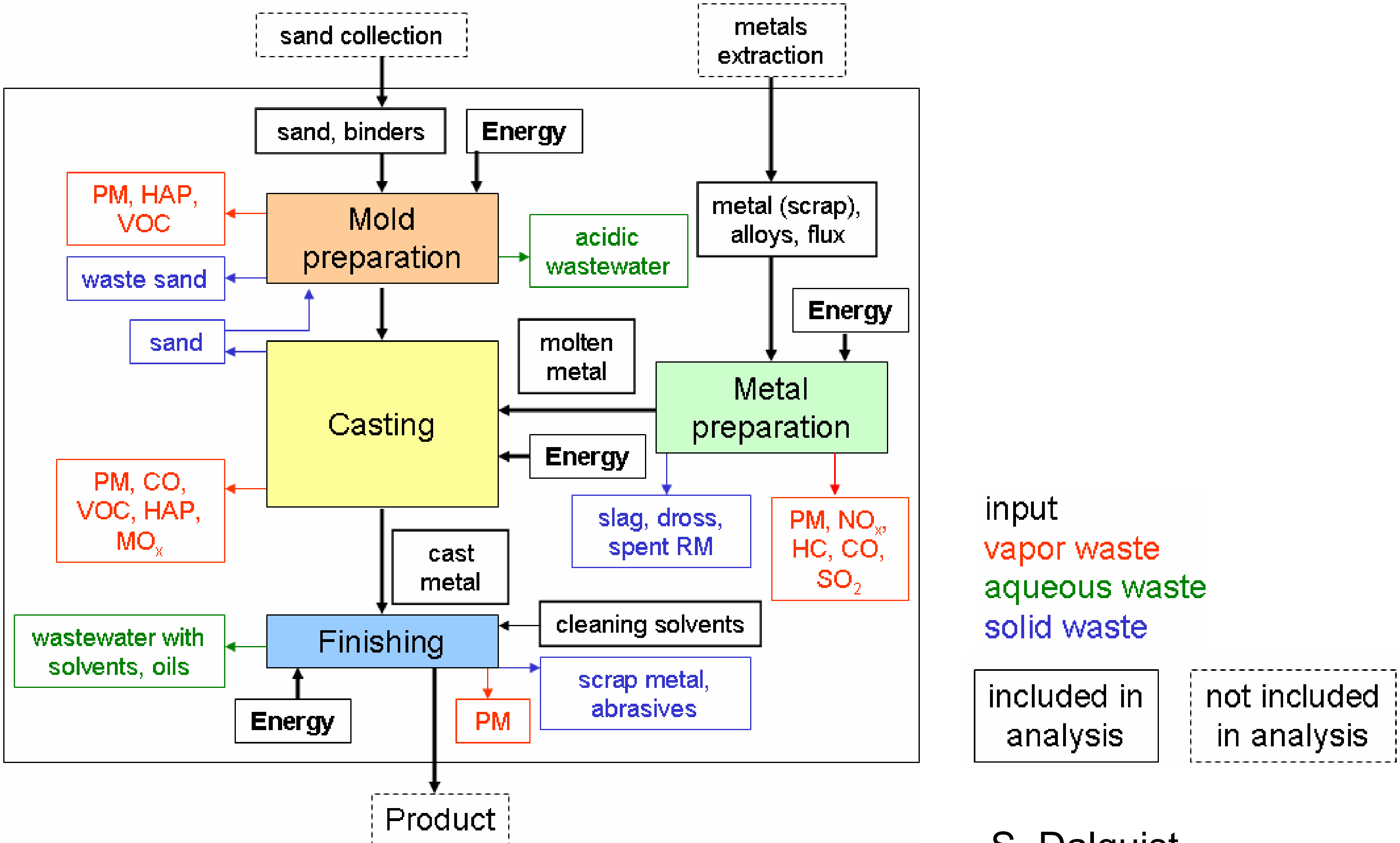
- Energy
- Materials
- Emission
- Off-gassing see AFS webpage on green sand emissions; http://www.afsinc.org/environmental.html

Process Material Flow



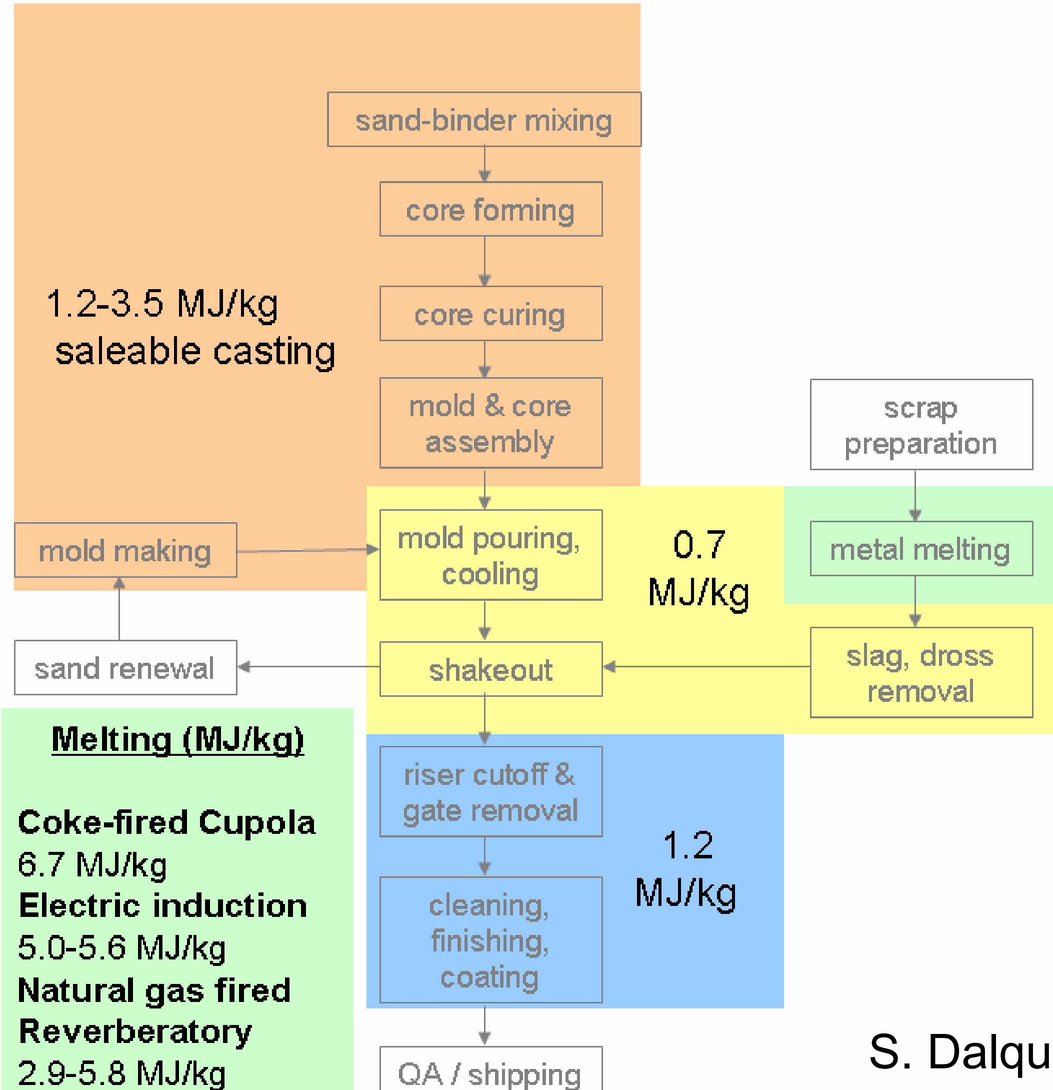
A. Jones

Sand casting; boundaries



S. Dalquist

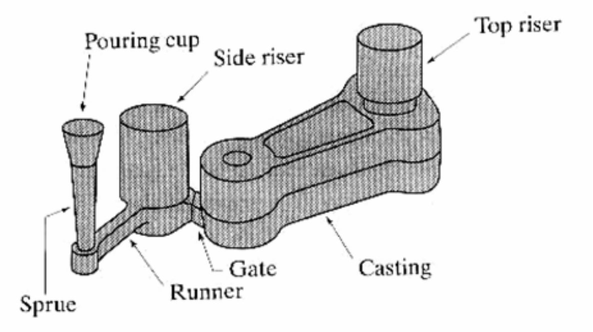
Sand casting; energy profile



S. Dalquist

- National statistics
- averages 6 to 12 MJ/kg (at the factory) of saleable cast metal
- Melting largest component

Nat'l statistics Vs model



- pour Vs part size ~ 2 to 3
- thermal energy

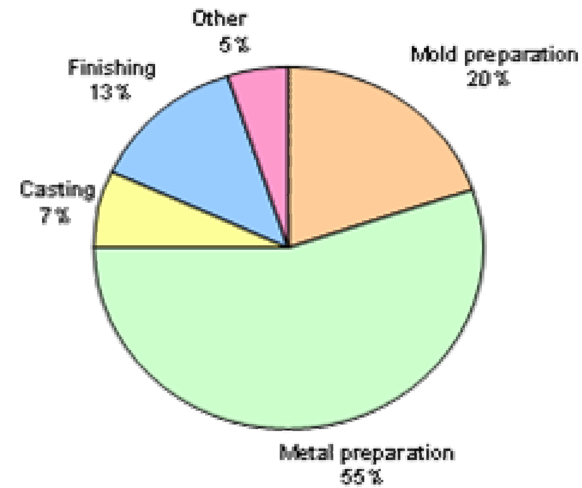
  $\Delta H = mC_p\Delta T + m\Delta H_f$ => 0.95 (aluminum), 1.3 MJ/kg (cast iron)

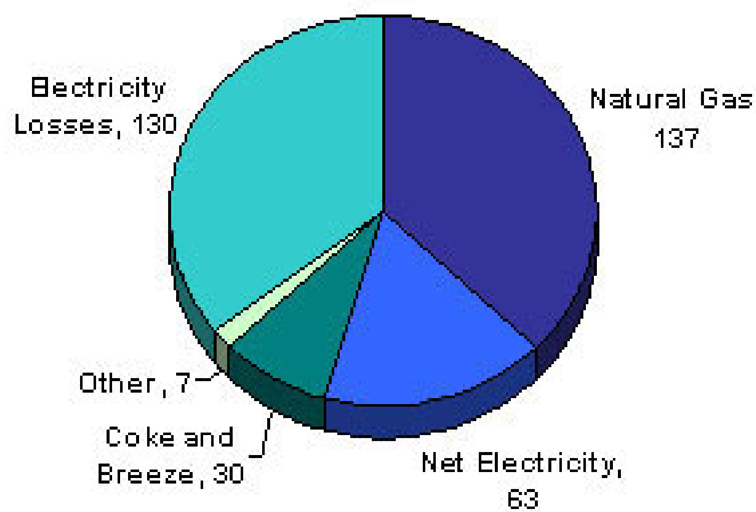
- furnace efficiency, $0.6<\eta<0.8$
- *melt energy*

≈ *3 to 6 (model) Vs 2.9 to 6.7 (statistics)*

Casting Energy Example

Stage	MJ/kg
Mold preparation	3.0
Metal preparation	5.8
Casting	0.7
Finishing	1.2
Total at foundry	10.7
Electricity losses	6.0
TOTAL	**16.7**



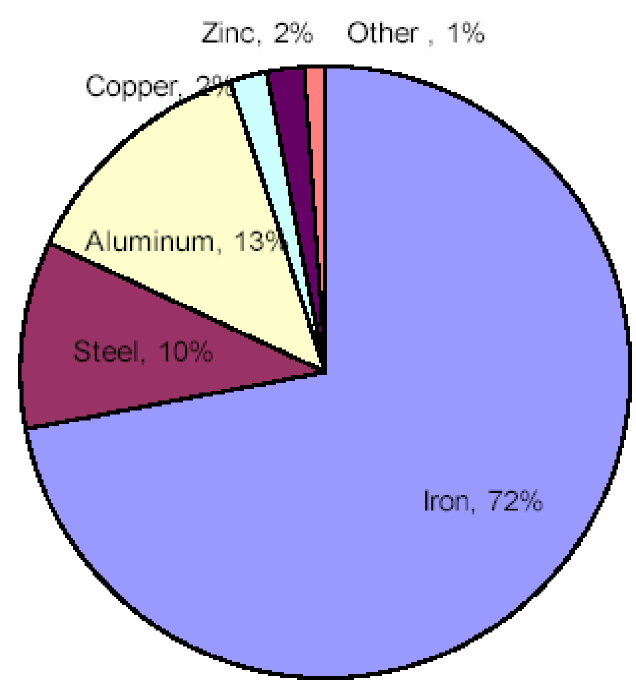


Source: DOE, 1999.

Source: EIA, 2001.

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



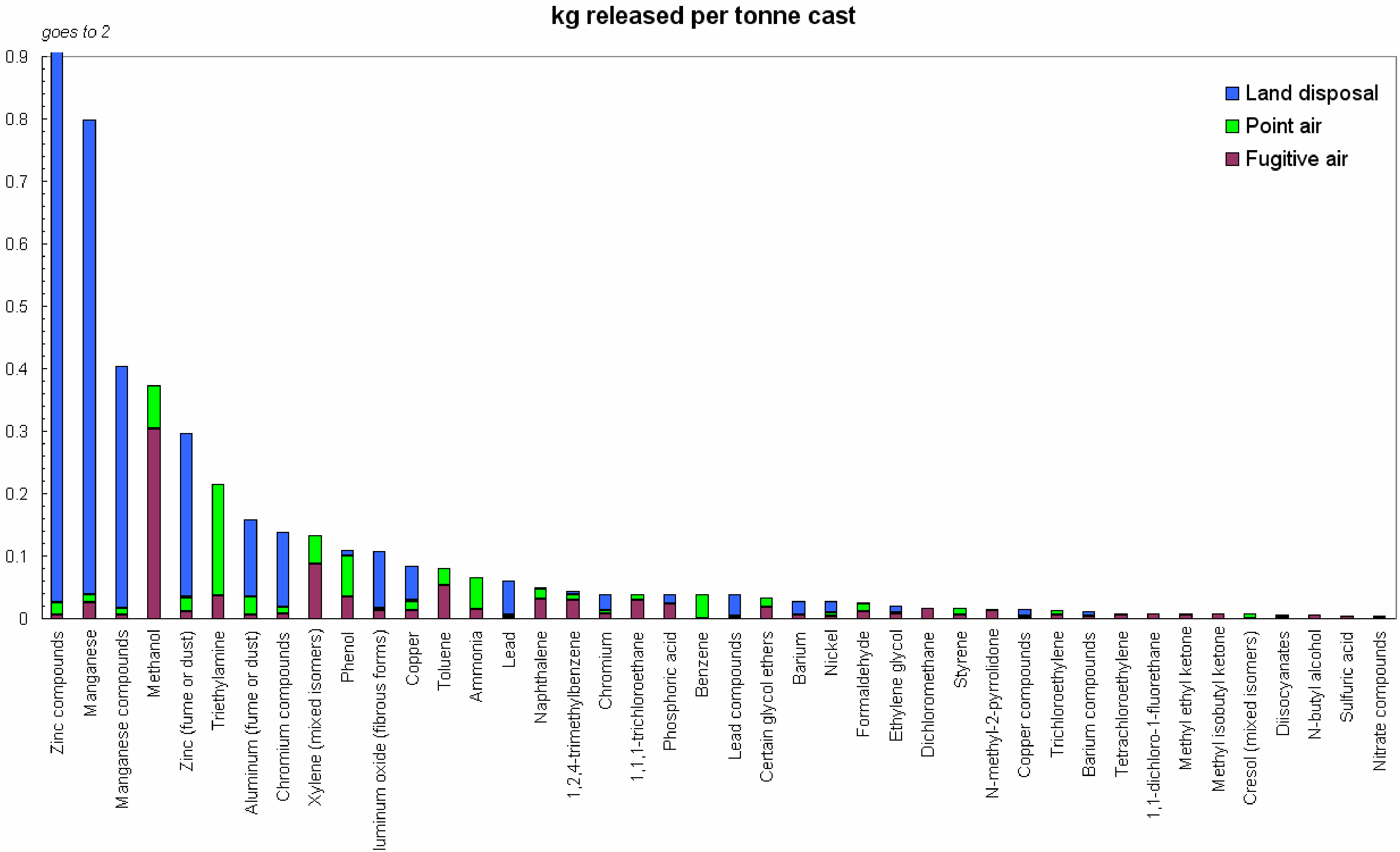
Source: DOE, 1999.

Improving sand casting

$$\eta_{II} = \frac{C_p \Delta T + \Delta h}{15 \frac{MJ}{kg}} \cong \frac{1}{15} \cong 7\%$$

- reduce pour size
- improve furnace efficiency
- use waste heat
- use fuel Vs electricity

Aggregate TRI data (toxic releases)



Sandcasting Emissions Factors

- Emissions factors are useful because it is often too time consuming or expensive to monitor emissions from individual sources.
- They are the best way to estimate emissions if you do not have test data.

Iron Melting Furnace Emissions Factors (kg/Mg of iron produced)				
Process	**Total Particulate**	**CO**	**SO_2**	**Lead**
Cupola				
Uncontrolled	6.9	73	0.6S*	0.05- 0.6
Baghouse	0.3			
Electric Induction				
Uncontrolled	0.5	-	-	0.005 - 0.07
Baghouse	0.1			

*S= % of sulfur in the coke. Assumes 30% conversion of sulfur into SO_2.

Source: EPA AP-42 Series 12.10 Iron Foundries
http://www.epa.gov/ttn/chief/ap42/ch12/bgdocs/b12s10.pdf

Pouring, Cooling Shakeout Organic HAP Emissions Factors for Cored Greensand Molds (lbs/ton of iron produced)	
Core Loading	**Emissions Factor**
AFS heavily cored	0.643
AFS average core	0.5424
EPA average core	0.285

Source:AFS Organic HAP Emissions Factors for Iron Foundries
www.afsinc.org/pdfs/OrganicHAPemissionfactors.pdf

TRI Emissions Data – 2003

XYZ Foundry (270,000 tons poured)

Chemical	**Total Air Emissions (lbs)**	**Surface Water Discharge (lbs)**	**Total on-site Release (lbs)**	**Total transfers off site for waste Management (lbs)**	**Total waste Managed (lbs)**
COPPER	69	9	78	74,701	**74,778**
DIISOCYANATES	0	0	0	20	**20**
LEAD	127	40	167	39,525	**39,692**
MANGANESE	274	48	322	768,387	**768,709**
MERCURY	14.35	0	14.35	0.25	**14.6**
PHENOL	6,640	5	6,645	835	**7,484**
ZINC (FUME OR DUST)	74	0	74	262,117	**262,191**
TOTALS			**7,300**	**1,145,585**	**1,152,889**

Readings

- G. Boothroyd et al., "Design for Die Casting"
- Flemings, "Solidification Process"
- Kalpakjian Ch 10-12, Skim Sec 30.9, 30.10,
- Skim Ch 32 (Ch 10-12, Skim Ch 29, 30)
- Dalquist, S… "Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting,"