Carbon equivalent in the range used in ductile irons has no effect on shrinking tendency and must not be chosen on this basis. Avoiding as-cast carbides, however, is of the greatest importance. Excessively carbide (more than 10 percent) ductile irons are often porous in their thermal centers. More will be said about this later.

The two main functions of the gating system are to let liquid iron into the mold and to keep slag in the iron from entering the mold. Sometimes the gating system also acts as a risering system.

The first function requires no further discussion other than that mold filling is retarded when the expanding air in a decreasing mold volume has no way of escaping except through the pores of the mold. For this reason, molds which have no open risers need always to be vented, with holes clearly open from mold cavity to the top of the cope. Such venting is difficult or impossible in high-speed, automated molding systems. As a compromise, parting line vents must, then, be used.

Slag can originate in the ladle or form through surface oxidation of the liquid ductile iron. When the latter happens inside the mold cavity, the gating system is of no use. Location of the gates is important; ideally, for quiet mold filling, joining the bottom of the mold cavity. Whenever possible, bottom gating should be applied. Usually, the gates must be in the parting with the casting cavity extending into both drag and cope. In this case gates must be located so as to cause minimum turbulence during drag filling.

Risering will be described in the following section.

**NOTE:** It is realized that the choice of gating systems is based on the economics between yield and quality for each casting. For complete information, see selection of guides in latest AFS publications list.
the rate of mold filling

Mold filling rate is determined by four variables —

1. pouring cup-to-choke* vertical distance, also called sprue height
2. mold cavity location in relation to choke
3. total choke cross-section area
4. frictional losses.

As long as the liquid level in the casting cavity is below the choke, only 1 and 4 above influence flow velocity through the choke cross section in the following way —

\[ v = c \cdot \sqrt{2g} \cdot \sqrt{H} \]

where

\( v \) is flow velocity through the choke (in./sec)
\( c \) is frictional loss factor
\( g \) is gravity acceleration. The value of \( \sqrt{2g} \) equals 28 in.\(^2\) sec \(^{-1}\) with adequate accuracy
\( H \) is sprue height as defined in 1. above (in.).

It is obvious that the flow velocity through the choke is largely dependent on sprue height which, in turn, is proportional to casting height.

Once the iron level in the casting cavity equals and rises above the horizontal of the choke, velocity will decrease due to backpressure created by the vertical distance between choke level and liquid level in the casting cavity. Velocity and rate of mold filling become time-variable after this event. The equation which describes filling rate at any given time is both complicated to solve and beyond the interest of practicing foundrymen. Total pouring time can be derived from this equation as —

\[ t = \frac{1}{f \cdot c \cdot \sqrt{2g}} \left( \frac{V_d}{\sqrt{H}} + \frac{V_c}{\sqrt{H - 2/3 \sqrt{b}}} \right) \]

where

\( t \) is total pouring time (seconds)
\( f \) is total choke cross-section area (in.\(^2\))
\( V_d \) is volume of the drag part of the casting (in.\(^3\))
\( V_c \) is volume of the cope part of the casting (in.\(^3\))
\( b \) is vertical distance from choke level to the highest point in the casting (in.).

* Choke is the cross section which determines flow rate or, in other words, that cross section through which the linear velocity is the greatest.
21. Unpublished research, Quebec Iron and Titanium Corp.
29. Patent held by Quebec Iron and Titanium Corp.
30. Patent held by Metallgesellschaft, A. G.
37. Unpublished research by Quebec Iron and Titanium Corp.
41. This section is the abstract of the gating part of, “Gating and Rising Gray and Ductile Iron Castings,” S. I. Karsay, Ferrous Foundry Consulting Co (1972).
42. This section is a somewhat extended but mainly abbreviated summary of the risering part of, “Gating and Rising Gray and Ductile Iron Castings,” Karsay, S. I., Ferrous Foundry Consulting Co (1972).
43. Cooperative research between AFS 12-G Committee, John Deere Foundry, East Moline, III and Quebec Iron and Titanium Corp.
49. Courtesy Ohio Brass Co.
53. Oil City Works, Corsicana, Texas.
often in the casting/riser junction.

Since the pressure relief mechanism is dependent on creating an initial shrinkage void in the riser, the gating system should be separated from the casting/riser complex through the use of thin (1/8-1/4 in. thick) gates.

pouring

The rule for pouring ductile iron is the same as for any other alloy: fill the pouring basin quickly and keep it full throughout the pour. The majority of ductile iron castings are hand poured at this date even in highly mechanized and automated foundries and the average human coordination can adequately fulfill this requirement.

At the same time it must be recognized that hand pouring is a demanding job and the pourer is exposed to some hazard. For this reason, and for potential economic and quality benefits, much effort is being invested into designing pouring machines.

The ideal machine is yet to be designed. Some of the existing devices are unsatisfactory from the point of view of casting quality in failing to simulate human coordination; i.e., pouring very fast initially, suddenly much slower to equalize flow rate through the choke and to end pouring quickly when the mold is full. These pouring devices use nozzles through which the liquid iron exits under gravity acceleration. Pouring can be activated by pulling a plug very much like in bottom pouring ladles (Fig. 87a) or by tilting the pouring device.

The above shortcoming can be overcome by providing the molds with pouring basins capable of containing almost the entire poured volume and by filling these basins very quickly. The quantity poured needs to be accurately predosed so that at the end of the pour the large pouring basins become empty. Such designs have not yet solved the problems associated with accurate and quickly changeable predosing and those of nozzle and (if present) plug wear. The shortcomings are unfortunate because these machines would lend themselves to pouring several molds simultaneously and, thus, be doubly economical.
Melting —

- equipment: in order of quality to make the pattern better are: cupola furnace (best), air furnace, coreless induction furnace, channel induction furnace and electric arc furnace (least desirable)

- metallic charge: in order of quality to make the pattern better are: special virgin irons (best), blast furnace iron, steel scrap and return ductile iron scrap (least desirable)

- temperature in the furnace: the lower the better

- holding time in the furnace: the shorter the better. From this the ideal charging sequence is tap-recharge-tap-recharge- etc., rather than taking several taps and recharging afterwards.

Inoculation —

- the better the inoculation, the less shrinkage tendency.

The practice of pressure-relief risering consists of attaching a blind riser to the heavy section(s) of the casting. Riser should be as near the casting as practical. Its volume-to-cooling surface area ratio should be about equal to that of the heavy section. The area-to-circumference ratio of the riser contact can be calculated from the following simple empirical formula:

\[
\frac{\text{Area}}{\text{Circumference}} = 0.09 + 0.43 \left( \frac{V}{S} \right),
\]

where

S is the adjoining casting section area in inches.

The effect of a pressure-relief riser can be described with reference to Fig. 85. Considering Graph 8, liquid contraction will first create a shrinkage void in the blind riser, since at the time when expansion starts there still exists liquid contact between casting and riser. The direction of liquid transport, then, reverses itself and sends liquid back into the riser. The extent of this “reverse” transfer is controlled, however, by the size of the shrinkage void created initially. Once the blind riser is completely refilled, reverse transfer stops and the remainder of the expansion puts the liquid under adequate pressure to compensate for secondary shrinkage.

The unmistakable sign of pressure-relief risering is a sound or nearly sound riser(s), as shown in Fig. 86.

If a deep shrinkage hole (pipe) is found in a pressure-relief riser, this indicates that either riser or contact or both were too small. As a consequence, the casting will likely contain internal shrinkage defects,
Fortunately, the ductile iron foundryman has two ways to avoid mold yield and internal shrinkage defects. First: the absolute extent of expansion is a material variable and it can be minimized through metallurgical control. Second: some of the expansion may be released through returning liquid iron from the casting into the riser. Well within the limits of reasonable process controls, the "left-over" expansion is adequate to compensate for secondary contraction but not so much as to cause elastic mold yield, as represented by the maximum and minimum lines in Fig. 84.

Volume changes caused by metallurgical quality are shown in Fig. 85. Graph A shows a good pattern of little volume change with temperature. Graph B is not as good as the pattern of Graph A, but is better than Graph C which shows the greatest change of volume with temperature and the highest pressures tending to cause deformation of the molds.

Recognized metallurgical facts affecting volume changes are described below. If the factor tends to make the volume change pattern more like Graph A, it is a beneficial factor. If it makes the pattern more like Graph C, it is a harmful factor.
Fig. 85. Volume change patterns dependent on metallurgical quality.

Fig. 86. Typical pressure-relief riser.

Chemical composition —

- increasing C, Si and CE: beneficial
- increasing contents of carbide stabilizers (Mn, Cr, V, Mo, Mg, etc): harmful
area ratio. When the riser is the pouring basin (large enough to fulfill this function) the gates act as riser necks. The dimension of the gate(s) are then determined first using Fig. 75 and 76. Relatively small gates will be required for small castings poured at high temperatures. Gate size increases with increasing section thickness to the point where a correctly proportioned gating system is no longer superior in casting yield to separate gating and risering. The approximate limit is set at a maximum \( \frac{V}{S} \) of 1/4 in. (6.5 mm). This limit can economically be extended through the use of a nonpressurized gating system to a \( \frac{V}{S} \) of 1/2 in. (12.5 mm) or even beyond. It will be noted in Fig. 75 that castings with larger than 0.32 in. (8 mm) \( \frac{V}{S} \) values require smaller riser necks as pouring temperature decreases. Figure 80 is an example of risering with the gating system.

**Chilling**

Large castings of ductile iron which require no risering need no chilling although chills can be used to refine microscopic structure and improve properties.

The logical application of chills is in the section size range from 3/4 to 2 in., in which range chills can replace risers, provided pouring temperature is less than a maximum of 1345C (2450F). This requirement arises from the fact that the net balance between expansion and total shrinkage is expansion only if the pouring temperature is less than 1370C (2500F) (Fig. 67).

Chills make ductile iron self-feeding by almost eliminating the liquid shrinkage period, causing the solid skin to continue growing and producing expansion which, in turn, compensates for liquid shrinkage.

Since the function of chills is the same as that of risers, i.e. to compensate for liquid shrinkage, a given casting can be either chilled or risered but

---

**Fig. 81. Recommended chill thickness for ductile iron castings (chilling on one side, cast iron or steel chill).**
logically not both. Exceptions are when chills are used for metallurgical reasons.

Recommended chill thicknesses are shown in Fig. 81.

**pressure-relief risering**

Until now the need for rigid molds has been emphasized. Industrial experience shows that this demand cannot always be satisfied. The largest number of ductile iron castings are poured into relatively weak molds, such as green sand or shell. Considering these most commonly used molding media, one should allow for not only the volume changes of the iron but also those of the container mold. When exposed to the temperature of the liquid iron, both green sand and shell molds will enlarge and this enlargement is additive to the contraction of the liquid iron.

This recognition applies particularly to thin castings which are to be poured relatively hot (Fig. 82).

![Fig. 82. Recommended pouring temperatures for ductile irons. Note that austenitic ductile irons need to be poured 55.5°C (100°F) hotter.](image)

The major problem with green sand and shell molds is that, depending on section thickness, elastic mold yield may occur with resultant swelling and secondary shrinkage defect.

The pressures which are created by expansion are dependent on section thickness (volume-to-cooling surface area ratio or V/S), as in Fig. 83.

Figure 83 shows that, depending on quality, green sand molds can withstand the expansion-induced pressures if the wall thickness is less than 3/8 in. and, at the best, up to 3/4 in.

In heavier castings, excessive elastic mold yield will take place, as shown in Fig. 84.

The result: internal (i.e., secondary shrinkage) defects.
rigidity needs to be increased or the pressure-relief method must be used. (See pp 126-130). In the absence of measurable mold wall movement, the only possible cause of secondary shrinkage defect is too large a riser neck ($\frac{V}{S}$).

Shrinkage defects which come and go, or appear in a certain portion of the total lot produced, invariably indicate inadequate control over pouring temperature and/or mold quality.

**riserless design**

As mentioned earlier, ductile iron castings do not always require risers. Distinction needs to be made between castings which need no risering and ones which do not require separate risers but are risered with the gating system.

**conditions for no risering**

Ductile iron castings which require no risering need to fulfill the following requirements —
- pouring temperature is low, less than 1340°C (2450°F) and, preferably, less than 1315°C (2400°F)
- pouring is fast and through thin gates which freeze quickly (see Fig. 59). Vents must be applied so that internal gas pressure does not reduce the pouring rate
- the requirement for low pouring temperatures limits the minimum section thickness to about 1 in. (25 mm). In addition, at least 30-50 percent of the casting volume needs to be thicker. A tentative minimum for thick sections is set at \( \frac{V}{S} \) of 3/4 in. (20 mm). There is no upper \( \frac{V}{S} \) limit within the commercially produced size range. Castings with \( \frac{V}{S} \) larger than 4 in. (100 mm) (corresponding to 8 in. or 200 mm thick walls) had been made sound with no risering
- mold self-expansion must be minimum
- the metallurgical quality of the iron must be high enough.

Conspicuously missing from the requirements is that for rigid molds. The reason: if mold rigidity is insufficient for the given section thickness, the casting will contain porosity, risered or not.

**conditions for risering with the gating system**

Every ductile iron casting which does not fulfill the five requirements for riserless design can be risered with the gating system. Whether or not this is practical depends only on \( \frac{V}{S} \), the significant volume-to-cooling surface

![Fig. 80. Ductile Iron casting risered with the gating system. Casting is shown upside down.](image-url)
Being infinitely long means that there is at least one section along the length of the riser neck which receives no heat from either casting or riser. This condition is obtainable only in horizontal riser necks or, if necessary, in necks which have a horizontal portion with the above defined minimum length. If the riser neck is vertical or slanted, thermal currents will pass from casting to riser, heating the neck area and delaying its freezing to an extent which is not possible to calculate.

There is no maximum length limitation for the riser neck. In other words, feeding distance is infinitely long.

**riser body design**

It is important to recognize that secondary shrinkage is neither necessary nor practical to riser. One, rarely practical exception, is when the thermal center is pulled out of the casting by a huge top riser.

Effective riser body volume must equal the liquid shrinkage of the casting which is 1.11 percent for every 56°C (100°F) difference between pouring and freezing temperatures. Feed metal requirements are shown in Fig. 78.

![Fig. 78. Feed metal requirements of ductile iron castings.](image)

Actual riser dimensions are always larger than what corresponds to the effective riser volume. First, that part of the riser below the top of the casting is not only ineffective but also requires risering and secondly, iron frozen initially next to the riser/mold surface is also ineffective. Riser dimensions must, therefore, be increased over the theoretical ones by a safe 1/4 in. (6.5 mm) on each side.

**number and location of risers**

Risers need to be attached to walls as thick or thicker than the significant one. In the rare event when casting segments are completely separated by walls thinner than the significant one, each segment needs to be risered separately. In the majority of cases one riser having infinitely long feeding distance suffices.
The use of cold risers, i.e. gating directly into the casting, is preferable. An oxide film can easily form on top of a partially full riser and if past the gating system the film can as easily enter the casting. Still, small castings poured in less than 10 sec can be gated into the riser. In large castings hot risers are not recommended. The mold in the riser neck area can heat up during pouring to such an extent that neck freezing is delayed sufficiently to cause secondary shrinkage defect.

**mold wall movement**

Mold wall movement is caused by massive freezing and expansion in a mold which is not sufficiently strong. When it takes place the riser must be separated from the casting by the frozen neck. For this reason, mold wall movement cannot be compensated for by risering. Excessive mold wall movement invariably results in secondary shrinkage defects in the form of porosity, when using this risering method.

**risering errors and corrective measures**

A riser neck and riser designed according to the preceding method will likely yield sound castings. Still, there is some probability of error with consequent shrinkage defects due to the following sources —

- incorrect choice of \( \frac{V}{S} \),
- pouring temperature outside the tolerable \( \pm 25^\circ C \) \( \pm 45^\circ F \) limit
- variations in the thermal properties of the mold
- variations in the mechanical properties of the mold
- various human errors.

When the defect is primary or liquid shrinkage, first the top of the riser needs to be examined. It might have frozen sooner than the riser neck. To aid in this examination Fig. 79 is included, showing freezing times in dependence of \( \frac{V}{S} \) and pouring temperature.

For the same reason, blind risers always need to be notched at the top or equipped with a Williams core. The latter can also be used for open risers, often called firecrackers.

Insulating or exothermic sleeves are invariably beneficial but the merit of exothermic topping is questionable for it can create a crust impermeable to air.

The second potential cause of a liquid shrinkage defect is inadequate effective riser volume and, finally, if all the above are found correct and liquid shrinkage is still present, the riser neck, i.e. \( \frac{V}{S} \) needs to be enlarged.

If the defect is secondary shrinkage only, casting dimensions need to be examined first. If excessive mold wall movement is found, either mold
The \( \frac{V}{S} \), (riser neck volume-to-cooling surface area) is simple to calculate provided the riser neck can be assumed to be infinitely long. Practical experience shows that the assumption is justified if the neck is at least as long as four times its thinnest dimension. Ratios for simple cross-sectional shapes are given in Fig. 77.

\[
\frac{V}{S} = \frac{a}{4}
\]

\[
\frac{V}{S} = \frac{d}{4}
\]

\[
\frac{V}{S} = \frac{bc}{2b + 2c}
\]

\[
\frac{V}{S} = 0.434\tau
\]
Fig. 75. Chart for determining riser neck cross section. The chart does not apply to austenitic ductile irons, instead the following equation is used:

\[
\left( \frac{V}{S} \right)_n = \left( \frac{V}{S} \right)_s \frac{T_p - 2250}{T_p - 1840} + \frac{Z}{1 + 0.0024 (T_p - 2250)}
\]

The freezing of an a-type casting is nearly continuous. In such a case a segment occupying less than 10 cumulative percent of the casting volume can be chosen as significant. During its freezing the significant section will pressurize the liquid long enough to compensate for shrinkage until massive freezing in the next, thicker section begins and so on.

In case b there is a long time interval between the complete freezing of segment 2 and the beginning of massive freezing in segment 3. To create pressure high enough to compensate for liquid shrinkage in the heavy section, the volume-share of segment 2 may need to be as much as 50 percent. This does not include segment 1 which obviously is negligible.
heat of fusion, casting volume-to-cooling surface area ratio and thickness of the layer frozen next to the mold wall at the time when massive freezing began. Fairly accurate values are available for all but pouring temperature which must be measured. Using this known data an equation has been made which is represented as a diagram in Fig. 75. Riser neck size can be designed based on this diagram.

The two coordinates, \( V \), (significant volume-to-cooling surface area ratio) and \( (\frac{V}{S})_n \) (riser neck volume-to-cooling surface area) need to be explained in detail. It is neither easy nor is it necessary to calculate total casting volume and surface area. With the exception of simple shapes, many castings have thin fins, ribs, etc., the total volume of which does not amount to more than 5-10 percent of the casting volume. The freezing of these thin sections can be complete long before freezing in the rest of the casting begins. In such a case, the expansion in the thin sections can be allowed to feed the riser (and the shrinkage of the liquid portion of the casting) in order to ensure that liquid shrinkage in the major portion of the casting is being compensated for by the riser. To avoid defects, freezing expansion in the thinnest section must not be lost. Choosing the significant section is easy for simple shapes and increasingly difficult as shapes become more intricate.

In the case of intricate shapes, every casting can be represented by a step-bar of increasing section thickness. To convert a casting into a step-bar, the casting is sectioned with imaginary vertical surfaces, each surface delineating a simple shape of uniform thickness. Volume-to-cooling
riser neck design

The most common type of risering defect, overrisering, is shown by line 3. Here, the riser neck remained liquid after massive freezing and expansion began and liquid iron escaped from the casting into the riser. Expansion fed the riser instead of building up pressure which would have compensated for secondary shrinkage. The result was a secondary shrinkage defect.

It is possible to design a riser neck which freezes at the correct time, that is, just before massive freezing begins. Even allowing for production variables and calculating errors, the following procedure will give a good approximation of the riser dimensions necessary for the proper freezing characteristics.

The rate of heat extraction by a green sand mold has been established by pouring cubes of various sizes and measuring the time needed for complete freezing. Measured times are shown in Fig. 74. Well in accord with Chvorinov’s rule, the rate of heat extraction can be described as

$$\frac{Q}{S} = 2387 \sqrt{t}$$

where

- $Q$ is rate of heat extraction by unit mold surface (cal/in.$^2$)
- $S$
- $t$ is time (min).

The quantity of heat to be extracted to reach freezing temperature (start of massive freezing) and that to complete freezing can both be calculated from pouring temperature, freezing temperature, density, specific heat,
Porosity is always found in the upper part of the thermal center of the casting. The thermal center is often in the area of large risers with large, short contacts. In such cases, porosity is found in the riser contact extending into both casting and riser.

The size of the pores depends on how far freezing has progressed at the onset of the vacuum. Under very bad conditions this can happen at an early stage, in which case one large hole may form. This can readily be differentiated from a primary shrinkage hole because secondary shrinkage holes are located in the upper thermal center area as opposed to being right under the top surface and the surfaces of secondary shrinkage holes are rough, covered with spikes (dendrites) of iron.

Large secondary shrinkage holes at the riser junction are shown in Fig. 72.

![Fig. 72. Large secondary shrinkage holes at the riser/casting junction.]

When the entire freezing is under vacuum created initially by liquid shrinkage, the primary shrinkage hole can continue downward as a secondary shrinkage hole. This defect is characterized by a smooth surface in the upper and a rough surface in the lower region.

**riser design utilizing full expansion for feeding**

The effect of risering is shown in the PFT diagram of Fig. 73. It will be shown that risering ductile irons is not always necessary.

Castings 1, 2 and 3 are identical except for risering. Casting 1 was correctly risered and the contact between casting and riser froze just before massive freezing and expansion began. The riser compensated for liquid shrinkage but its neck prevented transport of liquid iron from casting into riser during the expansion period.

Casting 2 was inadequately risered. Either the riser top or the riser neck froze too soon and, thus, the riser failed to compensate for liquid shrinkage. As in this example, primary shrinkage defects are often accompanied by secondary shrinkage defects also.
a resultant porous shrinkage defect, as shown in Fig. 70 and, in high magnification, Fig. 71.

Fig. 70. Typical secondary shrinkage defect (porosity).

Fig. 71. Porosity in ductile iron, nital etch, original 100X.
Fig. 69. Typical primary (liquid) shrinkage defect.

Under the pulled-in surface lies the heaviest section of the casting and, being the top surface (hotter than the bottom), the initially frozen skin is the thinnest, especially on the side where the gates are located. These conditions determine the site of the pull-in.

Pulled-in external surfaces are unmistakable signs of shrinkage defects due to contraction of the liquid and remedies must be based on this recognition. If the pressure-difference is not enough to deform the solid skin (as may be the case at low pouring temperatures) the vacuum will cause gas to precipitate, float and gather under it, forming one or more large gas holes. The presence of these large gas holes right under the cope surface is also a definite indication of liquid or primary shrinkage.

It often happens that liquid shrinkage begins even before a solid skin of any significant thickness can form. Atmospheric pressure will remain in direct contact with the liquid, pushing its level down at the hottest points of the top surface causing the casting to "pipe in." The surface of the piping-in (at least the upper portion) as well as that of the primary shrinkage hole is relatively smooth.

When a vacuum is created by secondary shrinkage at an advanced stage of the freezing the remaining liquid is divided into individual channels by the solids present. Under vacuum, gas will precipitate in each channel with
c'. Finally, secondary shrinkage at the end of the freezing causes the pressure to diminish from c' to below atmospheric d'.

It is postulated that shrinkage defects appear in any casting of ductile iron only if and when internal liquid pressure is below that of the atmosphere. In the example given in Fig. 68 there are two time periods when pressure is less than atmospheric (hatched areas) and, consequently, the casting will contain two types of shrinkage defects.

Fig. 68. The PFT diagram. P is internal liquid pressure, F freezing (thickness of frozen layer), T time, A atmospheric pressure and V is casting wall thickness.

primary (liquid) and secondary (porosity) shrinkage defects

It is of the greatest importance that the two different types of shrinkage defects which can occur in ductile iron castings be correctly identified. Each requires a different remedy.

When the pressure on its way down from a' to b' (Fig. 68) crossed the atmospheric value, there is no solid present other than the thin layer frozen next to the mold wall. With a vacuum prevailing inside, the atmospheric outside pressure can easily deform the solid skin, pushing it toward the inside at its weakest points, at the top or at internal corners. This mechanism, by decreasing internal volume, can restore atmospheric pressure inside the liquid. Such a pull-in defect is shown in Fig. 69.
Though the following discussion deals with molding in silica sand only, the principles apply to other molding media, such as zircon or chromite sand, and even to permanent molding.

There is more than adequate experimental evidence to prove that ductile irons form a solid, frozen skin next to the mold wall from the time there is contact, until the next 1 or 2 min. Thickness of the frozen crust depends on pouring temperature and can be as little as 1/16 in. (1.5 mm) or as much as 1/4 in. (6.5 mm). Shortly after completed pouring and after the gates freeze the liquid ductile iron will be fully enclosed by a solid crust (unless risers are attached).

Progress of freezing and the changes in the pressure of this liquid iron as time goes on are illustrated schematically in a double diagram (PFT) (Fig. 68). Freezing, as shown with vertical distances downwards from the OT line, is fast at the beginning (Oa). Mold chilling will slow down due to fast increase in mold temperature and the ab stretch is characterized by a very slow growth of the solid skin through which heat is conducted into the mold. This behavior is common for all eutectic alloys because no freezing can take place until the temperature of the entire casting reaches freezing. Then, freezing starts simultaneously throughout. Massive freezing occurs with no deviation if cooling is infinitely slow.

Actual castings, of course, cool at a finite rate. The first deviation from the ideal or equilibrium freezing is that of forming a solid crust due to very fast initial cooling by the mold. The second deviation is the slightly downward slope of the ab stretch and, finally, the third deviation is that the onset of massive freezing is not exactly simultaneous throughout. Were this the case, the curve showing the start of the freezing would become a straight vertical line from b to the horizontal line from F to V/2.

Freezing is complete when the "freezing ends" line reaches half wall thickness (V/2) from both sides.

The changes in the internal liquid pressure are shown in the upper part of the diagram. The horizontal marked A represents atmospheric pressure. The casting, in this case, is not risered.

Atmospheric pressure prevails to the time when the gates freeze, as shown as a$^0$ (ferrostatic pressures, being comparatively small, are disregarded). At the time of a$^0$, relatively fast freezing is still in progress. The corresponding slight expansion increases internal liquid pressure from a$^0$ to a'. The ab period of liquid cooling and liquid shrinkage reduces pressure from a' to b'. Massive freezing begins now with a significant expansion which, in a reasonably strong mold, increases pressure from b' to
The shrinking behavior of ductile irons is very different from that of other alloys and metals with the exception of gray cast iron. The major difference is in the fact that ductile irons expand during part of the freezing. This expansion is followed by a secondary shrinkage while the alloy is still in the process of solidification. Volume changes from pouring to complete freezing are shown in Fig. 67.

Expansion can cause shrinkage defects but if understood and properly used can feed the casting to such an extent that risers are not necessary.

The volume changes that take place in a casting are never exactly the same as in Fig. 67. Depending on the strength of the mold, expansion will be suppressed to various degrees (although never completely) and converted into pressure which will prevail inside the cooling liquid iron.

\[ \text{Fig. 67. Specific volume of ductile irons in the temperature range from pouring to freezing (schematic).}^* \]

*The volume changes that occur during ductile iron solidification have not been measured precisely. It is also believed that variables such as solidification rate, metal chemistry and initial metal temperature have an influence on these volume changes and that the degree of this influence is not completely understood. Since this volume change has an important bearing on riser design the reader must consult AFS publications lists for appropriate literature on the subject.*
skill. A deep, narrow lip is preferable to a wide shallow one and the width of the spout must, ideally, be 1-1/2 to 2 times the diameter of the sprue, although it must be recognized that very often molds with different sprue diameters must be poured from the same ladle.

As shown in Fig. 66, the spout must extend horizontally so that the midpoint of any mold can be reached without raising the ladle high above the mold which causes high stream velocity and turbulence.

![Fig. 66. Pouring ladle with a spout that is sufficiently long.](image)

Teapot ladles do more harm than good because maintenance costs are high; the first iron usually must be scrapped and protection against slag is far from complete. The slag which adheres to the dividing wall while emptying the ladle can become dislodged during the next pour.

general notes

The size of the pouring basin is a compromise between the desire to
improve casting yield and the skill of the pourer. An exception is the case when the gating system is used for risering and the pouring basin also acts as a riser.

Since it is much easier to position the ladle laterally than to try to mentally predict the point where the liquid stream will reach the mold, pouring basins elongated in the direction of pour are preferable.

Devices in the pouring basin such as dams or pullout plugs are not necessary, since the iron in the pouring basin is very turbulent and in any case it is not possible to prevent some slag from entering the sprue. Strainer cores are particularly damaging. The total area of the openings may equal that necessary for the sprue top in which case casting yield suffers. The area of the opening is often smaller than necessary; i.e. the strainer core is in fact a choke. Being located at the sprue top, this is harmful to casting cleanliness.

As mentioned earlier, the runner needs to extend past the last gate. When space limitations in the flask do not permit an adequately long extension this can be replaced with equal efficiency by a well equal to the volume of the missing length.

It is always a good practice to place a well under the sprue to absorb the impact of the first iron and to decrease turbulence at the start of runner-filling. Sprue wells are particularly important when the distance between the sprue and the first gate must be short.

A pressurized gating system is usually safer and less demanding on casting yield. Use of a nonpressurized system is indicated when a circular runner is inside the casting (such as a ring) and the gates branch off away from the center, when numerous small castings are poured in one mold (in this case casting yield of a nonpressurized system is superior), when parting is vertical and when pouring castings with 1/2 to 1 in. thick walls and the gating system is used for risering.

Fluxes are frequently being used to change the consistency of the slag so that it is more apt to stay in the runner. Most fluxes, proprietary or not, are either a 50-50 blend of cryolite and sodium fluoride or cryolite alone. The flux may be added with the treatment alloy, with the inoculant, or upon each reladling. Good results were also obtained by adding a small quantity of flux right into the pouring basin or sprue.

A sprue addition of a small quantity of red iron oxide is also reported to be beneficial for controlling slag.
can provide one more defense against slag. It was pointed out that there is a finite possibility for slag entry into the gates or, in this case, into the upsprues. If mold filling is stepwise, i.e. if the gates are not pressurized, the slag can enter the casting cavity as shown in Fig. 65. If, however, the upsprue is filled up very fast to above the topmost gate, the probability of slag entry is negligible. The condition to achieve such fast upsprue filling can be described using the symbols of Fig. 64 as —

\[
\frac{F_3}{F_1} = \frac{\sqrt{h_3}}{\sqrt{h_1} + \sqrt{h_2} + \cdots + \sqrt{h_n}}
\]

This system is nonpressurized at first but becomes pressurized as soon as mold filling begins.

**ladle design**

In a more general sense the ladle, and in particular its pouring lip, is also part of the gating system. It is necessary first to correlate ladle size with casting weight so that the ladle is emptied, preferably within 5 minutes and that the spout of the ladle be shaped so that good and quick control over the rate of pouring can be exercised without relying on exceptional human
choke, otherwise the system will become pressurized. Gate cross section is usually chosen between two to four times that of the choke. The relatively large gates are not completely full until after the liquid level in the casting cavity reaches the top gate level. This introduces the metal into the mold cavity with a velocity somewhat less than do pressurized gates.

It is obvious that the runner retains slag only if it is completely full. It is equally obvious that the runner cannot be full if the gates are not on top of it. Right and wrong runner/gate junctions are shown in Fig. 63.

![Fig. 63. Wrong and right runner/gate junctions in the nonpressurized gating system.](image)

**slag retention in gating systems for vertically parted molds**

When parting is vertical, gates or upsprues must branch off the top of the runner. (In gray iron practice, pressurized top gating has found some application.) As long as the gates are on top, the system must be nonpressurized and built according to principles and practice described for nonpressurized systems.

Conditions are different when the runner supplies iron to vertical upsprues and the adjoining gates are horizontal. Figure 64 illustrates such an arrangement. In addition to all others described previously, this system

![Fig. 64. Gating system for vertical parting.](image)
either a constant runner cross section or one sloping downward in a straight line toward the runner end. Slag traps, up-and-downsteps, serrations and the like, all cause turbulence and increase rather than decrease the danger of slag defects.

A straight runner is the best. If space limitations require bends, these must have a large radius and the gate after the bend must, again, be at some reasonable distance.

It is also necessary to ensure that slag does not enter through the gates during the initial moments of the pour, while the runner is not yet full. This is based on the fact that a moving mass, liquid or solid, does not change the direction of its movement unless energy is expended to force it to do so. As long as the runner is straight, the liquid flowing inside will bypass openings (gates) until after some sort of energy forces the liquid to change direction. This energy will be created by the height of liquid level above the gate openings, after the end of the runner stops the flow and the liquid level rises. Provided that the gate is not a straight continuation of the runner and that there is a reasonable distance between the last gate and runner end, the runner will be full or nearly so by the time iron starts streaming through the gates. The last gate starts filling first, continuing in sequence with the others toward the sprue and the initial slag, floating on top of the liquid, is well above the ingate joint.

To accomplish this, extend the runner beyond the last gate. Distances similar to those between sprue and first gate are satisfactory. Use tall, thin runners with heights approximately twice the average thickness. Use thin, wide gates, the width being approximately four times the height. Minimum gate thickness depends on pouring temperature and can be as little as 1/16 in. (1.5 mm) when pouring very hot. When pouring at or below 1315C (2400F) 1/2 to 5/8 in. (12.5-17 mm) minimum thickness is required in order to prevent gate freezing while pouring.

Avoid rounding-off the runner bottom with more than 1/16 in. (1.5 mm) radius when the entire runner is in the cope.

Bottoms of runner and gate(s) need to be in the same plane as shown in Fig. 62. Never place an ingate in straight continuation of the runner. The sprue cross section must be somewhat larger than that of the total of the gates to ensure that the latter acts as a choke. The most commonly used area ratio is 4 (sprue) : 3 (total gates).

**slag retention in nonpressurized gating systems**

The only correct location for the choke in a nonpressurized system is at the sprue-runner junction. It can be formed either through tapering the sprue
or through forming the choke in the runner in the near vicinity of the sprue junction. Whichever is the case the minimum ratio between sprue cross section at its junction with the pouring basin and choke cross section is —

\[
\frac{F_0}{F_1} = \sqrt{\frac{H}{h}}
\]

where

- \(F_0\) is sprue cross section at the pouring basin junction (in.\(^2\))
- \(F_1\) is choke cross section (in.\(^2\))
- \(H\) is vertical distance between top of pouring basin and choke (in.)
- \(h\) is vertical distance between top and bottom of pouring basin (in.).

Without sprue tapering or choking in the runner, choking will take place at the sprue top, with resultant extreme turbulence during part of or through the entire pour. Tapered sprues are also preferred for the pressurized systems but, since the system will completely fill up within moments after pouring begins, straight sprues are also acceptable.

Sprue filling is very fast in the nonpressurized system and is the first step in a defense against slag defects. The second step is the use of a large runner with a cross-section area (depending on the distance from sprue to first gate, the shorter the runner the larger the cross-section area) of 3 to 6-times the choke. The large runner is beneficial in two ways: flow velocity is low once the runner is full, which has its importance in floating up the slag during the entire pour and a wide, thin runner has a large horizontal surface area. Width must be approximately twice the thickness. This is most important at the beginning of the pour. The probability of slag entering through the gates in a nonpressurized system is proportional to the ratio between the total horizontal gate areas overlapping the runner and the total horizontal runner surface area. This ratio is never zero but can be as little as 1 percent.

Requirements for distances between sprue (or choke) and first gate and between last gate and runner end are the same as described for pressurized gating systems. Total gate cross section must be larger than that of the
Choke cross section can be calculated as shown above or it can be chosen using Fig. 61 which has been constructed from practical experience. Large castings which must be poured within a certain length of time and castings in high production benefit from calculation. Otherwise, Fig. 61 can safely be used.

![Choke cross-section areas for ductile irons](image)

**Fig. 61. Recommended choke cross-section areas for ductile irons.**

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**slag retention in pressurized gating systems**

A pressurized gating system is defined as one having its choke at the gate cross section. Both runner and sprue cross sections are larger than the total of the gates.

It is not only a possibility but a near certainty that some slag will reach the bottom of the sprue and enter the runner. This is the case particularly at the beginning of the pour. Slag suspended in or floating on top of the liquid iron will travel with the latter. The mode of slag movement is entirely dependent on runner design for the runner is the only part in the gating system capable of capturing and holding slag and preventing it from entering the casting cavity.

The mechanism of slag retention and the corresponding design principles are to ensure that all slag particles float to the top of the runner. This requirement is fulfilled if the flow is not turbulent and enough time is given for the suspended nonmetallic particles to float to the top.

To aid in this, minimize the flow velocity by choosing a cross-section area for the runner which is several times that of the gates branching off it. Ratios of 2:1 to 4:1 are recommended; the larger the ratio the shorter the distance between sprue and first gate. Minimum distance is dependent on sprue height and must be at least 2 in. (50 mm) even for the lowest sprue height. At 10-in. sprue height a minimum of 6 in. (150 mm) and at 30-in. sprue height a minimum of 10 in. (250 mm) is recommended. Maintain
Other symbols are the same as in the previous equation.

Of all the variables in the preceding equation, choke cross section is entirely the foundryman's choice. The larger the choke, the shorter the pouring time.

Ductile irons need to be poured relatively fast because fast pouring minimizes temperature loss and surface oxidation. In high rate production it is also beneficial to production economy. Recommended pouring times are shown in Fig. 59.

![Fig. 59. Recommended pouring times for ductile iron castings.](image)

Once pouring time, parting and sprue height are decided upon, only estimation of the frictional loss factor ($c$) remains before the previous equation can be used to calculate choke cross section. Deciding on the value of $c$ is often difficult because its value varies from 0.1-0.2 for thin castings to 0.7-0.8 for very heavy castings. The value of $c$ depends on a number of other variables as well, such as roughness of the mold surface, pouring temperature, gating system geometry and flow velocity. Figure 60, then, can be considered an approximation only.

![Fig. 60. Approximate values of the $c$ frictional loss factor.](image)