Prediction of Solidification Time: Chvorinov's Rule.

The **amount of heat that must be removed** from a casting to cause it to solidify is **directly proportional to the amount of superheating** and the **amount of metal** in the casting, or the casting volume. Conversely, the **ability to remove heat** from a casting is **directly related to the amount of exposed surface area** through which the heat can be extracted and the insulating value of the *mould.* These observations are reflected in Chvorinov's rule, which states that t_s, the total solidification time, can be computed by:

$$t_s = B\,(V/A)^n \qquad \text{where } n = 1.5 \text{ to } 2.0$$

The total solidification time is the time from pouring to the completion of solidification; *V* is the volume of the casting; ***A*** is the surface area; and ***B*** is the **mould constant**, which depends on the characteristics of the metal being cast (its density, heat capacity, and heat of fusion), the mould material (its density, thermal conductivity, and heat capacity), the mould thickness, and the amount of superheat.

Test specimens can be cast to determine *B* for a given mould material, metal, and condition of casting. This value can then be used to compute the solidification times for other castings made under the same conditions. Since a riser and a casting are both within the same *mould* and fill with the same metal under the same conditions, Chvorinov's rule can be used to ensure that the casting will solidify before the riser. This is necessary if the liquid within the riser is to effectively feed the casting to compensate for solidification shrinkage.

Different cooling rates and solidification times can produce substantial variation in the resulting structure and properties. For instance, die casting, which uses metal moulds, has faster cooling and produces higher-strength castings than sand casting, which uses a more insulating mould material. The various types of sands can produce different cooling rates. Sands with high moisture contents extract heat faster than sands with low moisture.

Solidification Shrinkage.

Once in the mould cavity, most metals and alloys contract during cooling. There are three principal stages during which shrinkage occurs: (1) shrinkage of the liquid; (2) solidification shrinkage as the liquid turns to solid; and (3) solid metal contraction as the solidified material cools to room temperature. The amount of liquid metal contraction depends on the coefficient of thermal contraction (a property of the metal being cast) and the amount of superheat. Liquid contraction, however, is rarely a problem in casting production because the metal in the gating system continues to flow into the mould cavity as the metal in the cavity cools and contracts.

As the metal cools between the liquidus and solidus temperatures and changes state from liquid to solid, significant amounts of shrinkage tend to occur, as indicated by the data in Table. This table also shows that not all metals contract. Some expand, such as grey cast iron, in which low-density graphite flakes form as part of the solidification structure.

When shrinkage occurs, it is important to know and control the form of the resulting void.

Metals and alloys with short freezing ranges, such as pure metals and eutectic -alloys, tend to form large cavities or pipes. These can be avoided by designing the casting to have directional solidification. Here, the

solidification begins furthest, away from the feed gate or riser and moves progressively toward it.
As the metal solidifies and shrinks, the shrinkage void is continually filled with liquid metal. Ultimately, the final shrinkage void occurs in the riser or the gating system.

Alloys with large freezing ranges have a wide range of temperatures over which the material is in a mushy state. As the cooler regions complete their solidification, it is almost impossible for additional liquid to feed into the shrinkage voids. Thus, the resultant structure tends to have small, but numerous, shrinkage pores dispersed throughout. This type of shrinkage is far more difficult to prevent by control of the gating and risering, and it may even be necessary to accept the fact that a porous product will result. If a gas- or liquid-tight product is desired, the castings can be impregnated (the pores filled with a resinous material or lower-melting-temperature metal) as a subsequent operation.

After solidification, the casting contracts further as it cools to room temperature. These dimensional changes have to be compensated for when setting the dimensions of the mould cavity or pattern.

Risers and Riser Design.

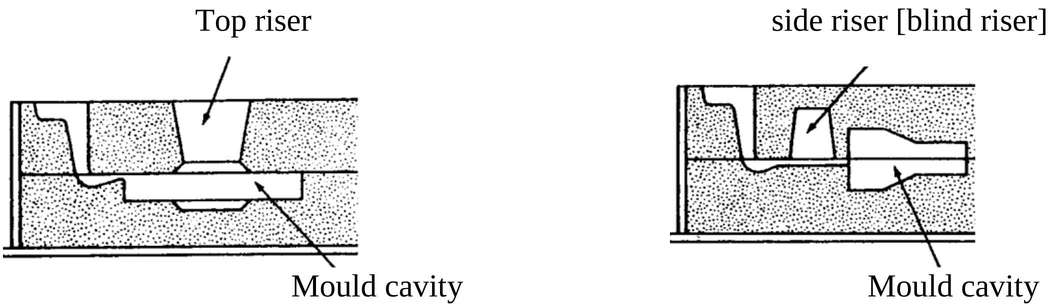
Risers are added reservoirs designed to feed liquid metal to the solidifying casting as a means of compensating for solidification shrinkage. To perform this function, the risers must solidify after the casting. If the reverse were true, liquid metal would flow from the casting into the solidifying riser, and the casting shrinkage would be even greater. Hence, the casting should be designed to produce directional solidification, which sweeps from the extremities of the mold cavity to the riser. In this way, the riser can "Continuously feed molten metal and will compensate for the solidification shrinkage of the entire mould cavity. If such solidification is not possible then multiple risers may be necessary, with various sections of the casting solidifying toward their respective risers.

Finally, risers should be designed to conserve metal. If we define the yield of a casting as the casting weight divided by the total weight of metal poured (sprue, gates, risers, and casting), it is clear that there is a motivation to make the risers as small as possible to still perform their task. This can often be done by proper consideration of riser size, shape, and location, and the nature of the connection between the riser and the casting.

By consideration of Chvorinov's rule, a good shape for a riser would be one that has a long freezing time or a small surface area per unit volume. A sphere would make the most efficient riser but presents considerable difficulty to the pattern or mould maker who must remove the pattern from the mould. As a result, the most popular shape for a riser is a cylinder, in which the height-to-diameter ratio is varied depending on the nature of the alloy, the location of the riser, the size of the flask, and other variables.

Risers should be located so that directional solidification occurs. Since the thickest regions of a casting are the last to freeze, the risers should be located so as to feed into these heavy sections. Various types of risers are possible. A *top riser,* one that sits on top of a casting, has the advantage of feeding by additional pressure (the weight of the metal), feeding a shorter distance, and occupying less space within the flask, thereby permitting more freedom for the layout of the pattern and the gating system.

Side risers are located adjacent to the mould cavity in the horizontal direction. Figure compares a top and a side riser. If the riser is contained entirely within the mould, it is known as a *blind riser,* while one that is open to the atmosphere is called an *open riser.* Blind risers develop a solid skin because of surface solidification and are generally bigger than open risers, because of the heat lost through the additional surface.



(a) (b)

FIGURE: Schematic of a sand casting mould, showing a top riser (a) additional pressure and a side riser (b).

Live (hot) risers receive the last hot metal that enters the mold and generally do so at a time when the metal in the mold cavity has already begun to cool and solidify. Thus, they can be smaller than *dead (cold) risers*, which fill with the colder metal that has already flowed through the mold cavity. Top risers are almost always dead risers. Risers that are part of the gating system are generally live risers.

The minimum size of a riser can be calculated from Chvorinov's rule by setting the total solidification time for the riser to be greater than the total solidification time for the casting. Since both will receive the same metal and are in the same mould, the mould constant, *B,* will be the same for both regions. Assuming $n = 2$, and a safe difference in solidification time of 25% (the riser takes 25% longer to solidify than the casting), we can write this condition as:

$t_{riser} = 1.25\ t_{casting}$ $\qquad (V/A)^2_{riser} = 1.25\ (V/A)^2_{casting}$

Calculation of the riser size then requires the selection of a riser geometry (generally cylindrical) and specification of a height-to-diameter ratio, so that the riser side of the equation will have only one unknown. For a cylinder of diameter *D* and height *H:*

$$V = \pi D^2 H / 4$$

$$A = \pi DH + 2 (\pi D^2 / 4)$$

Specifying the riser height as a function of the diameter enables the *V/ A* ratio to be written as a simple expression with one unknown, namely, *D.* The *VIA* ratio for the casting can be calculated from its particular geometry. Substitution of this information into the above form of Chvorinov's rule will then enable calculation of the required riser size. Note, however, that if the riser and the casting share a surface, as with a top riser, the common surface area should be subtracted from both segments since it will not be a surface of heat loss to either component. While there are a variety of more sophisticated methods for calculating riser size, the Chvorinov's rule method is the only one presented in this text.

A final aspect of riser design is the connection between the riser and the casting. Since it will ultimately be necessary to separate the riser from the casting, it is desirable that the connection area be as small as possible. On the other hand, the connection area should be large enough so that the link does not freeze before solidification of the casting is complete. Short-length connections are most desirable. The adjacent mould material will then receive heat from both the casting and the riser. Therefore, it will heat rapidly and remain hot throughout the cast, retarding solidification of the metal in the channel.