TALAT Lecture 3203

The Filling of Castings

22 pages, 21 figures

Basic Level

**prepared by John Campbell and Richard A. Harding, IRC in Materials,
The University od Birmingham**

Objectives:

- To describe the function and design of all parts of the running and gating systems used in the production of castings.
- The student will be able to tackle the design of a simple running system in a systematic manner.

Prerequisites:

- Basic knowledge of foundry processes. Basic mathematics.

Date of Issue: 1994

3203 The Filling of Castings

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Introduction

This lecture is concerned with filling the mould cavity with molten metal. Although this is one of the most important steps in producing a good quality casting, it is often the one which is the least understood and, as a result, it is often overlooked. It is all too common to see poor quality running systems in use in foundries, with consequential damaging effects on the quality of the castings produced.

Filling system

Figure 3203.00.01 shows a typical aluminium alloy casting - an engine mounting bracket. The filling system - which is also known as the running system - can be seen on the left-hand side and consists of

- a small pouring basin
- a downsprue, which is divided into two smaller branches
- a sprue base or well
- horizontal runner bars which lead the molten metal towards the bottom of the casting
- ingates, which introduce the metal into the mould cavity.

TALAT Training in Aluminium Application Technologies | Engine Mounting Bracket Cast in Aluminium Alloy | 3203.00.01

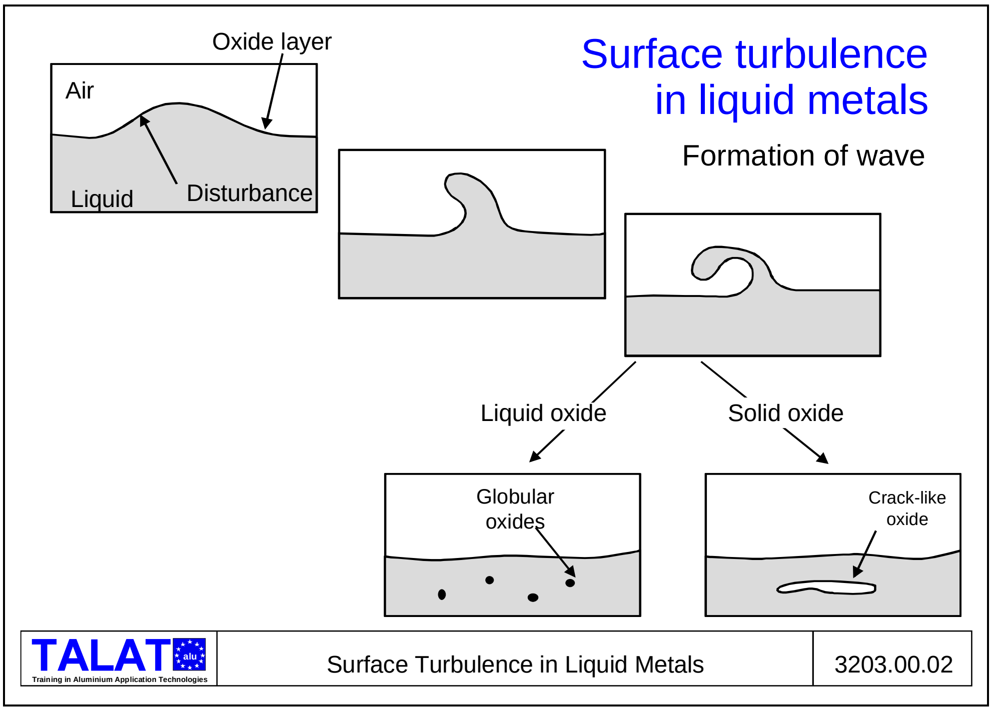
The feeding system, which is used to compensate for the shrinkage of the casting as it solidifies, is in two parts. One feeder can be seen on the top of the casting and another on the right hand side. It can be clearly seen that the filling and feeding systems are separate, which is appropriate since they perform completely different functions in the production of a casting. It should be noted that the filling and feeding systems can sometimes be combined (although it is usually much more difficult to design a combined system which accomplishes both functions equally well).

The difference between the very different functions of filling and feeding systems is emphasised when it is realised that, in the case of a typical casting, it might take ~ 10 seconds to fill the mould, whereas the feeding system would typically be operating for ~10 minutes as the casting solidifies. The present lecture will concentrate on the *filling* of castings, whereas a later one will concentrate on the *feeding* of castings.

In this example of an aluminium casting, it should be appreciated that the metal has been carefully introduced into the cavity through gates in the bottom of the casting. This is in contrast to many iron castings in which the metal is poured directly into the top of the casting cavity with very little thought being given to providing a proper filling system. In spite of this apparently rather crude approach to the filling of grey iron castings, they are nevertheless normally of quite a good quality. It is instructive to consider why this might be so.

Oxide Formation

All molten metals oxidise when in contact with the air, but the nature of the oxidation products varies considerably. For example, grey irons oxidise to form a liquid silicate skin, whereas aluminium and some other metals form a dry oxide skin. Molten aluminium is an extremely efficient 'getter' for oxygen and calculations show that a vacuum of less than 10^{-40} atmospheres would be required to prevent oxide film formation. (This is somewhat better than the vacuum found in outer space!!)



When a metal is poured rapidly into a mould, it enters in a turbulent manner, and it is inevitable that the oxide film folds over itself so that oxide-to-oxide contact occurs (see **Figure 3203.00.02**). Furthermore, as the metal tumbles over and churns about, the oxide film is continually being stretched and ruptured and also re-growing. In the case of grey cast irons, this is not too serious since the liquid silicate films can meet and fuse together, agglomerating to form droplets which generally float out of the molten iron. Even if they remain in the iron, they normally have a shape which does not have a detrimental effect on properties.

In contrast, when the solid alumina (Al_2O_3) films on molten aluminium meet, they do not 'knit' together, but instead form crack-like defects which remain in the casting as it solidifies. These introduce a mechanical weakness into the casting which will probably result in it being less reliable in service. Such crack-like defects also often result in leakage problems in castings which are required to contain a liquid or a gas. Unfortunately, aluminium castings have an unenviable reputation for being prone to leakage defects as a result of poor filling practice.

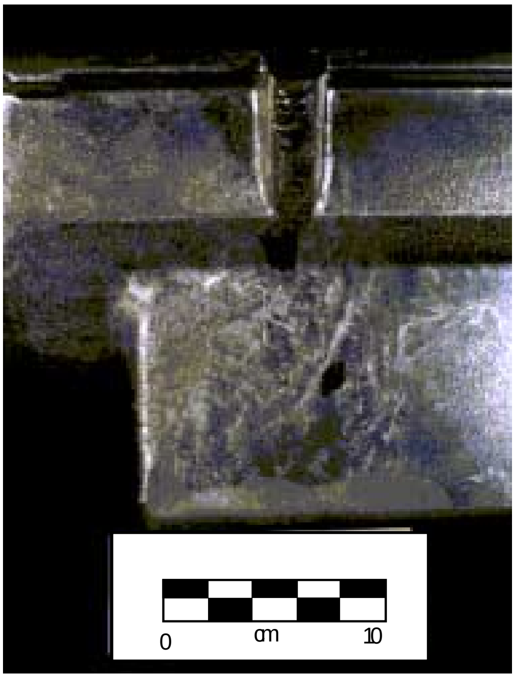
Casting Defects

Figure 3203.00.03 shows a considerably larger casting and is in fact a sump for a diesel engine. It weighs ~ 6 kg and has an average wall thickness of 6 mm. Although the casting is complete and apparently satisfactory, the trained eye can see from quite a distance away that in fact it contains defects.

TALAT Training in Aluminium Application Technologies | Diesel Engine Sump Cast in Aluminium Alloy - General View | 3203.00.03

Figure 3203.00.04 is a close-up of the same casting and shows a dull matt area which is the oxide film formed as the metal entered the mould. The casting was produced with several feeders (to compensate for the solidification shrinkage) and the metal was introduced into the mould through one of these. As it was poured into the mould, turbulence led to the formation of layers of oxide which got trapped in the metal, hanging in place like curtains and creating extensive planes of mechanical weakness.

In some cases, castings with defects such as these can crack spontaneously at any time after solidification. If these cracks are found, the castings would often be dressed to remove the cracks and then welded, but the thermal cycle resulting from this can lead to further cracks which then have to be removed and weld-repaired. Unfortunately, it is an all-too-common foundry experience that cracks can be ’chased round’ a casting!



TALAT alu Training in Aluminium Application Technologies	Diesel Engine Sump - Close-Up of Oxide Defects	3203.00.04

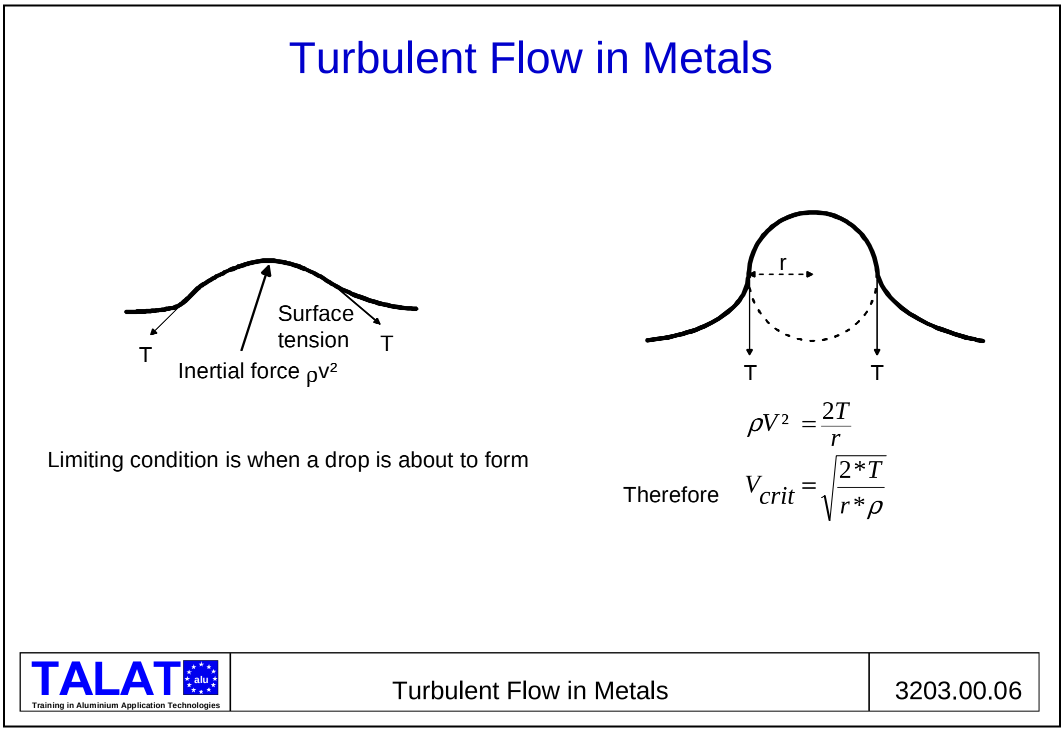
The fact that these oxide film defects often cause castings to fail leak tests clearly implies that the defects are continuous from one side of the casting to the other. Castings are normally tested by pressurising them with air whilst they are submerged under water so that the defects are revealed by a stream of bubbles. The operator then attempts to seal the porosity by peening over the surface, leaving these tell-tale marks on the casting surface (**Figure 3203.00.05**).

TALAT alu Training in Aluminium Application Technologies	DIesel Engine Sump - The Using of Peening to Stop Leaks	3203.00.05

The lesson to be learnt from this is that castings in metals such as aluminium should not be top-poured. The remainder of this lecture is concerned with how to fill a casting without creating this mess of entangled oxide films.

Critical Velocity

We will firstly consider a simplified approach to the formation of surface turbulence in a liquid metal. The top half of **Figure 3203.00.06** shows a slice through a liquid metal which is subjected to some vertically rising disturbance, such that a wave starts to form under an inertial pressure having an approximate value of $\rho \cdot V^2$, where ρ is the molten metal density and V is the velocity of the disturbance. The ultimate shape of the disturbance would be a droplet of radius r, but its formation is restrained by the surface tension T.



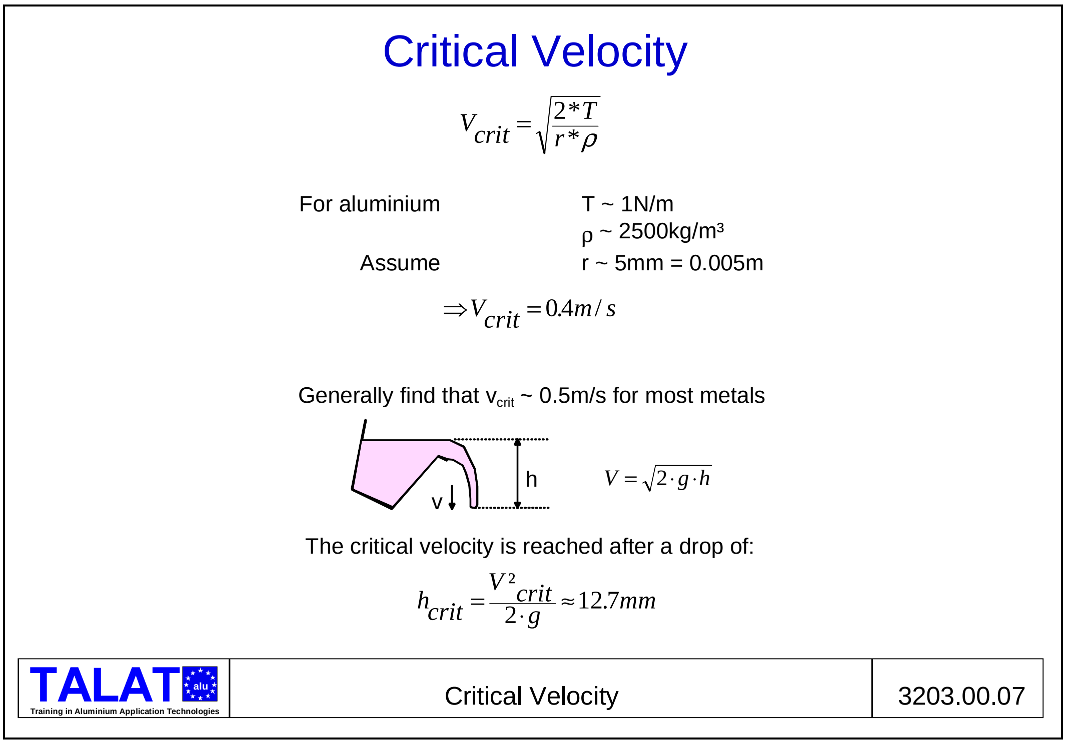
The limiting condition can be seen to be when the inertial force is balanced by the surface tension force, i.e. when

$$\rho \cdot V^2 = \frac{2 \cdot T}{r}$$

so that the critical velocity, V_{crit}, can be defined as

$$V_{crit} = \sqrt{\frac{2 \cdot T}{r \cdot \rho}} \qquad (1)$$

We shall now consider what this means when applied to aluminium.



Typical values for liquid aluminium are (see also **Figure 3203.00.07**)

$T = 1 \text{ N m}^{-1}$

$\rho = 2500 \text{ kg m}^{-3}$

$r = 5 \text{ mm} = 0.005 \text{ m}$ (assumed radius of aluminium droplet)

and so

$V_{crit} = 0.4 \text{ m s}^{-1}$

Slightly more accurate values for these parameters give a value of V_{crit} of about 0.5 m s^{-1} for aluminium and it is found that most other liquid metals tend to give similar values within a factor of 2. This is because T tends to increase as ρ increases, so keeping the ratio T/ρ roughly the same from one metal to another.

The above values of V_{crit} therefore provide an indication of the critical velocity of molten metal in a mould. Once these values are exceeded, the surface of the metal will behave in a turbulent fashion, i.e. there is a real risk that the surface will break up into waves and droplets, causing the oxide film defects seen earlier.

It is instructive to obtain a feeling of how readily this critical velocity is reached. It can be shown from a simple energy balance (of potential and kinetic energies) that when a stream of metal has fallen a height of h, its velocity V has become

$$V = \sqrt{2 \cdot g \cdot h} \qquad (2)$$

where g is the acceleration due to gravity.
Combination of equations (1) and (2) shows that the critical drop height, h_{crit}, before the critical velocity is reached is given by

$$h_{crit} = \frac{V_{crit}^{2}}{2 \cdot g} = 12.7 \text{ mm}$$

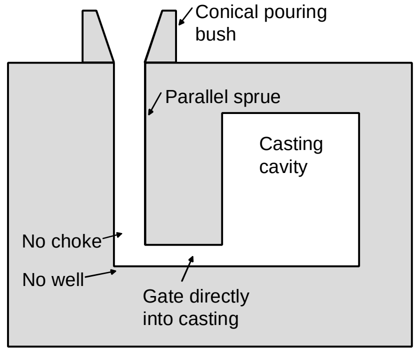
when $V_{crit} \sim 0.5 \text{ m sec}^{-1}$

This shows that once the metal has fallen by *only* 12.7 mm, it is already at a critical velocity, i.e. it has sufficient energy to break its surface in a turbulent manner, and is therefore likely to cause defects. This implies that it is *never* possible to fill a casting from the top and therefore the only solution is to fill it from the bottom.

Casting Design Assessment

I would now like to consider the various elements of the running system and will start by examining what constitutes a deliberately bad running system (**Figure 3203.00.08**). Unfortunately, it is one that is seen all too often in foundries.

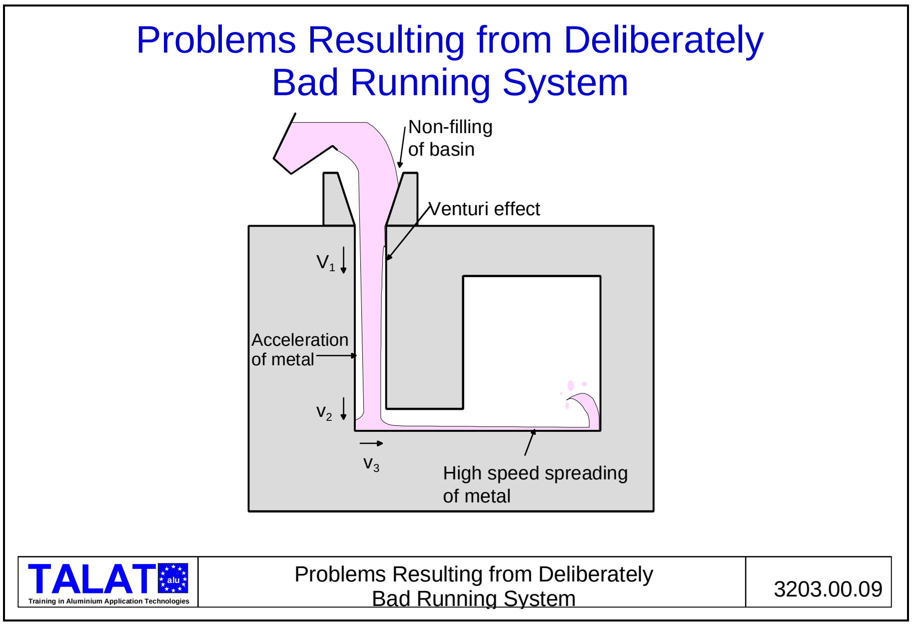
Deliberately Bad Running System



TALAT | Deliberately Bad Running System | 3203.00.08

This a section through a mould and shows four deliberate mistakes, namely a conical pouring bush, a parallel sprue, no choke and no runner bar, so that the metal enters directly into the casting. We will now consider the effect of these bad design features.

As the metal is poured directly from the ladle into the conical pouring bush, it is already moving quite quickly as it enters the top of the sprue. Its velocity V_1 will be determined through the height through which it has fallen. Thus, this basin design is bad because it has no decelerating effect on the metal. As the metal runs down the sprue, it accelerates due to gravity and so the stream gets thinner, reaching a velocity V_2 at the bottom. Since there is no 'choke' at the bottom of the sprue, neither it nor the pouring basin ever fill up completely. As a result, there is a Venturi effect with air being sucked into the metal stream through both the sand walls of the sprue and the incompletely filled pouring basin, thereby creating conditions to form oxides (**Figure 3203.00.09**)



The metal stream then hits the bottom of the sprue. One might intuitively expect that it would then form a splash but slow-motion video photography has shown that, contrary to expectation, the stream spreads out in a relatively thin film along the horizontal surface of the gate with a velocity of V_3 which can be significantly greater than V_2. It therefore enters the casting at speed, hitting the far wall where it rebounds in an uncontrolled manner, forming a splash and creating conditions for further oxidation.

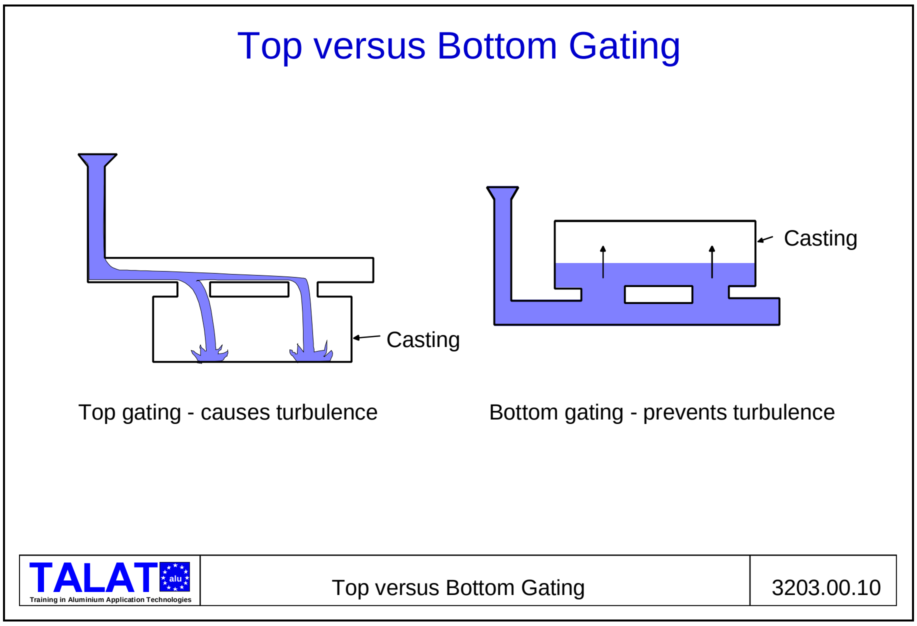


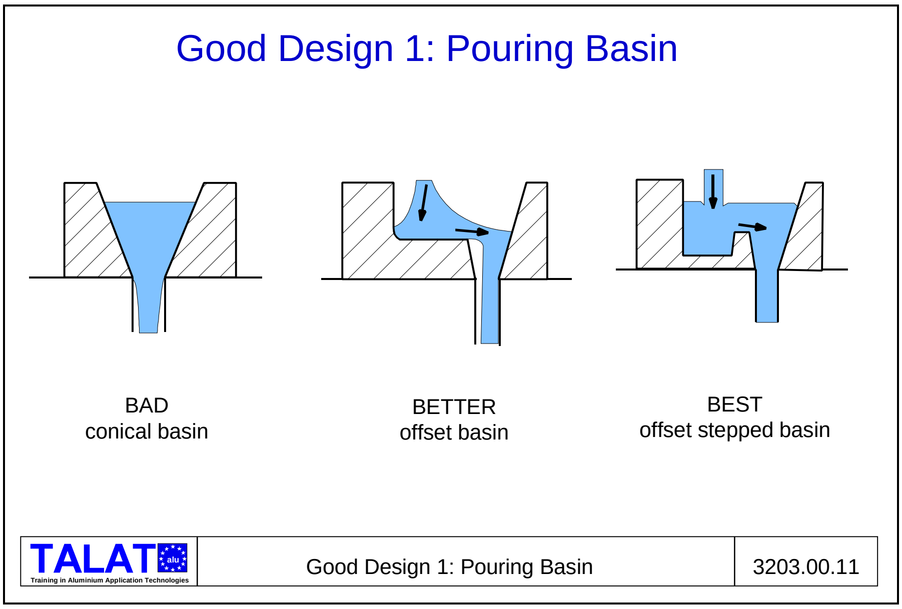
Figure 3203.00.10 shows another common mistake, in which the metal is introduced into the top of the casting cavity, i.e. by top gating. The critical velocity is readily exceeded and the resulting turbulence and splashing cause oxidation of the molten metal. The preferred technique is to use bottom gating, i.e. to introduce the metal uphill into the casting although, as we will see, it is still important to limit the velocity with which the metal enters the mould.

Having considered ways in which a casting should NOT be produced, we will now look at the proper way to design a running system, starting from the pouring basin and working our way through in order.

Pouring Basin

As we have already seen, it is important to avoid the use of a conical pouring basin since this does not decelerate the metal and also acts as a venturi and causes air ingress.

One improvement would be to use an offset pouring basin which helps to decelerate the metal stream before it enters the sprue. However, a jet of metal still travels at high velocity across the top of the sprue, hitting the far side, and there is a tendency for the metal to flow down only one side of the sprue (**Figure 3203.00.11**).



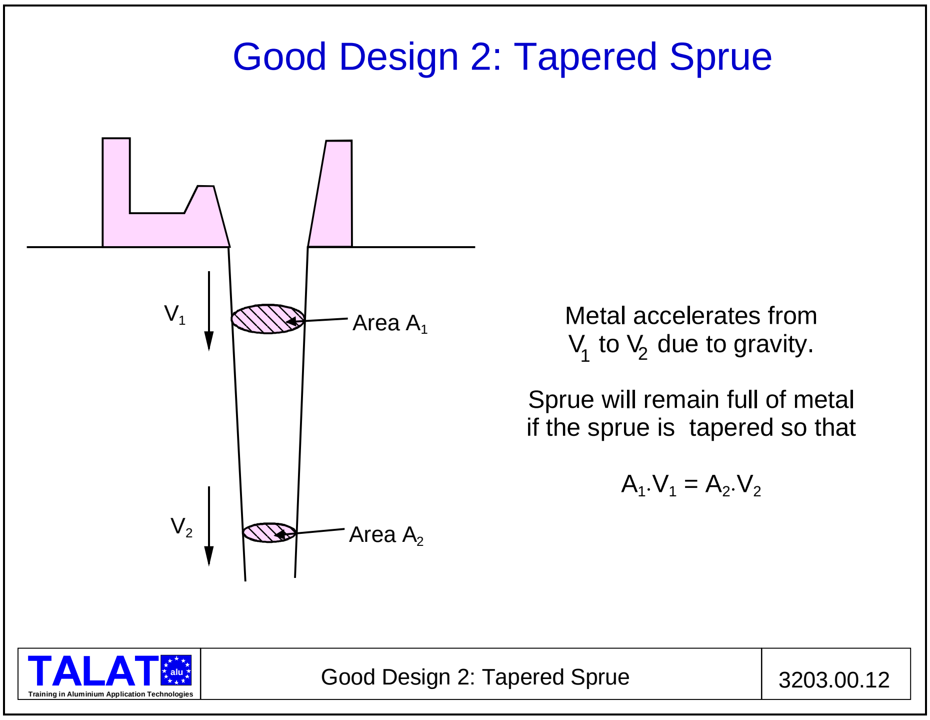
The best design is to introduce a step into the basin to give an *offset stepped basin.* The step acts to stop the rapid motion of the metal over the top of the sprue and helps to ensure that the latter is completely filled.

Tapered Sprue

The next point is to ensure that a tapered sprue is used (see **Figure 3203.00.12**). The stream of metal will accelerate from a velocity V_1 at the top of the sprue to a velocity V_2 at the base of the sprue and the conservation of matter requires that its cross-sectional area will decrease from A_1 to A_2. It can therefore be seen that the sprue will remain full if the following criterion is satisfied:

$$A_1 \cdot V_1 = A_2 \cdot V_2$$

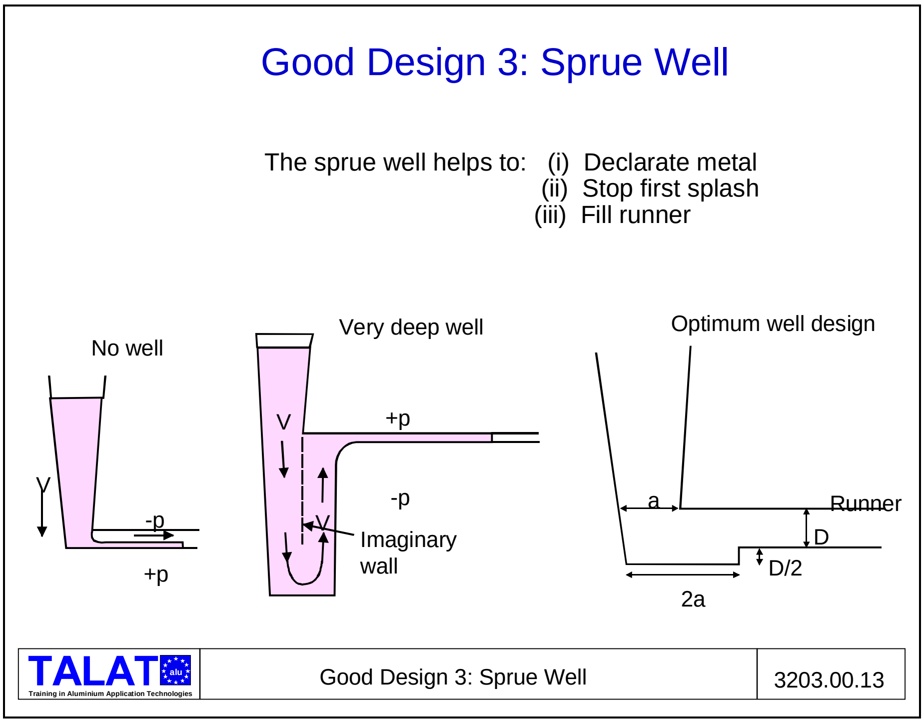
A tapered sprue can be readily moulded into vertically-parted moulds, but is more difficult to produce in horizontally-parted moulds because the sprue pattern has to be withdrawn from the top of the mould. (If the sprue pattern is fixed to the pattern plate then, of course, the sprue automatically has an incorrect, negative taper, with much consequent damage to the liquid metal entering the mould.).



Sprue Well

The next stage is to transfer the metal from the sprue into the runner bar via a sprue well (also called a sprue base). This has three important functions:

(i) it helps to decelerate the metal,
(ii) it constrains the first metal as it exits from the sprue and prevents splashing,
(iii) it helps to ensure that the runner bar is filled.

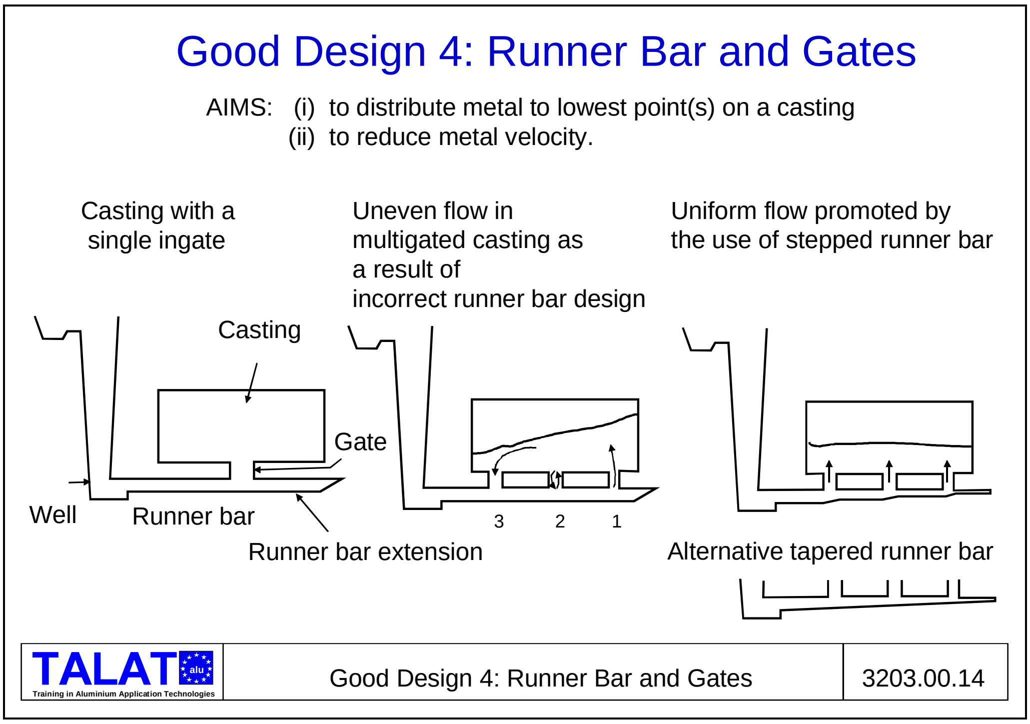


If there is no well, the falling metal stream hits the bottom surface of the runner bar at a velocity V and spreads along the bottom surface of the runner (see **Figure 3203.00.13**). In doing so, it creates a pressure, + p, which is balanced by a negative pressure, - p, on the top surface of the runner bar. This tends to draw in air through the permeable sand mould, leading to oxidation of the metal.

We shall now consider a hypothetical case of a very deep well designed such that the falling metal stream reaches the bottom of one side of the well and then returns up the other side without meeting the falling metal. If we assume that there are no energy losses due to friction, then as the metal is about to exit from the well into the runner, its velocity will again be V, the same as when it entered. This time, however, the metal hits the top surface of the runner bar and spreads along it. In doing so, it creates a pressure + p on the top surface and a corresponding pressure - p on the bottom surface. It can therefore be seen that a very deep well completely reverses the metal distribution and pressures that are produced when there is no well.

This purely hypothetical reasoning (a kind of thought experiment) indicates that some intermediate well design will be 'neutral', i.e. metal will tend to fill the cross-section of the runner and to create equal pressures on the top and bottom surfaces of the runner bar. Rather surprisingly, there has been little detailed research on well design. However, recent experiments suggest that the optimum well design has a base with a depth in the range D to D/2, where D is the depth of the runner bar. The well should have a width of 2 a, where a is the diameter of the bottom of the sprue.

Runner Bar and Gates

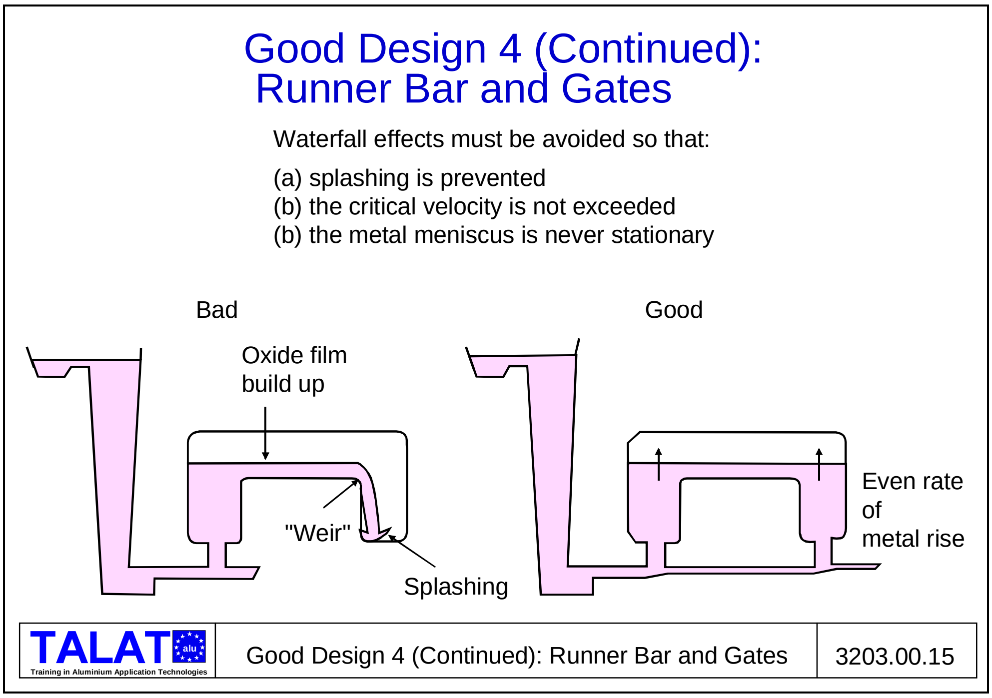


The well should be the lowest point of the casting and filling system and the metal should always progress uphill thereafter (**Figure 3203.00.14**). In doing so, it firstly passes through the runner bar which distributes it through gates to the lowest point or points on the casting. Careful thought has to be given to how the metal will flow through the runner and casting, bearing in mind the need to keep the speed low in order to avoid surface turbulence.

In some castings, only one gate will be required. In such cases, the runner bar will be a simple parallel sided channel, arranged so that the metal rises uphill from the sprue base, through the runner and gate and into the casting. It is good practice to have a runner bar extension which can be used to receive the first metal poured into the mould and which often contains air bubbles and slag particles.

In other castings, it may be necessary to use two or more gates, in which case the runner bar must be stepped to promote equal flow through both gates. If this is not done, in the case of three gates for instance, the furthest gate (gate1) tends to fill first and so becomes super-heated, whereas metal tends to flow out of gate 3 and the latter becomes cold. Gate 2 takes on a neutral character. Uneven flow leads to an uneven temperature distribution and an increased risk of turbulence-induced defects. The runner bar should therefore have a gentle tapered step at each gate to promote even metal flow.

In extreme cases, where there are many gates or a single gate along the length of the casting, the runner bar can be tapered along its length.

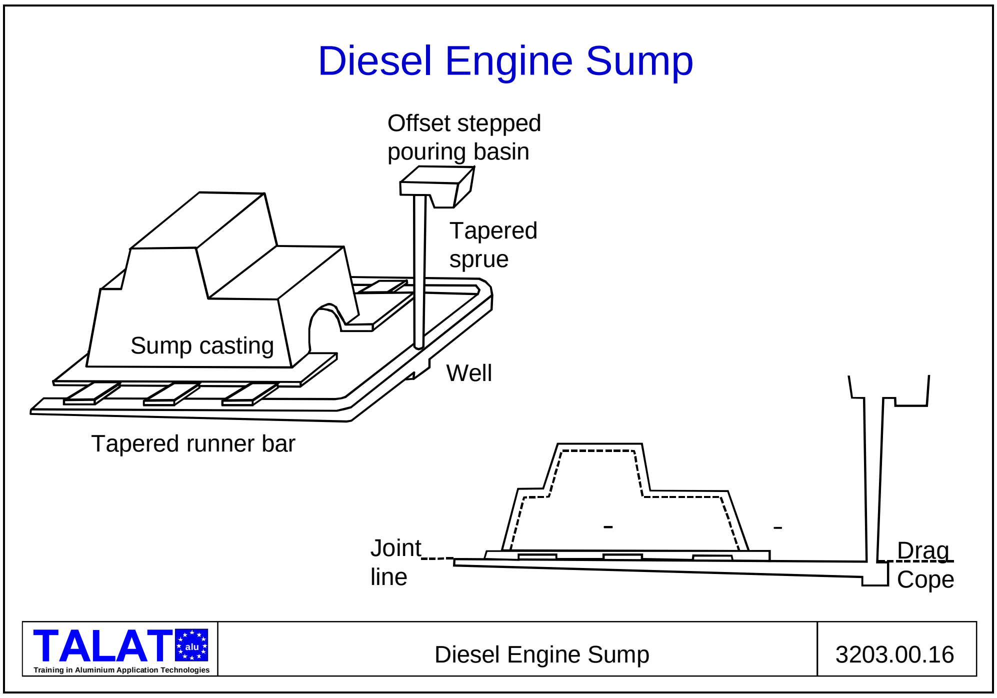


Another important feature is that the gating arrangement must avoid waterfall effects (see **Figure 3203.00.15**). In the first example shown here, metal is introduced into only one leg of an inverted 'U' casting. As one leg fills up, the point is reached where the metal splashes over the 'weir'. The splashing leads to unwanted oxidation of the metal and is of course particularly bad if the fall exceeds the critical height defined earlier (12.5 mm in aluminium) since the critical velocity condition will then be reached. At the same time, whilst the metal is filling the non-gated leg, the top meniscus is static. As a result, its oxide surface layer will be rapidly growing in thickness and will become increasingly difficult to move once the waterfall effect has finished. The molten metal will then tend to flow over the top of the thick oxide skin, leading to an entrapped defect which is known as an **oxide lap.**

The solution is to use more than one gate, so that metal rises in both legs at the same time. This avoids both the waterfall effect and the development of thick oxide films. For castings with multiple isolated low points, a separate ingate is required for each low point.

Good Designing Example

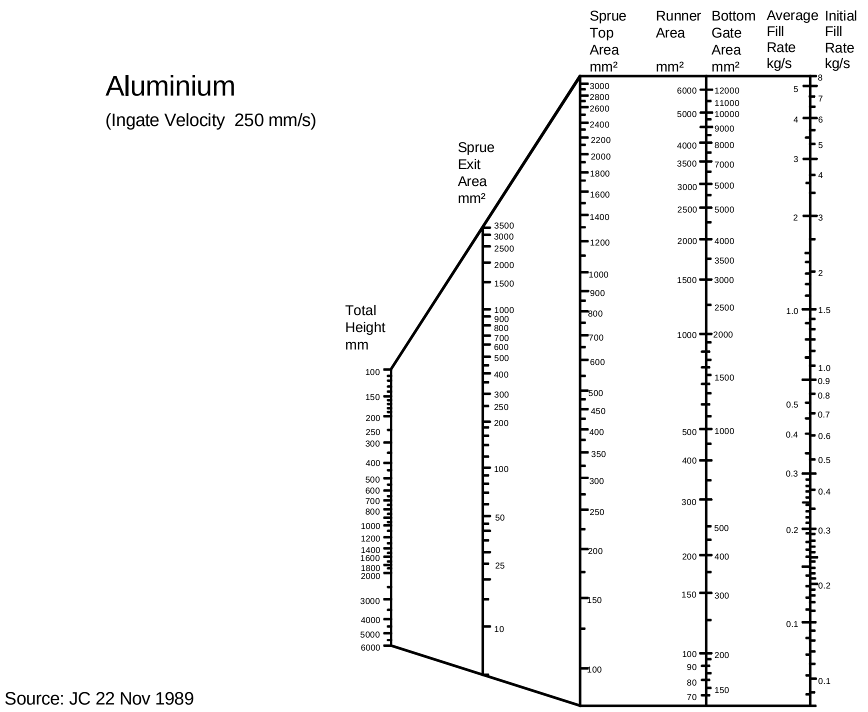
Figure 3203.00.16: Some of these aspects of good design will now be examined in a little more detail by reference to the sump casting that we saw at the beginning of the lecture. You will recall that this contained extensive oxide defects which led to leakage problems. This was originally top poured, i.e. the casting was the other way up to that shown here and the metal was poured in through the flanged area.



This shows a much better way of making the casting. Firstly, the casting is inverted. The metal is poured into an offset stepped pouring basin to reduce the velocity at the top of the sprue. The sprue is tapered so that aspiration of air is prevented as the metal accelerates and the stream reduces in area. The metal passes through a well which acts to control the metal as it enters the horseshoe shaped runner bar. This design is used to distribute the metal to both sides of the casting. (If the metal were delivered only to one side, then a waterfall effect would occur over the semi-circular cut-outs in the end walls.) Gates are taken off the top of the runner and into the bottom edge of the casting, thus fulfilling the requirement to fill from the bottom up. Calculation showed that 3 ingates were required per side to ensure that the critical velocity of 0.5 m s^{-1} was not exceeded through the ingates. It would have been possible to use a stepped runner bar, but in this case it was considered simpler to mould a tapered runner bar.

Nomogram for Running System

I would like to finish this lecture by briefly considering how running systems are designed by using this sump casting as an example. Their dimensions can be calculated from first principles but, in practice, it is easier to use nomograms designed for the purpose.



TALAT Training in Aluminium Application Technologies | Nomogram for the Design of Running Systems | 3203.00.17

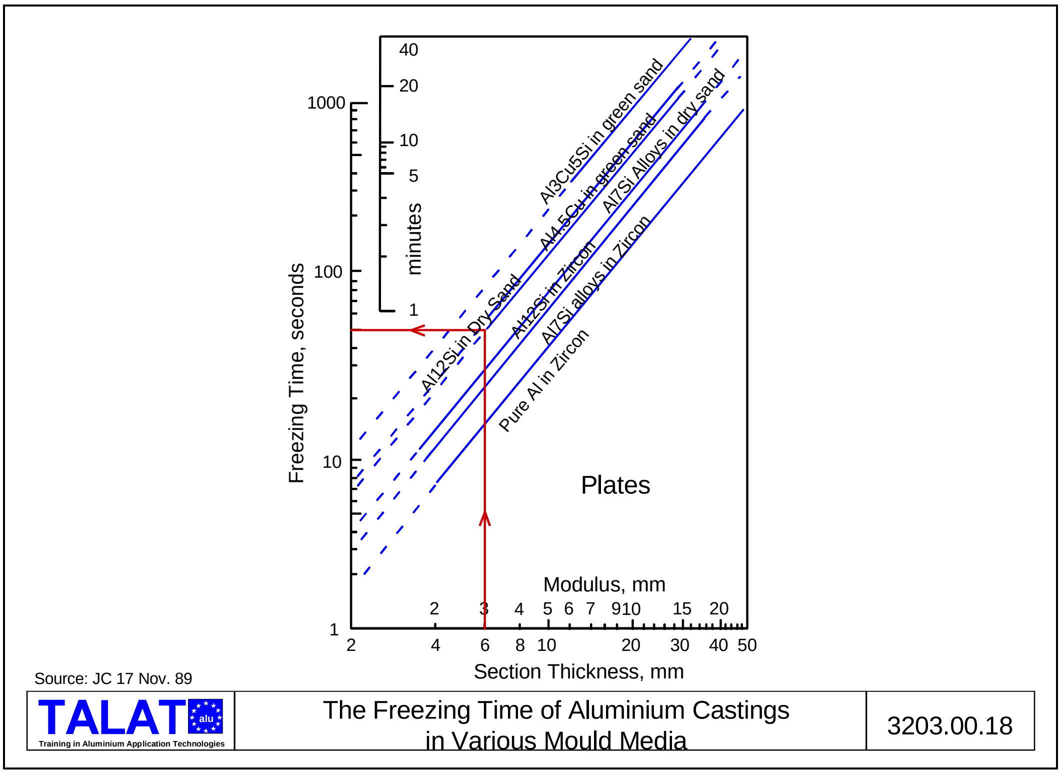
Figure 3203.00.17 is a nomogram for the design of running systems for aluminium castings and will ensure that the maximum ingate velocity does not exceed 250 mm s^{-1}. This is half the critical velocity and will therefore provide a certain safety margin.

We start on the right-hand side of the nomogram and move to the left. The first thing we need to calculate is the average filling rate. The weight of the casting is easy enough - it weighs 6 kg. We also need to know the weight of the running system which is of course unknown until it has been designed! However, as a first estimate, we can use previous experience to guess a weight of 4 kg, therefore giving a total weight of 10 kg.

We next need to select the time it will take to fill the mould. Again, this is not easy and is based on experience and basically a question of trying to imagine how the metal will flow through and fill the mould on the foundry floor. In this case, we could imagine that it might take 10 seconds for the metal to fill the mould, giving an average filling rate of 1 kg s^{-1}.

Solidification Time Assessment

Another way of approaching this is to predict the solidification time for the thinnest section of the casting, using information such as shown here (**Figure 3203.00.18**), and then to use this as a guide to selecting the filling time. This graph shows that our 6 mm thick casting produced in an Al-7Si alloy in a dry sand mould would solidify in about 50 seconds. Clearly, it is important that the casting is poured in less than that!! A filling time of 10 seconds would appear to be appropriate.

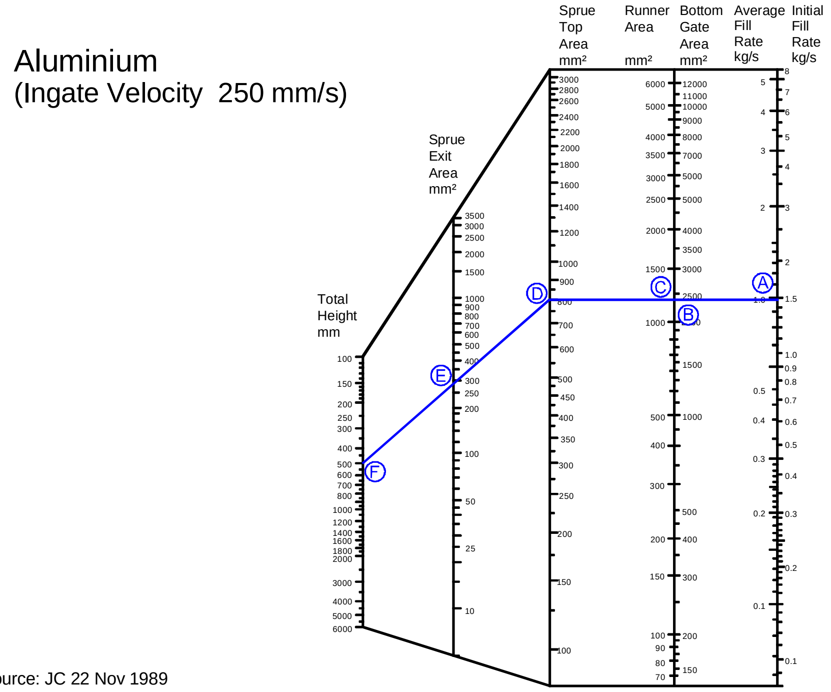


Gates

Returning to the nomogram, we can now place the average filling time of 1 kg s^{-1} on the right hand axis (point A in **Figure 3203.00.19**). A horizontal line is then drawn to intersect the next two vertical axes. The intersection at point B gives the required gate area of 2400 mm^2. We then have the freedom to select how we wish to use that available gate area - whether we want one gate of 2400 mm^2 or whether we want a multiplicity of gates having a total area of 2400 mm^2. In this case, it is wished to run the metal into both sides of the casting and it is felt appropriate to use three gates on each side. We therefore now have 6 gates, each having an area of 400 mm^2, and again it is our responsibility to choose the actual dimensions. To ease cut-off, it might be best to use thin gates, so one possible choice would be gates of 4 mm thick x 100 mm long. In choosing the gate thickness, consideration must be given to the resulting junction between the gate and the casting: this is considered in greater detail in **Talat Lecture 3206**.

Also on the same vertical axis, we see that the runner area should be 1200 mm^2 (point C). Since it is a horseshoe runner, each leg should have an area of 600 mm^2 at the start. Again, it is the Methods Engineer's responsibility to choose the actual dimensions, one choice being an approximately square runner of 24 x 25 mm. This would then be tapered down at each ingate, as we have previously seen.

Moving to the intersection with the next axis, point D gives the area at the top of the sprue as 800 mm^2 which could be satisfied by a square sprue of about 28 x 28 mm or a round sprue of 32 mm diameter.

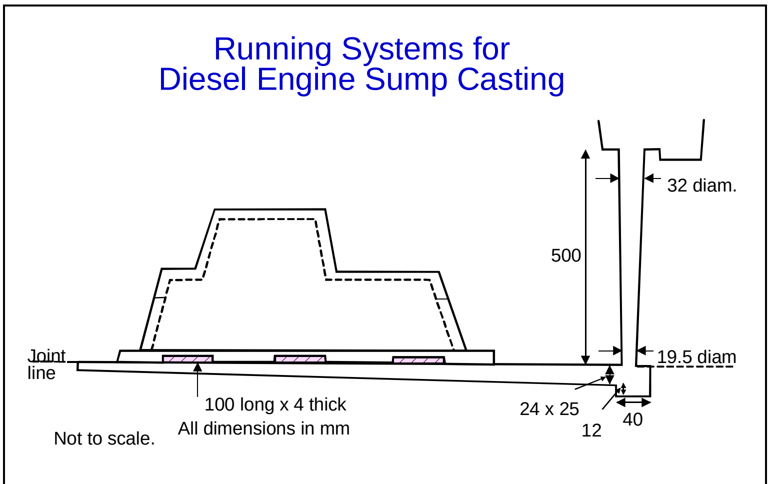


Source: JC 22 Nov 1989

TALAT Training in Aluminium Application Technologies	Nomogram for the Design of Running Systems: Exercise	3203.00.19

Sprue Height

We then need to decide how high the sprue will be. This will be determined by the height of the casting, plus any feeders on the casting, and by the minimum sand thickness over the top of the casting. In this case, a sprue height of ~500 mm was required. This is entered on the nomogram as point E on the left-hand axis. A straight line is then drawn between points D and E, to give an intersection at point F on the Sprue Exit Area axis. The value can be seen to be 300 mm^2, which could be satisfied by, for example, a square sprue of 17 x 17 mm or a round sprue of ~19.5 mm diameter. This sprue exit area will act as the 'choke', i.e. it will control the flow of metal so that the fill time will be 10 seconds, which is the value selected at the start of the calculation.



TALAT | Running Systems for Diesel Engine Sump Casting | 3203.00.20

Figure 3203.00.20 shows the calculated dimensions of the runner system. It has been assumed that square sections are used for the sprue and runner, although other cross-sectional shapes could be used, so long as the areas are correct. The remaining important feature to be designed is the well base which is based on the optimum dimensions which have already been defined in **Figure 3203.00.13**.

When working out the dimensions of a running system, it is helpful to follow a logical sequence of calculations. It is recommended to use a worksheet such as shown here (**Figure 3203.00.21**) which is designed to be used in conjunction with the nomogram.

Runner and Gating Design Worksheet

Customer : Motor Co. Inc			Material:
Description : Diesel Engine Sump			Signature: RAHarding
Part No. : A12345			Date: 5 June 1993
Calculations	#1	#2	#3
Description:			
Casting Wt (kg):	6		
Gating System Wt. (kg):	4		
Total Weight (kg):	10		
Choose Fill Time (s):	10		
Arg. Fill Rate (kg/ s):	1		
Gate Area (mm²):	2400		
No. of Gates:	6		
Gate Size (mm X mm):	4 X 100		
Runner Area (mm²):	1200		
Number of Runners:	2		
Runner Size (mm X mm):	24 X 25		
Sprue Top Area (mm²):	800		
Sprue Top Dia. (mm):	32 ∅ or 28 □		
Sprue Height (mm):	500		
Sprue Exit Area (mm²):	300		
Sprue Exit Dia. (mm):	19,5 ∅ or 17 □		
Wall Dia (mm):	40		
Wall Depth (mm):	12		
Notes:			

TALAT Training in Aluminium Application Technologies	Runner and Gating Design Worksheet	3203.00.21

Conclusion

In conclusion, this lecture has considered the right and the wrong ways of filling a mould cavity with liquid metal. All too often, foundries do not use the correct practice, with the result that castings of an inferior quality are produced. This is especially true when the molten metal is particularly sensitive to the formation and entrapment of oxide films, such as is the case with aluminium. However, methodologies do exist for designing filling systems which, if followed carefully, will ensure that high quality castings are consistently produced which are suitable for service under the most arduous conditions.

Literature

Campbell, J.: Castings, Butterworth Heinemann, 1991.

List of Figures