

Figure 10.2 illustrates the complexity of the casting industry by the wide variety of its moulds. The use of permanent metal moulds brings the advantages of rapid freezing, giving castings with good mechanical properties, but also the penalty of having to wait for the casting to freeze before opening the mould and the ejection of the casting. For moulds manufactured and destroyed each time from aggregates, the cooling is slower usually giving poorer properties to the casting, but there is no waiting time for solidification. Productivity is now governed by the speed at which moulds can be made. This can be impressively high for highly productive green sand plants; a mould every 10 s is possible. Furthermore, it is common for the mould to contain more than one impression.

This broad brush description requires much, very much, qualification as is attempted in this chapter.

15.1 INERT MOULDS AND CORES

Very few moulds and cores are really inert toward the material being cast into them. However, some are very nearly so, especially at lower temperatures.

Metal moulds have the great advantage that they are relatively inert toward the liquid metal. They are usually used warm and dry, so their intrinsic hydrogen content is low, in sharp comparison to the various aggregate moulds that contain sufficient moisture and other volatile and reactive components to make copious and generous hydrogen contribution to the cast metal.

The usefulness of a relatively inert mould is emphasised by the work of Stolarczyk (1960), who measured approximately 0.5% porosity in gunmetal cast into steel-lined moulds, compared with 4.5% porosity for identical test bars cast in greensand moulds.

For light alloys and lower-temperature casting materials, investment moulds are largely inert. Interestingly, dry sand moulds (i.e. greensand moulds that have been dried in an oven) have been found to be largely inert, as shown by Locke and Ashbrook (1950).

Carbon-based and graphite dies have been found useful for zinc alloys. However, their lives are short for the casting of aluminium alloys because of the degradation of the carbon by oxidation. All the more impressive therefore is the use of graphite moulds for steel, used for the casting of millions of railroad wheels by the Griffin Process. Carbon-based moulds are used for the casting of titanium alloys in vacuum. Oxidation of the mould is reduced by the vacuum environment, but the contamination of the surface of the titanium casting with carbon is severe, promoting the formation of an outer layer of the alloy where the titanium alloy α -phase is stabilised. This surface layer is known in titanium castings as the *alpha-case*. It usually has to be removed by machining or chemical dissolution.

15.1.1 PERMANENT METAL MOULDS (DIES)

The use of a mould that is permanent has always been attractive to founders ever since the use of hollowed out pieces of stone used to cast multiple copies of bronze axes and arrow heads.

The concept remains popular because usually the customer will pay for it, and once paid for, the mould then costs little more in service, provided no catastrophe overtakes it. Unfortunately, it has to be noted that catastrophic failure, often as a result of thermal fatigue aided by internal stress from its heat treatment, is not unknown.

The practice of using permanent moulds is, with some significant exceptions that will be listed later, usually confined to low melting point alloys; aluminium alloys being the most common. Other cast materials include alloys of magnesium, zinc and lead. Only rarely are permanent moulds used for the higher temperature alloys such as brasses and bronzes and cast iron.

The major metallurgical benefit of a metal mould, compared with an aggregate mould, is the relatively rapid freezing, conferring higher mechanical properties. Moreover, the liquid metal and mould are practically inert toward each other, so that there are no significant chemical reactions. This is an additional and significant metallurgical benefit of metal moulds that is often overlooked.

The major challenge provided by permanent moulds is that the mould has to be designed to disassemble to release the casting. This obvious point is not to be underestimated because for many castings this presents major limitations to both the casting and the filling and feeding systems. Sand castings have no such problem because the mould is destroyed to release the casting, thus allowing geometries of almost any complexity or sophistication.

Gravity and Low-pressure die-casting dies (Permanent Moulds)

For dies filled simply by pouring under gravity, they are not surprisingly called *gravity dies* (known in the United States, also not surprisingly, as *permanent moulds*). The service conditions for a gravity die are not too severe because the die is to some extent protected from direct contact with the melt by the application of a die coat.

Low-pressure die casting dies are extremely similar; being made from iron or steel, depending on the service requirements, and once again enjoy the protection of a ceramic die coating applied as a wash by painting or spraying.

One of the most notable high temperature developments of low-pressure die casting is the famous Griffin Process for steel railway rolling stock. In this case, the dies are machined from graphite. Although a successful process has been built on this process, the machining of graphite is always a somewhat messy and dirty occupation. There seems little doubt that the process might have been operated with greensand with practically no loss of accuracy and no loss of performance of the steel casting. It would be interesting to see a comparative evaluation of the two types of mould for this high volume product.

High-Pressure die-casting dies

High-pressure die casting (HPDC) is known in the United States, confusingly, as die-casting.

Dies for pressure die casting are hardly inert, partly because of the gradual dissolution of the unprotected steel die, but mainly because of the overwhelming effect of the evaporation of the die-dressing material. This may be an oil- or water-based suspension of graphite sprayed onto the surface of the die that is designed to cool and lubricate the die between shots. The gases found in pores in pressure die castings have been found to be mainly products of decomposition of the die lubrication, and the volume of gases found trapped in the casting has been found to correspond on occasions to nearly the volume of the die cavity.

A little-known problem is the boiling of residual coolant trapped inside joints of the die. Thus as liquid metal is introduced into the die, the coolant, especially if water-based, will boil. If there is no route for the vapour to escape via the back of the die, vapour may be forced into the liquid metal as bubbles. If this happens, it is likely that at least some of these bubbles will be permanently trapped as blow holes (note the *correct* and rather rare use of the term 'blow hole' in this instance) in the casting. This problem is common in pressure die and squeeze casting processes.

The recent development in pressure die casting to separate the functions of (1) cooling of the die and (2) its lubrication, is seen as a positive step toward solving this problem. The approach is to use more effective cooling by built-in cooling channels, whereas lubrication is achieved by the application of minute additions of waxes or other materials to the shot sleeve.

When used for its common purpose of casting aluminium or magnesium alloys the dies are necessarily made from good quality hot work tool steel, H13. In this case grey iron would not have the adequate surface integrity because of the presence of graphite flakes in the material, and would not have the strength or fatigue resistance. No protective coating is applied to the surfaces of the die. The result is an excellent surface finish. The danger of cold laps is reduced by extremely rapid filling, and by high pressure that is subsequently applied to ensure faithful reproduction of the profile of the mould. Even so, of course, the high speed of filling causes other serious problems that we shall consider later.

Like all dies, however, it is regrettable that they are not really permanent. An aluminium casting weighing up to 1 kg might be produced tolerably well for up to 80,000 or 100,000 shots before the die will need to be refurbished as a result of heat checking (cracks from thermal fatigue of the die surface that produce a network of unsightly raised fins on the cast surface).

Magnesium alloy HPDCs are much kinder to dies, giving perhaps five times or more life. This is partly the result of the lower heat content of Mg alloys and partly because of the low solubility of iron in liquid magnesium that reduces its action to dissolve the die surface. In contrast, liquid Al has a relatively high solubility of iron, resulting in a phenomenon known as 'soldering' of the casting to the die. This action is particularly destructive to dies. It is countered to some extent by the addition of high levels of iron to HPDC alloys, thus pre-saturating the liquid metal with iron and so greatly reducing the tendency for the melt to dissolve the die.

Attempts have been made to cast molten stainless steels by HPDC. In this case the only die material capable of withstanding the rigours of this process was an alloy of molybdenum. Even these 'moly' dies suffered early degradation by thermal fatigue cracking, threatening the commercial viability of the process. So far as the author is aware, partially solid (inaccurately called 'semisolid') stainless steels have not been extensively trialed. These cooler mixtures that have already given up practically half of their latent and specific heat during freezing would greatly benefit die life. The commercial viability of the somewhat more expensive mixture would remain a potential show-stopper of course.

Because of the very high pressures involved in HPDC internal cavities are usually limited to those formable by straight withdrawable steel cores. If the core cannot be withdrawn, then the usual alternatives such as sand cores are totally unsuitable because they are penetrated by the liquid metal. One of the very few options to make undrawable cavities in HPDCs is salt cores, described later.

15.1.2 SALT CORES

Salt cores are a class of components that once again can be extremely dry and can be used hot. Provided the salts are mainly chlorides and fluorides, these highly stable compounds have very little reaction with most molten metals.

They are useful to provide the undercuts and other difficult-to-mould features permanent mould and in HPDC of Al alloy parts, where simple two-part dies are preferred for robustness and mechanical simplicity. The core is subsequently dissolved out by immersion in water. Salt cores have been used for many years worldwide for the production of oil galleries in Al alloy gravity cast pistons. There is still interest in Japan on improving these core materials still further (Yaokawa, 2007).

Loper and colleagues (1985) review how salt has been used in various ways to make cores in Al alloy and grey iron castings. They describe many different mixtures of salts, including NaCl, KCl and CaCl₂. The only problem they reported was the loss of some mechanical properties of the cores during periods of high humidity. The cores were dissolved out by simple immersion in cold water, but faster in hot water, and faster still by pressurised water jet.

1. Solid salt cores have been made by the casting of molten salt using a gravity die (permanent mould) process.
2. Solid salt cores can be made by pressure die casting. Their successful use for internal combustion engines includes such achievements as closed deck cylinder blocks, as demonstrated by the Mercury Marine company in the United States since 1976. The heat content of the salt is sufficiently low that the dies have never been observed to suffer from any heat checking (cracking) problem. The cores are used almost immediately, being ejected from the first machine and loaded into a second pressure die casting machine standing nearby to make an Al casting. The cores may be subjected to a temperature equilibration treatment in an oven, the high coefficient of thermal expansion of the salt allowing an adjustment of size of the core if necessary.

One of the major advantages of the salt core technique in HPDC is its flexibility. It allows expensive tooling to be adapted, simply changing the salt core dies to revise the inner features of the casting, for a fraction of the cost of complete new tooling. With changes to cylinder bore diameter, or iron sleeves, etc. a block can be refurbished quickly and at minimal expense, compared with conventional HPDC tooling. Also, of course, the cores can provide much more complex internal detail. Major complex parts for small engines such as closed deck cylinder blocks could not be made without the use of such cores.

The cores are characterised by excellent surface finish and accuracy. Core breakage problems appear to be practically unknown. Furthermore, the salt casting is optimised for internal porosity simply by holding it against a light because it is translucent. No costly X-ray radiography is required.

Although to make an HPDC it is first necessary to make 'a second HPDC' tool for the core, the salt casting costs only about one quarter or one fifth of the cost of the Al die casting so the economics are not discouraging. The rate of production of cores matches the rate of production of Al castings, and the rate of washing out is twice this rate.

3. Salt cores formed of aggregates bonded with salt have sometimes been used. The aggregates have been alumina, iron oxide or silica sand and up to 40% by volume of salt has been used.
4. Other varieties of salt core have been formed from mixture of grains of an inert aggregate with grains of salt both bonded with a resin binder. The best solution rates were achieved using a similar size of sand and aggregate grains because this maximised the permeability of the core. The production technique has the benefit of being a cold process using normal core production techniques.

These versatile moulding materials probably deserve wider use throughout the industry.

15.1.3 CERAMIC MOULDS AND CORES

The other category of inert moulds are the ceramic moulds. Thus lost wax moulds are fired at high temperature (usually 1000°C or above) and thus are especially dry. In addition, of course, ceramic moulds can be used at high temperature, so there is a greatly reduced chance for reactions with volatile mould components.

Ceramic moulds are such a specialised technology that only an outline can be given here. A tremendous and unique advantage is the freedom to select an appropriate mould temperature for casting. Ceramic moulds are usually fired to a relatively high temperature before casting. Thus they are generally free from outgassing and reactivity problems with melts. Ceramic moulds for light metals are often pre-heated to a temperature in excess of the freezing point of the melts so that there are no problems of fluidity – if a sufficiently long fluidity test could be devised the melt would run for ever! For Ni- and Co-based superalloys for single crystal turbine blades, the moulds are similarly held above the freezing point of the melts during filling and only slowly withdrawn into a cooling zone to grow the crystal under conditions of controlled speed and temperature gradient.

Investment Shell (Lost Wax) Moulds

As a monarch might be *invested* in the *vestments* of royalty, the verb *to invest* means *to coat, cloak or enrobe* and thus nicely enshrines the concept of the making of an *investment coating* around a wax pattern which is *invested* (i.e. *coated* by dipping) in successive layers of a slurry of finely powdered mineral, most commonly zircon or aluminium silicate (mullite), and binder (typically a very fine dispersion (a sol) of silicic acid). A coarser mineral (stucco) is applied to each layer of slurry before drying, so as to gradually build up a shell. The investing process is the special feature that confers the admirable surface finish and fine detail that investment castings enjoy. After drying, the shell is steam heated, typically in an autoclave to melt out the wax, giving the process its other well known name, the *lost wax* process. Having lost its wax, the shell is then fired to (1) burn out any residual carbon remaining from traces of wax and (2) develop the full strength of the shell. Strength development during firing comes about as a result of the silicic acid losing its water and being converted to a ceramic substance (cristobalite). Sometimes the shells are cooled to room temperature once again and checked for cracks which are then repaired. Otherwise, the shells are taken directly at the firing temperature and filled with metal.

When the casting has cooled to room temperature the shell has to be removed. This can present a problem. Many shells are stronger than the light alloy castings they contain, so that mechanically breaking off the shell can easily damage the casting. Analogously, the Ni-based single crystals are vulnerable, because any impact damage can cause a recrystallisation event during the subsequent heat treatment, thereby scrapping the blade.

Other disadvantages with the lost wax process include high unit cost, high energy consumption and that the spent shells are not reclaimed, although work is in progress to redress this issue. It is also difficult and expensive both to make cores for investment casting and to remove them afterwards. One common approach is to prepare a core by injecting a hot dispersion of slurry and wax into a core box cavity, cooling the resultant product and then firing it. The core can be

removed from the casting mechanically or by washing with caustic soda acid, techniques which are only feasible for ferrous metal castings.

Yet more potential problems should be highlighted: accuracy starts to be a significant problem for larger investment castings. This mainly results from distortions that occur in the wax before investment. For this reason, the provision of costly jigs and fixtures to straighten wax patterns is sometimes essential to guarantee accuracy.

Graphite-based investment shells have been used, particularly for very reactive metals such as titanium and zirconium (Howe, 1965).

Several recent developments are promising to revolutionise the lost wax process. These include new low-cost aggregate systems, new binder systems, techniques enabling shells and cores to be made far more quickly and cheaply and shells and cores that can be removed by washing with water after casting. This may lead to a growth in the popularity of lost wax investment casting, particularly for light metals.

Investment 2-Part Block Moulds (Shaw Process)

The investment block moulds, originally called the Shaw Process, originated in England by two British scientists, Clifford and Noel Shaw, in 1938, the year of my birth.

Although the process has generally fallen into disuse because of the apparent economy of simply making a lightweight shell, it has interesting strengths and advantages. For instance, a key difference between the shell and the block processes is that the block mould is made up as a cope and drag by the use of normal patternwork (not a wax pattern).

Ceramic slurry is prepared as a colloidal suspension of silica in alcohol, to which is added various ceramic fillers to make a smooth cream. The slurry is poured (invested) over a pattern, filling up to the top of a surrounding frame. After the mould is nearly set, but retains some flexibility as a gel, it is stripped from the pattern and placed on a board to dry and develop its green strength. At this stage the alcohol is flamed off, causing the surface of the mould to develop its characteristic micro-crazed structure, conferring essential permeability and thermal shock resistance to the mould. In this way, a drag half of a mould can be made. The cope half is made similarly. The two halves are then assembled, fired and cast. The cope and drag technique for mould assembly allows cores to be placed. Errors from the distortion of the wax pattern are also avoided. Lubalin and Christensen (1960) give a good description of the process and the wide range of castings that can be made.

One can envisage a more modern variant of this process in which the mould halves are injection moulded and thus produced rapidly for volume production with a fully robotised process. This concept seems ripe for re-examination and fuller exploitation.

Plaster Investment Block Moulds

Plaster of Paris ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$) is used as a mould material to make block moulds by a variant of the lost wax investment process. Plaster formulations contain 15–25% plaster, the remainder being inert fillers such as quartz and cristobalite and often Portland cement.

After energetic mixing of the powder mixture with water to make a paste, the mixture can be subjected to a vacuum and mechanical vibration to encourage the detrainment of bubbles, after which the mixture is poured around the wax pattern. The plaster takes up water of crystallisation, converting to gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and turns solid. Controlled slow drying follows, then de-waxing, and final firing at about 700°C (any higher temperature would cause the gypsum to lose its water of crystallisation and break down to a powder once again). In this way a one-piece block mould is made by a variant of the lost wax process.

The combination of this process with the application of a reduced pressure applied to the base of the permeable moulds (the steel box is open at its base) is the principle of the vacuum-assisted casting, allowing the pouring in air of extremely thin-walled castings only a fraction of a millimetre in wall thickness. The natural high fluidity noted in this process arises because of the high temperature of the mould (above the freezing point of the alloy, so that 'fluidity' in terms of flow distance is effectively infinite) and its extremely low thermal diffusivity. The process is ideal for aluminium and magnesium alloys, but can also produce some copper-based products if the castings are not too heavy.

The castings can be de-moulded by placing the moulds in water, causing the mould material to spall, pieces jumping off in a series of energetic and noisy explosions. The final traces of wet mould are brushed or washed away.

15.1.4 MAGNETIC MOULDING

The concept of holding a mould of fine steel shot together as a rigid mould by the application of a magnetic field has an alluring attraction. This apparently attractive process was invented in 1971 (Wittmoser 1971, 1972 and 1975), but never seems to have come into general use. Steel shot is 'frozen' into position around the pattern by the application of a magnetic field. After the casting is poured and solidified, the magnetic field is switched off, allowing the mould to disintegrate and the casting to be removed.

The reality, however, may be something else. Since Wittmoser first publicised his work in Germany relating to magnetic moulding in 1975, little has been done to extend and confirm this early sign of promise; this early failure to develop the process has never been explained. Wittmoser poured cast iron into lost foam moulds surrounded by steel shot in an Al alloy moulding box, the shot being held in place by a powerful magnetic field. This early work was almost certainly undermined to some extent by the mould material exceeding the Curie temperature of mild steel at approximately 900°C. Above this temperature, the ferromagnetic property is lost, so that parts of the mould would have become effectively non-magnetic. This may have explained some of the difficulties with the original experiments. Later workers (Geffroy et al., 2006) trialed Al alloys. At this lower casting temperature, the process might have been expected to have achieved more success. However, all these early trials continued to use a lost foam pattern as a starting point. This starting point may have been necessary to support the steel shot, but the process appears never to have been tested without this support, so remains unclear. If the magnetically held mould did not require the foam pattern for support it would have been valuable to know.

A further important disadvantage, apparently never mentioned in print, would be the cost of maintaining the powerful magnetic field that would have been required. In times gone by, this would only have been possible with the use of powerful electromagnets, thus consuming significant amounts of power for all the time the mould is made, assembled and cast. A hold-up on the casting line would have been particularly expensive. Nowadays a sufficiently powerful field may be available with modern permanent magnets, such as the neodymium-iron-boron types. As with all permanent magnets, such devices can be effectively switched on or off by the use of keepers. This possible option appears never to have been tested. Even if viable, the extensive use of such magnets in a foundry would probably represent an eye-watering capital outlay.

Although claims have been made that the technology combines the benefits of sand moulding with the rapidity of freezing of metal mould, Geffroy finds this to be largely untrue. The solidification rate is much nearer to that of sand moulds. This follows from the reduced contact between steel particles and the lower overall bulk density of the packing of the steel.

This process might be significantly more attractive if freed from the lost foam approach. The ability to make conventional 'lost air' magnetically moulded castings in copes and drags may yet hold promise. However, finally, we have to conclude that we all remain in the dark about the viability and economic value of this technology.

15.2 AGGREGATE MOULDING MATERIALS

Ken Harris (2008) has passed on to me a useful little formula from Dr Robert Sparks (2000). It is approximately

$$\text{AFS Number} \times \text{micrometers} = 15,000$$

Thus the widely quoted American Foundry Society fineness number for aggregates, particularly sands, can be approximately converted quickly into average grain diameters. Thus, we obtain some rough equivalents that are useful to commit to memory

$$\text{AFS } 50 = 300 \text{ } \mu\text{m}$$

$$\text{AFS } 75 = 200 \text{ } \mu\text{m}$$

$$\text{AFS } 100 = 150 \text{ } \mu\text{m}$$

$$\text{AFS } 150 = 100 \text{ } \mu\text{m}$$

$$\text{AFS } 200 = 75 \text{ } \mu\text{m}$$

When the molten metal enters an aggregate mould, the mould can react violently. Frenzied activity crowds into this brief moment of the birth of the casting: buckling, outgassing, pressurisation, cracking, explosions, disintegration and chemical attack. After all these possibilities, the survival of a saleable casting should perhaps be a matter for surprise. In this section, we examine the options for the casting engineer to ensure that the moulding and casting processes are appropriate, economic and under control.

Non-permanent moulds made from particulate materials that are designed to be broken up to release the casting after it has solidified are commonly known as sand moulds. However, there are now so many options for aggregates that are no longer really 'sands' that it hardly seems appropriate to continue to call them sand moulds. We should be calling them aggregated moulds (but the reader will notice occasional lapses by the author).

The many aggregates that can serve as adequate moulding sands have been reviewed many times. The reader who would like more detail is referred to reviews by Middleton (1964), Garner (1977), Rassenfoss (1977) and Harris (2005).

The nature of aggregate moulds is nicely illustrated by the observation that patterns transferred from old jolt-squeeze machines to new high pressure moulding machines produced castings that were undersize (simply because the mould were harder. The earlier softer moulds yielded under the weight of the melt, or the pressure generated by the graphite precipitation when casting iron, so becoming oversize).

15.2.1 SILICA SAND

Naturally, the most common aggregate still in use is silica sand because of its worldwide availability, appropriate particle size and distribution and high melting point. Even so, the situation is undergoing rapid change as a result of the danger of breathing in silica dust leading to the danger of silicosis, an incurable and sometimes deadly affliction. At the time of writing, silica sand in foundries is already banned in New South Wales, Australia.

In addition, the alpha quartz to beta quartz transition at around 530°C is accompanied by a total volume expansion of about 2.5% leading to length changes in the mould of around 1.5%. This is a serious volume change and gives the founder many problems of mould failure and loss of control over casting accuracy. For instance, in a mould 600 mm long with a delicate central core, when surrounded by liquid aluminium at 700°C, the core would easily exceed 530°C, but the mould would only achieve less than half of this increase, making a differential expansion of the order of 1.0%. Thus the core would expand relative to the mould by $600 \times 1/100 = 6$ mm. For a modern lightweight casting with walls at each end of the casting only 4 mm thick, the walls might be only 1 mm thick if the expansion were symmetrical. If not, the wall thickness could easily be 2 mm at one end and zero mm at the other. It is understandable that customers do not warm to the offer of windows in their castings in exchange for walls.

The problem of the large and non-linear expansion of silica sand is even worse in ferrous castings, particularly where castings are made with new sand. However, repeated reuse (re-cycling) of silica sand can reduce the problem because the proportion of more stable forms of silica such as cristobalite tends to increase each time the sand is heated to higher temperatures. Light-alloy foundries do not generally heat enough of the sand sufficiently to gain this benefit, although light metal foundries that use thermal sand reclamation methods may do so.

The thermal shock responsible for the change of crystalline form of silica leads to increased fracture of the sand grains. This will cause a good quality, round-grained silica sand to become steadily more angular in shape, thereby increasing binder demand for the same sieve analysis, impairing surface finish of the castings, and wearing out tooling and plant at an enhanced rate (as witnessed by the huge accumulation of iron filings on the magnetic separator in the sand re-cycling system).

There are other natural sands that do not have these problems. These include zircon (zirconium silicate, a white, yellow or orange sand mainly produced in Florida and Australia, and rather expensive because of its rarity). Another is chromite, usually available as a black, crushed mineral. The other common crushed moulding aggregate is olivine (that derives its name from its olive colour when new, although turns brown after use for casting) and widely used in steel casting both to reduce expansion and metal/sand interactions. These three products contain little or no free silica and have relatively low and linear thermal expansion coefficients.

Finally, it is of interest that some silica sands, such as those produced in Sweden, contain quantities of feldspars (up to 25–30%) that help to reduce the deleterious effects of silica expansion. These feldspars work in two ways: (1) by virtue of their lower, more linear expansion and (2) because some melt at lower temperatures than silica, thus counteracting the general expansion of the mould or core from which they are made. These facts do however argue against these sands being used for high temperature work, e.g. large steel castings.

Some suppliers offer additives that can be mixed in various proportions with silica sand to reduce the effects of the expansion caused by the change in crystalline structure. Common to many of these is a content of iron oxide (Naro, 2000). These would appear to function in a similar way to the naturally occurring feldspar/silica sands described previously; however, they may have a role to play where such sands are not locally available. A novel approach showing much promise uses additions of sodium bicarbonate to urethane-bonded sand. The approach appears to work by generating a foam structure in the bond material which allows the core sufficient plasticity to avoid cracking (Schrey, 2007).

15.2.2 CHROMITE SAND

Chromite is a widely used aggregate valued for its relatively low thermal expansion and good chilling power, particularly for steel castings.

However, the general problem with chromite is only found in steel casting operations where it is commonly employed as a facing sand for silica moulds. Here the surface of the casting can become coated in so-called ‘chromite glaze’, the result of chromite being fluxed by silica or clay, or simply by the decomposition of chromite as discussed later. This is difficult to remove and results in a poor finish to the casting (Petro and Flinn, 1978).

The chromite glaze problem has been assumed to be the formation of fayalite (ferrous orthosilicate Fe_2SiO_4 with a melting point of 1205°C) as the reaction product between silica and chromite. Fayalite is not magnetic and so cannot be separated from the sand magnetically. During the re-cycling of the sand, this low melting point constituent therefore builds up, lowering the refractoriness of the moulding aggregate. It seems likely that another ferrous silicate, grunerite (FeSiO_3), also non-magnetic, with a melting point of about 1150°C may also contribute to the impairment of the foundry sand for ferrous castings. These issues have yet to be properly researched and clarified.

An additional problem with chromite is that it is not particularly stable at steel casting temperatures. In oxidising conditions, it slowly oxidises to Fe_2O_3 and Cr_2O_3 but in the presence of carbon from organic binders its iron oxide constituent can reduce to liquid iron. Drops of liquid iron form microscopic beads on the surfaces of the sand grains (Scheffer, 1975; Biel et al., 1980) causing the sand to become highly magnetic (as quickly tested by the reader with a hand-held magnet). The reducing conditions are of course avoided by the use of carbon-free inorganic binders such as silicates. Whether oxidised or reduced, the weakened grains subsequently crumble to fragments.

Most chromite sand is derived from crushed ore, and so as well as being therefore rather angular, dust is created during conveyance which in turn increases the risk of reaction with silica sand. In general, it is estimated that 20–30% of chromite sand is lost each time that the sand is reused.

15.2.3 OLIVINE SAND

Olivine sand is sometimes used as an alternative to silica, primarily by foundries that cast high-alloy steels. Olivine possesses several advantages compared with silica, the most important being a lower and more uniform thermal expansion and inertness toward certain difficult alloys, notably manganese steels. Because olivine does not react with chromite, unlike silica, it can be tolerated at far higher levels in reclaimed chromite sand, and vice versa. Furthermore olivine with low loss on ignition (LOI), having a low serpentine content, is not regarded as being hazardous to health. Olivine sand does not react with alkaline binders. Some foundries use a ‘dead-burnt’ serpentine/olivine which is brown in colour and behaves similarly to ordinary olivine.

In spite of these valuable advantages, olivine is not widely used for two main reasons. The most important is that it is incompatible with the common binder system, furan no-bake (FNB), and requires specially formulated phenol-urethane no-bake (PUNB) binders. This means that olivine is used almost solely with alkaline binders and this leads to low sand reclamation rates with conventional equipment. A secondary disadvantage suffered by olivine sand is that it is, like chromite, made from crushed rock and thus possesses an angular grain shape that causes dusting during conveying and mixing. Finally, the refractoriness of olivine is related to its iron content which for steel casting should not be greater than 8% and for certain goods e.g. large carbon steel castings, maximum 6%.

15.2.4 ZIRCON SAND

Zircon sand is a light colour and generally in the form of fine rounded grains. Its extremely low and linear coefficient of expansion allows it to make extremely accurate cores and even whole moulds. Its high bulk density almost exactly matches the density of liquid aluminium, so that cores have close to neutral buoyancy which makes zircon the ideal aggregate for delicate and poorly supported cores in Al alloy castings.

Zircon has a fairly high thermal diffusivity compared to silica, giving it greater chilling power and faster freezing of castings. However, this effect is not great, and in any case, greater chilling power is a two-edged sword; although conferring slightly improved properties for the casting, the achievement of thin-walled sections is made more difficult.

The high density of zircon (nearly double that of silica sand) leads to significantly greater mechanical handling challenges in the foundry. Robots for conventional sand moulds will usually find zircon moulds too heavy to lift and sand silos will require strengthening. Vibrating equipment and pneumatic conveying systems require twice the energy.

The rate of wear of patternwork and tooling is a serious consideration when using denser moulding materials. Zircon in particular is found to be especially abrasive toward tooling as a result of its hardness and its high density thus requiring high blow pressures on core blowing machines to fill core boxes. As the percentage of broken zircon grains increases with cycling around the sand system, the increasing number of sharp edges greatly increases the rate at which it can inflict wear damage on the core boxes and other expensive tooling and plant. Although founders that use zircon complain about its high cost, the real hidden cost is the rate of destruction of the tooling.

15.2.5 OTHER MINERALS

There seems no shortage of minerals that would make good moulding materials (Ramrattan et al., 1996). Of growing interest is the possibility of using quite new minerals for moulding that could be available as fines, the unwanted by-products of crushed aggregates for other purposes such as road making, and thus in plentiful supply and at low cost. One such material is Norite. Another might be anorthosite. When it is realised that there are probably 10–20 local quarries for every foundry, supplies of such materials seem virtually unlimited (Harris, 2005). In addition, the relative closeness could mean considerable savings for some casting operations that are hundreds of kilometres from a source of the more traditional sands, and for whom the transport cost of the sand is the major part of the mould costs.

From time to time investigators have reported the benefits of moulding in various kinds of bonded metal shot. For instance, Al shot has been used for the casting of Al alloys, and steel shot is commonly used for many alloys. The rusting corrosion of these metals is a source of trouble that prevents the easy re-cycling of the material. Also, of course, for steel shot the moulding material is heavy and requires strengthened storage silos, and expensive, heavy duty cranes and mould handling equipment.

There has been a long-standing interest in moulding with hollow ceramic spheres that originate as a component of flue-gas dust from fuel-fired power stations. The particles are occasionally known as cenospheres. They are extraordinarily light and insulating and have a melting point in the region of 1400°C. Because of their extremely low thermal

diffusivity metals tend to run twice or three times as far in such moulds. They have wide uses for the casting of many metals up to the melting point of cast irons (Showman 2005, 2007). Their suitability for re-cycling at a reasonable rate is questionable however, because the spheres are relatively easily broken during mould compaction or possibly by the thermal shock of casting.

15.2.6 CARBON

Carbon has been used for moulds in a variety of ways. Investment moulds have been mentioned previously. However, its use as an aggregate represents a major application.

The aggregate particles can be round, fine grains that can be bonded with clay and water mixes (Saia and Edelman, 1968) or enhanced with syrups (Kihlstedius, 1988) to make a 'greensand'. Alternatively, they can be bonded simply with a resin binder (Clausen, 1992). The light weight of graphite does not provide it with much thermal capacity, but its excellent thermal conductivity can be useful. Its stability of dimensions is the result of its extremely low coefficient of thermal expansion, and its chemical stability has found good use in the casting of the extremely reactive Mg-Li alloys (Saia and Edelman, 1968), copper-based alloys (Clausen, 1992), titanium alloys (Pulkonik, 1967) and uranium (Edelman and Saia, 1968). Practically, of course, in the foundry environment, it is welcome as a result of its light weight, greatly easing the handling of moulds and cores.

For ferrous alloys, most 'carbon sand' has an uncomfortably high sulphur content, sometimes as high as 7 wt% (Gentry, 1966). This can contaminate the surface layers of steel castings, and lead to loss of nodularity in the surface layers of nodular cast irons. The sulphur content can be reduced during the manufacture of the sand, boiling off the sulphur at treatment temperatures in the region of 1000°C.

Another major use of carbon is in permanent moulds, machined from solid blocks of graphite. Mihaichuk (1986) describes the successful use for the casting of ZA (zinc-aluminium) alloys. The process is also highly successful for the casting of steel rail road wheels as seen in the Griffin Process.

The author has only one experience of attempting to introduce the large-scale use of carbon in the foundry. This was a trial using carbon fibres for reinforcing delicate water jacket cores for high-performance cylinder heads. The fibres flew about in the atmosphere, were trodden and crushed underfoot and reduced to powder at several other stages of manufacture. After a week or so, the powder eventually found its way into our numerous electric motors and other equipment around the plant and shorted these out, bringing the plant to a stop. The trial was immediately discontinued and never repeated.

15.2.7 SYNTHETIC AGGREGATES

Recently, some synthetic aggregates have become available which appear particularly attractive; they are formed from such stable inert refractories as alumina, mullite or bauxite and are formed into spherical grains which have excellent flowability and packing density. Because of their intrinsic hardness and wear resistance, they do not break down or wear so as to create dust. Their spherical form bonds efficiently, requiring reduced levels of mould binder. If the foundry can discipline itself to reduce sand losses to nearly zero, these attractive aggregates can be afforded as one-off capital items, otherwise aggregate costs are sufficiently high that even a small percentage loss could prove uneconomic.

It may be necessary to select the variety of synthetic aggregate with some care. One example is formed from a molten oxide mineral, atomised by a jet of air. This production route gives a solid spherical grain which will be expected to perform well as a casting sand.

At least one other synthetic aggregate is formed by a solid-state route: aggregating powders are rolled around on an oscillating tray with a temporary sticky organic binder. The aggregated spheres are heated to burn off the temporary binder and are sintered. The sintering is only sufficient to produce rather porous spherical particles. Some early experience with the casting of aluminium has indicated that the mould binder gets into the pores of the spherical particles, and on contact with the hot metal boils and explodes out of the pores, peppering the surface of the casting with porosity in the form of micro-blows.

15.3 BINDERS

Aggregate moulds such as sand moulds require the individual particles to be held together with some kind of binder. There are very many binders from which to choose but the broad categories are listed later.

15.3.1 GREENSAND (CLAY + WATER)

Greensand is perhaps the most widely used moulding medium, consisting of the aggregate, bonded with a mixture of mainly clay and water.

Greensand can be almost any colour including brown, red or black, but I have never known it to be green. It should be written as one word, 'greensand', not as 'green sand'. Its 'greenness' refers to its weak, plastic condition in contrast to that of dried moulds which are extremely hard and rigid. The greenness concept is common to other industries such as ceramics where a ceramic component has only 'green strength' until it is fired to melt the glaze bond, after which it becomes as hard and brittle as glass. The origin of the concept of greenness almost certainly lies in forestry and timberwork, where the wood is green and flexible when full of sap, unseasoned, before drying. In the 1850s in Sheffield, hand files were made of steel carburised and hardened to a limited depth, retaining a soft centre known as 'the sap'.

Greensand always has been and remains one of the most important and common binder systems. It is low cost, environmentally friendly (because there can be minimal toxic additions) and re-cyclable. However, most important of all, it is extremely fast. Compared with chemically bonded moulds which can be produced at perhaps 60–100 per hour, modern greensand plants can produce 600 moulds per hour. This awesome rate follows from simple fundamentals: once all the grains are evenly coated with the clay/water binder, the bond is formed simply by forcing the grains together. Thus the bond is formed instantly simply by pressure. No other process can compete for speed of moulding. Busby (1996) gives a good review of greensand versus other moulding processes.

The disadvantages are that the mould is somewhat plastic (i.e. remains rather 'green') so that if the aggregate is not particularly well-consolidated, the mould can distort, producing an inaccurate casting. For instance, the mould can sag under the weight of heavy cores, or the weight of the casting, or soft spots can yield under the pressure of liquid metal leading to local swells on the casting (the pressure can be high from the depth of metal in a tall casting, and from the expansion of graphite in cast irons).

These disadvantages are now countered rather successfully by modern moulding plants that in addition to their high speed, give a mould that is impressively well-consolidated. Whereas a mould compacted by hand could show a complete hand print (including the finger prints on all fingers), a really strong mould made on a modern automatic greensand moulding plant is so hard that only a rather limited thumb print is all that the average person can easily make.

The limit to the hardness of greensand moulds is set by the pressure at which the whole mould and its steel moulding box will distort elastically, causing the mould to spring into a new shape on being stripped from the pattern. This limit seems to be about 1.0 MPa (150 psi). It creates problems for the founder because such elastically distorted mould halves do not close properly. The faces of the mould bow elastically into a convex form, causing the two mould halves to impinge in their central areas, producing features such as sharp edges in the centre of the mould face to break off. This effect is generally controlled by the relief of the tooling to give the region adjacent to such edges sufficient clearance to avoid direct contact, but not sufficient for the metal to penetrate to cause expensive flash. Such clearance is generally in the region of 0.1 mm and 5–10 mm wide.

Cores may absorb water from the greensand, particularly if a delay happens between coring up and casting, as when a stoppage on the line occurs. Similarly, condensation may occur on metal chills. Condensation occurs even in rather dry resin-bonded sand moulds if left closed overnight. This is because the moulds cool during the night, but during their re-heating in the morning vapours are driven inwards by the inward flow of heat, thus condensing the volatiles onto the interior metal chills, still cold from their overnight cool. If cored-up moulds are required to be stored overnight they should be left open. Condensation problems are then avoided.

There is a strong move nowadays to reducing or eliminating the organic additions to greensands (Grehorst and Crepaz, 2005). Organics heat up and pyrolyse or burn, often giving off unhealthy emissions. Thus the motivation is to

return to inorganic mixes based on simpler clay/water binders. This subject is too extensive to be reviewed in this work. The interested reader is referred to the important series of researches published over several years by Heine and Green (1989–1992).

Nearly all the important engineering metals continue to be cast in greensand, including Al, cast iron and steel.

For a small number of hand-moulded castings, a special form of greensand is made up using oil instead of water. Oil-bonded greensand is a traditional moulding material still popular with model-makers as a result of its plasticity, conferring easy moulding and yielding a good surface finish of the castings. The oil/clay/sand mix has such good flowability that it is appropriate for small parts, but, as a result of it being generally 'greener' than water-based greensands, it is not suitable for castings weighing more than about 1 kg (Butler and Lund, 2003).

15.3.2 DRY SAND

Dried greensand cores were one of the traditional solutions to the unsuitability of greensand as a core material. The drying process increased the strength enormously and reduced the outgassing from the relatively high water content (often in the region of 2–4 wt%) of greensand. The cores had to be supported in their green state on cradles called 'driers' before being transferred to drying ovens. The process was akin to that used for linseed oil-bonded cores. Naturally, the drying process was lengthy and energy intensive. Furthermore, the hardening 'out of the box' meant that core distortion was a common problem despite the hundreds or thousands of 'driers' that were in use at any one time.

Dry sand cores and oil baked cores have now been practically entirely superseded by the various chemical binder systems. These later processes harden cores in the core box, thus enjoying the benefit of a huge increase in accuracy. The appellation 'no-bake' applied to many of the modern binder systems is a reminder of the slower, less convenient binders dating from earlier days, based on oils that required baking in a core oven for many hours.

15.3.3 CHEMICAL BINDERS

There are now so many chemical binder systems that the subject it is not possible to review the field here. For those wanting to review the first efforts to use a variety of vegetable and mineral oils and resins, the review by Middleton (1965) is interesting. Later reviews of more modern binder systems are provided by Webster (1980) and by Archibald and Smith (1988), but the reader needs to be aware that binder development is proceeding apace; it is now difficult to keep abreast of these advances.

A perfect binder would have low viscosity so that the aggregate mix had good fluidity, but in its cured form was strong, so that little addition was needed, retaining the void content of the aggregate to maximise permeability. It should also react minimally with the melt. However, of course, the chemical interactions increase in number and severity with increasing temperature, so that whereas aluminium may not suffer too much, irons and steels can be significantly damaged by interactions with the mould. The reactions occur with both the mould surface and with the atmosphere formed in the mould during filling with the hot metal. Working our way up the temperature spectrum of casting alloys we have the following.

1. Low-melting-point lead and zinc alloy liquids generally cast at temperatures up to 500°C are too cool to cause significant reactions.
2. Magnesium and aluminium have casting temperatures commonly up to 750°C. They react with water vapour and various organics to produce the solid oxide skin and free hydrogen that can diffuse into the melt. These reactions continue for some time after solidification and during cooling. This source of hydrogen is likely to be important in growing pores that are located just under the casting surface. We shall return to the subject of the growth of subsurface porosity later. Despite this reactivity at the surface of the liquid metal, it is worth noting that the temperature at which light alloys are cast does not lead to extensive breakdown of the chemical constituents of the mould, as is clear from Figures 4.1 and 4.4. Thus light alloys have the widest free choice of binder systems.
3. Copper-based melts up to 1300°C take part in several important reactions as will be described later.

4. Irons and steels (including Ni- and Co-base alloys) in the range 1400–1600°C are especially reactive in many ways. Aggregates and binders start to be a problem, greatly constraining the choice of materials for the steel caster. We shall devote some space to adequate solutions.
5. Titanium and zirconium in the range 1600–1700°C are so reactive they are problematic to cast into moulds of any type. Reactions with most moulding materials cause the formation of the troublesome alpha-case on titanium alloys, in which the alpha-titanium phase is stabilised by interstitial elements (oxygen and/or carbon) absorbed from the breakdown of the mould. The alpha-case usually has to be removed by machining or chemical dissolution.

There are many different types of chemical binders. They divide into two main types: organic and inorganic. The molecular chemistry for keen chemists is described in detail in the work edited by Webster (1980). We can only give an outline here, concentrating on their practical application in foundries.

15.3.3.1 *Furans*

Sulphonic acid cured furan no-bake (FNB) binders are based upon furfuryl alcohol (2-furylmethanol) and are very widely used in ferrous casting because they provide excellent mould and core strength, cure rapidly and allow the sand with which they are used to be reclaimed at fairly high yields, generally 75–80%, where due allowance is made for the need to keep total sulphur content below 0.1%. In passing, it may be noted that furan foundries generally exceed this sulphur level to minimise sand consumption and accept poorer surface properties of the casting! Foundries that wish to reduce the sulphur content of a conventionally reclaimed furan bonded sand do have several alternatives to using a sulphonic acid, and both phosphoric and lactic acid are sometimes used for this purpose. These are, however, weaker acids and will cure furan resins more slowly than the sulphonic acids, and particularly so for lactic acid. The use of phosphoric acid may necessitate a lower reclaim rate.

Furan binders are more or less anhydrous and commonly used at a rate of about 1% on (silica) sand. Experience shows that properly reclaimed furan-bonded sand that contains less than 0.1% total sulphur can be used with phenolic urethane no-bake (PUNB) binders.

The use of furan binders is associated however with several casting defects, the most serious being sulphur damage, which leads to poor surface finish in some steels, and destruction of near-surface graphite spheroids in ductile irons. The presence of urea-based polymers in some types of furan binders may also lead to nitrogen damage. As mentioned elsewhere, furan binders appear also to reduce chromite sand, forming iron metal.

Finally, and giving rise to most concern, furan binders have been found to be carcinogenic and decompose at casting temperatures with the emission of toxic gases; they contribute significantly to air pollution and the general blackening of the foundry environment, particularly the windows, thus further contributing to our dungeon-like furan foundries.

15.3.3.2 *Alkaline phenolics*

Alkaline phenolic (A-P) also called phenolic ester binders are fairly widely used in non-ferrous and steel casting, particularly where the use of furans can lead to difficulties, e.g. where alloys are cast that are sensitive to nitrogen or sulphur compounds and where hot tearing is prevalent. A-P binders contain about 50% water and are typically used at an addition rate of about 1.3% on silica sand. A-P binders are typically cured by the addition of an ester, such as di- or tristearin, by injecting methyl formate gas.

A-P-bonded sand is more difficult to reclaim conventionally than furan-bonded sand; reclaim rates being typically 70–75%, leading to higher volumes of waste per tonne cast. Reclaim rates are somewhat lower with silica sand than with olivine because the alkali in the binder reacts with the silica to form a surface film of sodium silicate that is highly resistant to attrition during conventional processing. Alkaline residues in the sand make it difficult to use reclaimed A-P bonded sand with PUNB or FNB binders. Like furans, alkaline phenolic binders may also cause deterioration of chromite sand and both the binders and their pyrolysis products are considered to be as toxic.

15.3.3.3 *Phenol-urethane (cold box)*

At the time of writing this binder system is probably the most widely used in the non-ferrous casting industry.

It can be used in an 'air hardening' form (the curing process has in fact nothing to do with air) in which its excellent bench life, followed by a sudden and rapid curing is convenient for moulders, and the timing is widely adjustable by varying the catalyst addition at the mixer.

It is also important as a core binder in which the resin is hardened by an amine gas. The gassing time is usually a few seconds, but is required to be followed by an air purge that can last several times longer. The whole cycle for the production of an average core weighing a kilogramme or so would be in the range of 30–60 s. This rapidity of production, together with its high strength, requiring low resin additions, has promoted this system to number one choice at this time. The reek of amine gas is tenacious however, and can be unpopular on arrival home at the end of the day. The amines in the exhausted gases need to be removed by washing with dilute acid, which adds costs.

15.3.3.4 Sodium silicates (waterglass)

The inorganic types are typified by one of the earliest of the chemical binders, sodium silicate, or waterglass. Several good reviews are available (Srinagesh, 1979; Harris, 2004). This substance can be 'cured' (better: 'set') by passing carbon dioxide gas through the mould to precipitate silica. For this reason the process is widely referred to as the *CO₂ process*. However, many foundries prefer to use esters such as di- and tristearin to accomplish this. Ester curing is easier to control and more uniform, although slower and more expensive than *CO₂*. That sodium silicate binders are not thermally degraded and may indeed melt during casting can cause moulds and cores made with these binders to be difficult to break down after casting, so it is often difficult to remove the casting from the mould and even more difficult to remove the core from out of the casting. Many Al-alloy castings have been scrapped as a result of internal cores that are rock hard, and impossible to dislodge.

These properties also make silicate bonded sand difficult to reclaim at high yield by conventional mechanical methods, whilst thermal reclamation is more or less useless. A typical reclamation yield for a standard shake-out + screening operation may be as low as 50%.

It has been such historical difficulties that forced the ferrous casters to move away from silicates to organic binders. The main reason for the move appears to be the difficulties associated with core removal and sand reclamation, particularly with the older silicate systems that required additions of 4–6% of binder.

Silicate binders are inorganic bulk products, not based on oil, and are thus much cheaper both per tonne and per tonne of metal cast than the other binders considered here. The newer systems provide in most cases more than adequate strength and are typically used at the rate of 2.5–3%.

Silicate binders possess several technical advantages, including greater resistance to hot tearing of the casting, almost complete lack of emissions, a considerable chill effect that can make the use of chromite facing sand unnecessary for steel casting and yield castings having an excellent surface finish. Silicate binders can also be formulated to cure as rapidly as furans, although the silicate process is better described as 'setting' rather than 'curing'.

However, even with the modern silicate systems, silicate-bonded sand is still difficult to reclaim. Furthermore, the presence of alkaline binder residues means that conventionally reclaimed silicate-bonded sand cannot be used with FNB or PUNB binders. The limited bond strength of silicate binders may restrict the size of boxless moulds that can be lifted and moved.

More recently, however, there have been considerable advances in the use of sodium silicate, allowing it to become the binder of choice for both light alloy and steel castings. The use of hot air to dry the binder has the effect of providing a uniform set of the binder without limiting its bench life. It has the great benefit of environmental friendliness, low cost and low gas evolution on casting. Heating of the cores to about 300°C removes the remaining water of crystallisation, making the cores virtually inert, free from outgassing problems. This is a massive benefit, allowing the use of core designs impossible in other processes. In addition, for Al-alloy casting, the binder can be made soluble in water, allowing the moulds and cores to be removed easily after casting.

Other recent developments in inorganic binder systems include the use of mixtures of silicates with phosphates and even borates. The sodium polyphosphate glass binder deserves special mention, simply requiring warm air to remove excess water to cure the bond. This process is attractive for difficult-to-vent cores because of its extremely low gas evolution on casting (Armbruster and Dodd, 1993). These recent inorganic materials promise a revolution in casting techniques.

Concerns about the costs and environmental aspects of organic binders and thermal reclamation have led some of our major light-metal foundries to devote a growing amount of attention to silicate binders and advanced mechanical reclaim systems. Inorganic silicate binders are commonly used in ferrous and particularly steel casting because of their low cost and excellent casting properties. However, the major growth area for these binders is light-metal casting. The benefits will be enhanced if foundries were to use non-silica sands. Because many such sands have a rather angular grain shape, it may be a good idea to use a grain-rounding attrition process, to minimise binder consumption and improve the surface finish of cast parts.

Cores made with silicate binders for ferrous casting can, if necessary, be removed in the dry state by vibration, although this might damage light metal parts, in which case a water-soluble core system might be preferred. New technology is becoming available that promises to provide rapid manufacture of cores with minimal gas development during casting, minimal environmental impact and that can be removed from the finished casting by washing out with water.

The recent re-introduction of the inorganic sodium silicate binders has been a success story. However, not all inorganic salts are suitable as binders. For instance, many have large quantities of water of crystallisation that is released when heated by contact with the liquid metal, causing blow defects in the castings. An example is MgSO_4 which contain five molecules of water for each molecule of magnesium sulphate. Although common salt, NaCl , has no combined water, it has not so far been found to have useful binding properties.

15.3.3.5 Hot box and warm box processes

The hot box and warm box processes use a liquid thermosetting resin binder. The mix is blown into a heated steel core box and allowed to cure for 10–30 s before ejection. Some post-curing may be needed outside the box, aided by the exothermic heat provided by the chemical reaction. The process has enjoyed wide popularity for the production of water jacket cores for such castings as automotive cylinder heads and blocks as a result of the strength of the cores and their relatively low volatile content, reducing blow problems.

15.3.3.6 Croning shell process

Often known simply as the *shell process*, it was patented in Germany by Johannes Croning in 1943 for making moulds or cores. The binder was based on a thermosetting resin. Mariotto (1994) gives a good review of the development of the process. The sand grains are pre-coated with the resin, which can then be handled as dry, free-flowing sand. The sand is put into contact with a heated metal pattern, against which the resin melts and sets after about 30 s. The remainder of the unheated sand further away from the pattern can be poured away to leave the shell to complete its hardening process, after which it can be ejected from the hot pattern. Mould halves can be made in this way, or hollow cores can be made if there is a print sufficiently large that can be used to pour out the un-reacted sand. If there is no large core print, the core can be produced solid, at additional cost of material, and possibly introducing the possibility of core blows if the core cannot be vented in some other way. Taft (1968) describes how the process was used with great success in his family foundry using 100% zircon sand, and specialising in hydraulic castings in grey iron. These casting benefited by improved dimensional accuracy, soundness and more easily cleared cored passageways, eliminating the risk of the contamination of hydraulic circuits.

When moulds are made by putting together two mould halves, this shell mould can be cast with its parting line oriented horizontally or vertically. For vertical orientation, a good filling system can be provided that runs around the parting line; even a good pouring basin design can also be incorporated. The problem with vertical orientation is that the mould halves require to be supported by backing up with steel shot or other technique. If shot is used, it is usually consolidated by vibration although too much vibration can crush the mould. The mould backup requires some engineering and associated cost, but has the potential for making excellent castings.

If the two shell halves are put together to make a horizontal mould, the filling system now becomes problematic to the point that I normally recommend owners of such lines to shut them down. The sprue is now necessarily wrongly tapered and no pouring basin of any respectable design can be incorporated. Thus the castings are necessarily at significant risk from entrainment defects. Such defects are therefore common in horizontal shell moulded castings. Some reduction of defects can be made by such means as the provision of filters at the base of the sprue or at the entrance to the runner, so as

to assist the sprue to back-fill as effectively as possible. Overall, however, despite its relatively wide use and evident surface finish advantages, the horizontally-cast shell process is not a casting system to be recommended.

15.3.4 EFFSET PROCESS (ICE BINDER)

The Effset process was invented by Fred Hoult in the 1970s, together with the H-Process. Impressively, this double achievement was made after his retirement at the age of 60 (I am encouraged that there may be hope for me yet). Silica sand mixed with a little clay (2–5%) and selected amounts of water allowed moulds to be made by consolidating in a core box. The moulds had sufficient green strength to be stripped from the box and laid out on a specially profiled support like a cradle. The mould on its support was transferred into a cryogenic chamber where liquid nitrogen was rained on to the moulds. Only sufficient nitrogen was applied to freeze the surface of the moulds, which were then extracted from the cryogenic chamber, assembled (usually in a stack) and cast. I have happy memories of a conference in which Fred was projecting an image of his process onto the screen. The image was of a stack of moulds that had just been filled with liquid iron, revealing hoar frost still over parts of the mould, and gentle clouds of white steam rising from disintegrating moulds. In his characterful English accent, Fred announced with tremendous enthusiasm, to the entertainment of all, “You can *see* it doesn’t smell!”

The process was used in Fred’s Rotherham foundry for many years, giving excellent surface finish and showing no problems of chill (i.e. white iron) in his iron castings (Hoult, 1979). Omura and Tada (2012) find that the fluidity of aluminium alloys in frozen moulds is higher than that in greensand. However, the Effset process has never been taken up in volume production. It seems the high energy cost involved in the use of liquid nitrogen inhibits its use. An effort at re-examination of ice as a binder was provided by Abbas and colleagues (1993). Even so, as energy costs and cryogenic gas availability changes the environmental benefits of this process suggest it should be kept under review.

15.3.5 LOAM

Loam is a kind of mud. It is a mix of sand, clay and water, plus on occasions time-honoured fibre strengthening additions such as manure from horses fed with a high diet of straw (horses chew the straw, chopping the fibres into exactly the right lengths, whereas cow manure is of no use because the fibre content, fibre length and strength based on grass is not helpful). The sticky and sloppy mix is usually applied by hand to build up a mould or core, and is particularly useful for the forming of moulds for bells which are formed to final shape by a *sweep*, a kind of *strickling* action made by a shaped blade rotated around a central axis. Additionally, the loam surface is conducive to finishing by *sleeking* with a wet brush. At that stage, letters and ornamentation can be carefully impressed into the surface for the insignia and decoration of the casting. The shape is then transferred to an oven where it is subjected to a careful and thorough drying treatment taking typically several days. This is not a process designed for high production.

An interesting historical account of John Wilkinson, an English iron master from the seventeenth century, describes how his iron cannons out-performed all other cannons. His were cast solid and the bore machined afterwards, compared with the normal manufacturing route in which cannons were cast with a loam core to form the bore. To the solidification scientist, this may have been surprising because the long freezing time of the solid casting should have yielded a coarser and weaker structure. However, this expectation overlooks the casting problems associated with loam cores. The core would have probably have been formed around an iron rod for strength, then wrapped with rope to provide some permeability and allow gases to escape and finally sleeked with loam and dried. The drying process could never be complete, because the clay itself would contain a significant volume of water in its crystal structure overwhelming the ability of the rope to convey away the volume of gases. Thus the core would be expected to outgas violently, causing the melt to boil, probably fountaining out of the mould, but leaving behind a mass of entrained bifilm and bubble defects that would have greatly weakened the casting.

The long and slender aspect ratio of the cannon core meant that its narrow rope vent was hopelessly inadequate. The bell survives because its loam core is usually made hollow, on a perforated steel former of large area, and outgases easily via its large base.

15.3.6 CEMENT BINDERS

The mixture of sand, cement and water forms an extremely hard mould capable of withstanding the loads imposed by very large castings, particularly ships' propellers. It was popular in the days when one of the only alternative mould materials was greensand which was far too weak for such products (Menzel, 1937). Later work summarised much earlier studies and investigated improved mixes and enhanced breakdown after casting (Wallace and Hrusovsky, 1979). The process is still in use for large heavy castings such as propellers in Ni/Al bronze and 40 tonne ductile iron gears.

15.3.7 FLUID (CASTABLE) SAND

Castable sand was invented in Russia in the 1960s by Liass and Borsuk (Liass, 1968). A small amount of wetting agent added to the sand caused a foaming action during mixing. The special feature of the process was the low liquid content, the fluid properties of the mix being achieved by suspending the sand grains in an air/liquid foam, reducing the friction between grains and allowing the sand mix to flow rather like water. As such, it could be poured into a moulding box, where the kinetic energy of the fall would provide the necessary compaction. The mix had a fluid life of around 1 min, and would subsequently harden by a chemical reaction. The process was analogous to the forming of lightweight concretes, and similar to the production of foamed plaster moulds.

Setting mixtures such as sodium silicate and dicalcium silicate were originally used, later superseded by various cement mixes. The process attracted world attention in the early days because of its contribution toward a cleaner foundry environment, reduced labour requirement and a higher productivity. Mixing a 250 kg batch would take around 4 min, and could be discharged into a mould or core box, building up large moulds or cores in layers (with nearly undetectable joints between the layers) or could of course be discharged into a rapid succession of smaller boxes. The application of a wax parting agent to the pattern-work was necessary (Hassell, 1980).

But the use of foam caused the moulding material to have relatively poor resistance to metal penetration resulting in poor surface finish to the castings (Brown, 1970; Nicholas, 1972). Later developments using no wetting agent improved on this problem (Tsuruya, 1974). Even so, the process seems only ever been applied to simple-shaped castings. These include ingot moulds, slag ladles and machine bases, but has on occasions been extended to the production of medium to heavy cores for large valve castings using a furane resin binder (Hassell, 1980).

Despite the enthusiasm that accompanied its launch, fluid sand is probably no longer used today.

15.4 OTHER AGGREGATE MOULD PROCESSES

15.4.1 PRECISION CORE ASSEMBLY

The use of hard cores hardened 'in the box' has led to the possibilities of highly accurate cores and moulds that can be assembled with extreme precision, often measure in micrometres. Thus the name 'precision core assembly' arose to describe this new standard of achievement. The castings from this process were some of the first to team up successfully with robotised pickup and machining systems, although this achievement is now shared by many of the high-pressure greensand lines, and, of course, by-products of the various forms of HPDC.

15.4.2 MACHINED-TO-FORM

This process is not a moulding process at all. A rigid block of chemically bonded sand is simply machined by programmed robot or machining centre. In this way a mould can be shaped with tolerable accuracy and with tolerable surface finish. It is a technique for rapid prototyping, in which the digital model sitting in the computer memory is used to produce a mould directly, eliminating the lengthy intermediate stage of the production of dies or patterns. The process can of course also be used for the production of a limited series of parts. Critics of the process complain that the robot or machining centre wears out rapidly (despite the best protective measures) as a result of the creation of fine abrasive ceramic dust that the cost of replacement of the machining facilities should form a major component of the cost of the mould, but is frequently overlooked. Advocates of the process say this problem is now solved.

15.4.3 UNBONDED AGGREGATE MOULDS

Both the lost foam process and the V Process use unbonded aggregates. These moulding processes are integrally defined together with the casting process. As a result, they are dealt with in Chapter 16, *Casting*.

15.5 RUBBER MOULDS

It is not easy to describe rubber as an engineering material for moulds. Even so, for a relatively few zinc alloy castings it can be excellent. A liquid silicone rubber is poured around the pattern, contained within a frame and compressed between platens. After curing, a knife is used to slice into the rubber, opening up a cut sufficiently wide that the rubber can be peeled back to release the pattern. The mould is closed and replaced between the platens, constraining the mould to retain its overall shape. The low melting point alloy can be poured directly into the rubber, with surprisingly faithful accuracy for the casting. Usually, the process seems confined to castings of up to 100 g, although reports of castings up to 1 kg are not unknown.

As an alternative to using cast rubber form as a mould, many foundries instead use the cast rubber shape as a pattern, and produce from it a plaster mould. Such moulds are used, for instance, to cast millions of Al alloy turbocharger impellers per year because for these small 100 g castings the rubber pattern will flex, allowing it to be withdrawn vertically from the cured plaster (the complex helical shape of some blades cannot be perfectly withdrawn even if the pattern were twisted on withdrawal) creating accurate castings with excellent surface finish.

15.6 RECLAMATION AND RE-CYCLING OF AGGREGATES

The greensand system, based essentially on a clay/water bond, has enjoyed the attention of enormous development, with the result that whole books are devoted to this important technology. We shall not attempt to reproduce this extensive fund of knowledge.

The reclamation and re-cycling of greensand has always been a major factor in the success of this moulding system. The burning out of a percentage of the clay in ferrous foundries has been dealt with by the dumping of a similar percentage and top up with new sand and binder. New sand introduced via cores, if any, can provide all or part of the top up. Even so, despite its enormous importance, it has to be admitted that the re-cycling of greensand has the problems of being both capital intensive, requiring large plant and equipment for major foundries, and energy intensive, as a result of the energy of crushing, sieving, and re-mixing (the word 'mulling' is often used, the process being carried out in a 'muller'. The word 'mull' being the German word for 'mill' as used by millers for milling grain to make flour).

One of the dangers of the reclamation of greensand has been the addition of uncontrolled water makeup; if this has contained chlorides, as is common in drinking water, the gradual buildup of chlorides in the re-cycled sand seriously reduced the strength of the bond. Boenisch (1988) was the first to point out this problem which was quickly confirmed in independent tests by Hold and coworkers (1989).

Turning now to those foundries using chemical binders, the re-cycling of chemically bonded sands has provided new challenges to the industry. In this section we shall confine ourselves to the complexities of foundries with a variety of chemical bonding processes which in general have so far not been treated in foundry textbooks.

A conventional sand reclamation line will typically consist of a shake-out unit coupled with a vibrating sieve that functions as a low energy lump crusher. Some foundries employ a mill to break down small lumps to individual grains and remove binder residues. The sieved sand can then be passed through a sand cooler, often a fluid bed that also functions as a deduster.

15.6.1 AGGREGATE RECLAMATION IN AN AL FOUNDRY

The standard reclamation system works satisfactorily with sand bonded with organic binders as long as the binder is fully thermally degraded, which is normally the case for steel cast at low sand/metal ratios. However, in an Al alloy foundry,

resin binder residues are only partly degraded and alkaline binder residues are fused onto the surface of the sand grains. Conventional reclamation imparts relatively little attrition energy and cannot efficiently remove these residues.

Most sand reclamation equipment is designed to target a low LOI. The LOI of the sand consists of four components: (1) char; (2) partially degraded binder films; (3) un-degraded binder films and (4) carbon as a thin film around the sand. Attrition processes remove components (1) and (2) efficiently, but is less effective with (3). Component (4) is not removed and is in fact a desirable component in the sand! Thermal reclaim removes, of course, all four of these components, and could therefore be regarded as overkill.

Grain attrition processes appear to work well enough for binders that are brittle after casting, such as furans. These binders spall off the grains as shell-like fragments forming a light dust, allowing much of the binder to be removed via the dust extraction system. However, attrition can be difficult to use with binders that remain in an elastic or plastic state after use because such binders can become soft during grain compaction and redistribute themselves, smearing onto other sand grains.

The rather low casting temperatures in an Al foundry mean that the residual binder adhering to the PU-bonded sand grains risks still being non-brittle. This means that it cannot easily be removed by the attrition forces that are encountered during the lump reduction and screening processes (so-called primary attrition) widely used. For this reason, many light metal foundries that use PU binders have chosen to reclaim their sand thermally.

Embrittlement of phenol-urethane (PU) binders starts at about 200°C but proceeds rapidly at higher than 350°C. The reclaim rate for sand processed by secondary attrition will therefore, for a given LOI (or more accurately that large proportion of the LOI that derives from un-degraded binder), depend upon the sand's thermal history, which in turn is a function of sand-to-metal ratio. Because the heat capacities of aluminium and silica are roughly similar on a kilogram-for-kilogram basis, this suggests that PU binder would be sufficiently embrittled at sand-to-metal ratios of up to about 4 to be removed, allowing the achievement of rates of sand reclamation characteristic of thermal processing.

After the reduction of the sand to grain size, secondary attrition ('scrubbing') can expose the sand particles to higher energy processing. Grain impact techniques throw particles against either (1) a fixed target such as a steel plate or (2) against other sand particles (particle-on-particle, [POP], attrition). Consider these systems in order.

Impact attrition systems accelerate the sand particles to high speed, using compressed air or a rotating disc. The grains are impacted onto a stationary steel target to dislodge the binder. Sand processed by air attrition will almost always suffer a disproportionate loss of the largest particles. Naturally, the system is self-destructing, particularly if high air speeds are employed to remove recalcitrant binder residues, and it is not uncommon for parts to be replaced every 1–2 months. Use of a fluid bed deduster additionally results in loss of useful sand from the bed because of fluctuating conditions. A further limitation is the size of the individual units, typically 0.5–2 tonnes per hour, so that several must be mounted in parallel if a higher capacity is needed.

When a grain is subjected to impact, the collision force will concentrate at the binder–grain interface thereby detaching the surface layer in accordance with its brittleness. However, if the collision is too energetic, it may cause the sand grains themselves to fracture. Poor quality silica sand will have grains that contain defects and thus more likely to break, each sand variety having its own effective fracture threshold. The more energetic the collision, the more sand grains will be broken and thus the greater the loss of sand as fines. A good attrition system requires an impact velocity that can be adjusted according to the individual sand/binder system. A single collision between a sand grain and an immovable plate will, if it is to remove the binder residue effectively, require that the grain has a higher energy than if it were to experience multiple collisions at close to the fracture threshold.

POP attrition conditions provide the desirable multiple collisions between grains. Furthermore, these minor impacts will be mainly glancing collisions which absorb less energy than when one of the 'targets' is fixed. In addition, glancing collisions cause particles to spin rapidly, so that subsequent collisions become a mass of buzzing grains. The frictional energy dissipated by spinning and chattering against their neighbours is usefully employed to erode away fragments of binder and round off corners of grains.

Attrition by particle-on-particle collision can be nicely controlled, giving a scrubbing action to the grains. Binder residues are stripped from the sand as small flakes, up to 0.2 mm in size, as well as dust. The process will yield reclaim rates of around 90% or more with all chemically bonded sand systems. The quality of sand processed in the equipment is

steadily improved, becoming steadily more rounded and will generally be better than new sand, especially for crushed aggregates.

In some foundries, a useful compromise is reached by reclaiming all sand by POP but using a small thermal unit to provide sufficient sand for cores only. Sand used in moulds will then consist of perhaps 12% new sand (from approximately 7% reclaim loss + 5% general losses in the foundry) and 88% mechanically reclaimed sand. If we assume that 10% of the total sand in circulation is core sand, the mould sand will consist of 12% new sand, 10% sand with low LOI from cores and 78% reclaimed mould sand. Provided the foundry runs at sand-to-metal ratios lower than about 8 this should reduce LOI sufficiently to allow moulds to be made without problems.

Attrition requires to be followed by a classification process. In many foundries, this is merely a fluid bed acting as a deduster, but the action of the fluid bed is sensitive to variations in both feed rate and particle size distribution. Both these factors need to be carefully controlled if the system is to function optimally. Most foundries that use fluid bed equipment tend to set the air speed for average or even worst case conditions, leading to excessive loss of useful sand if the feed should contain more fines or is processed at higher rates.

In contrast with a fluid bed, a cross-flow air classifier is a true classifier, using laminar air flow for separating useful sand from fines, flakes and oversized particles. The design is simple and relatively low cost, but has been demonstrated to be robust and tolerates far wider variations in feed rate and particle size distribution than a fluid bed deduster. Sand and fines fall into categories which allow the sand distribution to be controlled as desired.

At the time of writing, there are clear moves toward (1) mechanical as opposed to thermal reclaim and (2) inorganic as opposed to organic binders. There are several good reasons for preferring mechanical reclaim, with perhaps the most important being the following.

1. Mechanical systems are more flexible as regards feed and can be used to reclaim sand bonded with organic, alkaline phenolic and inorganic binders.
2. When used with sand bonded with organic binders, POP mechanical systems will provide yields of high quality sand similar to that provided by thermal reclaim, i.e. reclaimed sand that can replace new sand.
3. Thermal systems are ineffectual for reclaiming inorganic bonded sand and do not offer particularly good yields.
4. POP mechanical systems improve the sand's grain shape and particle size distribution, allowing binder consumption to be reduced and improving the surface finish of cast parts; this is particularly valuable for foundries located in areas having poor quality local sand.
5. Mechanical systems are far cheaper to install and operate than thermal systems.

15.6.2 AGGREGATE RECLAMATION IN A DUCTILE IRON FOUNDRY

As an example of the complexities of some real foundries, it is worth considering the problems of reclamation of core sand in a ductile iron foundry using greensand, and furan-bonded sand for moulds and furan- and PU-bonded sands for cores.

This mix of bonding processes arises from fundamental considerations: a greensand line cannot, of course, use cores made in greensand because the material is relatively weak, and contains up to 10 volume % of binder in the form of moist clay. (Most of the voids between the sand grains are filled with clay, making the mix nearly impermeable, and its high water content therefore leading to inevitable outgassing problems from cores.)

Thus cores for greensand lines are typically chemically bonded. The high strength of the chemical binders means that only a relatively small percentage addition of binder is required (often approximately 1 wt%, corresponding to approximately 3 volume %), which, together with a larger and closer grading of sand particle sizes, gives tolerable permeability, allowing outgassing to occur more easily via the core prints.

Alongside the greensand system, a POP type secondary reclaim system together with an efficient cross-flow air classifier can reclaim up to 94% of organically bonded mould and core sand from iron casting. The reclaimed sand can have a low LOI and, more importantly, a low total sulphur content ($\leq 0.12\%$). Once loose char, dust and fines are removed from the sand, total sulphur is also reduced, and constitutes the prime determining factor for making good ductile iron castings with this binder system and for using reclaimed furan-bonded sand with PU binders.

Experience shows that a foundry using such a reclaim system to make sand for PU-bonded cores (and moulds) from reclaimed (furan-bonded) sand experiences the following benefits:

1. Lower scrap rate because of lower thermal expansion of reclaimed sand compared with new sand.
2. Lower binder consumption than with standard reclaimed sand because the POP system will provide sand with better grain shape and optimised particle size distribution (giving higher bulk density but with better gas permeability).
3. Minimised sand consumption and dumpsite costs. Of course, the energy consumption, which for a small plant is about 3.5 kWh per tonne processed, is far lower than a thermal unit (approximately 200 kWh per tonne).
4. A better working environment

A suggested optimisation of the foundry reclaim system might be as follows.

1. All chemically bonded sand to be reduced to grain size through primary attrition, then mixed with the required amount of new makeup sand to replace losses, and finally put through secondary attrition (preferably POP type).
2. This sand (so-called 'unit' sand) is then used for *all* cores, i.e. those used in both greensand and chemically bonded sand moulds. Reclaimed sand has a lower thermal expansion than new sand and will have a grain shape and particle size distribution that is as good as or better than new sand. Furthermore, the addition of new sand to this unit sand will reduce LOI to well below any level that might cause problems for ductile iron chemistry.
3. New sand is used for chemically bonded moulds, although of course reclaimed sand could be used here, too.

An example known to the author was a furan/PU foundry that ran a POP attrition plant, reclaiming 94% of the furan sand and using this to make its PU-bonded cores without any problems arising (something that it had been unable to do before the POP unit). Although a maximum 1% LOI for reclaimed furan sand was traditionally thought to be the limit when using PU binders, the LOI was found to fall from about 3.5% to only 2.6% (i.e. about 1/3), but, somewhat surprisingly, was observed to cause no problems. On closer examination, it was found that the total sulphur content had fallen from more than 0.3–0.12% (i.e. 60% reduction), almost certainly accounting for the improved behaviour.

LOI on its own can, of course, be misleading; for example the presence of the carbon film around the sand grains (which shows up as LOI) can be beneficial, effectively insulating the grain from chemical attack by the metal and its vapours.

15.6.3 AGGREGATE RECLAMATION WITH SOLUBLE INORGANIC BINDERS

The use of inorganic binders that are soluble in water has great attraction in the foundry. The chemicals are without smell, clean and mostly free from any toxicity problems.

The most widely successful of the inorganic binder systems have been based on sodium silicate. The curing action has traditionally been effected by carbon dioxide gas. The 'CO₂' process, as it has become known, has a long history. It can deliver hard moulds tolerably quickly. One of its major drawbacks is the tendency of the silicate binder to melt at casting temperatures, fritting like a glass to make cores extremely problematic to remove.

Alternatively, for light-alloy casting, the mould can be cured simply by drying. This approach has the great advantage that the binder remains soluble in water. Thus after casting, the mould can be ablated (i.e. eroded off by water jets) off the casting without damage to the casting. This is especially valuable in an Al alloy foundry in which the castings are relatively weak and soft, and so easily damaged, when breaking out the moulds. The ablation casting process, patented by Alotech in about 2006, takes advantage of the solubility, removing the mould while the casting is still at least partially molten, hence greatly enhancing the rate of solidification.

By removing the mould by jets of water, the atmosphere of the foundry is freed from dust, eliminating the huge and expensive dust extraction systems. The elimination of fume means that operators enjoy clean conditions, in contrast to most resin-bonded binder systems in which the pungent fumes unpleasantly cling to skin and permeate fabrics.

Sodium silicate does contain some combined water, but this does not seem to create significant problems for Al castings. Measured gas evolution from silicate-bonded cores has been found to be low (Wolff and Steinhauser, 2004). For

steel casting, the release of water vapour at the higher temperature seems a positive advantage because its evaporation conveys heat away from the casting, causing silica sand to achieve the chilling power of chromite sand. Several steel foundries have abandoned the use of chromite as a facing sand, adopting instead a simpler and less costly one-piece mould bonded with a sodium silicate binder.

The reasons which traditionally have inhibited the widespread adoption of silicate binders in foundries include the following.

1. Shake-out difficulty for cores. This problem has been addressed by (a) organic additions to the silicate and (b) in quite separate developments avoiding carbon dioxide, using drying in air.
2. Long cycle times for curing by drying have meant that a core weighing a kilogram or so may require several minutes to be dried sufficiently to be useable. This contrasts with PU binder systems, currently the norm in the industry, that require perhaps only 5 s cure by an amine vapour, followed by 30 s or so of purge air to remove the vapour, giving a total cycle time in the core machine of approximately 40 s. However, developments are taking place to reduce the cycle time for the drying of silicates by using higher temperature and faster air flows, together with reduced sand thickness using shell techniques.
3. Large energy requirement of curing by evaporation of water. It is true that the energy required to evaporate water is unusually high (2.26 MJ/kg). However, most of the water from re-cycled sand can be eliminated by simple draining, or possibly centrifuging which is not energy intensive, leaving only a percent or two to be removed by evaporation. Each percentage of moisture per tonne of sand requires approximately 6.4 kWh to convert it to vapour, so that a maximum of about 12 kWh/tonne would be needed for 2% of residual moisture. (This compares with the energy requirement of at least 200 kWh/tonne for thermal reclamation at 700°C.) Furthermore, because the binder to be added to the reclaimed sand is water-based, not all the residual moisture need be removed because the added binder can be concentrated, achieving the correct mix when diluted with the residual moisture already present in the returning sand.

Thus it can be seen that inorganic binders appear to be addressing the issues that originally prevented their use. It is expected that they will become progressively more important in the casting industry during the next few years.

15.6.4 FACING AND BACKING SANDS

Occasional foundries using chemical binders have simplified their operations to the point that only a single sand, sometimes called a 'unit sand', is used for both moulds and cores, together with a single binder system. This unusual achievement has clear benefits to the economics and management of the foundry.

However, several ferrous foundries, particularly those making larger castings in relatively low numbers, will often use a facing sand and a backing sand. Chromite and zircon sands have been commonly used to face moulds and cores for two reasons: (1) they act as a chill and help to stop penetration by molten metal and (2) they act as a barrier to stop silica backing sand coming into contact with the molten metal. This latter point is especially useful when casting high-manganese steel because silica reacts with manganese steel to form a low melting point manganese silicate, causing a severe burn-on problem. In contrast, olivine is perhaps the most resistant of all aggregates to attack by manganese steel.

When chromite is used as a facing sand in silica sand moulds, or in cores, silica and chromite unfortunately become mixed during the re-cycling of the sand. Although fluid bed separation has been reported (Perbet, 1988), the more usual magnetic separation represents a significant investment in the re-cycling system. Chromite is slightly magnetic so that 50–75% can be separated out as a roughly 80–85% rich fraction (Sontz, 1972). Normally two magnets are required: the first to remove unwanted iron and steel (it is always amazing how much iron and steel gets into sand re-cycling plants) and the second a more powerful (and more expensive) rare-earth magnet that is required to remove the magnetically weaker chromite. If the chromite and silica are not effectively separated during re-cycling, the sand becomes practically unusable for steel casting, as discussed in the section on chromite.

Steel foundries have used zircon for facing because they wish to employ a silica sand backing. They have shied away from chromite to avoid the risk of (what is assumed to be) fayalite formation and the hassle, cost and uncertainty of

magnetic separation. Zircon cannot be reclaimed separately, and thus is lost into the backing sand after re-cycling. The rising cost of zircon as world supplies diminish is now closing this option.

The re-cycling of the silica backing sand can be carried out at or better than 90% efficiency (particularly for alkali phenolic bonded sand) with modern reclaim systems that can simultaneously improve the grain shape by a progressive rounding action during each cycle. However, the effects from any buildup of low melting point phases when using chromite with improved reclaim systems do not appear to be known at this time.

An interesting potential solution for steel foundries is to continue with chromite for facing but replace their silica backing sand with olivine, operating a single stage magnetic separation. This completely avoids the risk of iron silicate formation and will allow foundries to increase their re-cycle yields of both chromite (no longer lost as an iron silicate) and olivine (because of lower binder residues). In summary, a facing sand of typically 80% chromite will not be degraded by reaction with its 20% content of olivine because this mixture is effectively inert (in contrast to an 80/20 chromite/silica mixture). Also, of course, the chromite content of the olivine backing sand is also not damaging.

Silica-zircon foundries could change to olivine-chromite and need only invest in a simple magnetic separation stage. These are relatively modest investments that would be repaid rapidly. The more expensive olivine is envisaged to be more than offset by the higher rates of reclamation that are offered by POP re-cycling systems.

Finally, we should note that the benefits of the unit sand concept are enjoyed by some steel foundries who have found a facing sand to be unnecessary. They have discovered that by using a silicate-based binder they are able to avoid using the chromite facing sand. The reason for this seems to be the significant chill effect provided by the silicate binder: its free water together with its water of crystallisation is driven off and the superheated steam carries with it a huge transfer of latent heat into the depths of the mould, as discussed in Chapter 4 on evaporation and condensation zones.