

# The production, properties, and selection of ferrosilicon powders for heavy-medium separation

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## SYNOPSIS

There are basically two types of ferrosilicon powder available to operators of heavy-medium plants in South Africa: spherical and milled grades. The production processes are described, and the properties of the two types are examined and compared. Guidelines are given for the selection of the correct grade of ferrosilicon for any particular application.

## SAMEVATTING

Daar is basies twee soorte ferrosilikonpoer beskikbaar vir diegene wat swaarmediumaanlegginge in Suid-Afrika bedryf: steriese en gemaalde grade. Die produksieproses word beskryf en die eienskappe van die twee soorte word ondersoek en vergelyk. Daar word leidrade aangegee vir die keuse van die korrekte graad ferrosilikon vir enige bepaalde gebruik.

## INTRODUCTION

Ferrosilicon of 14 to 16 per cent silicon has become widely accepted as the most suitable medium for the heavy-medium separation of ores having a specific gravity in the range of approximately 2,5 to 4,0. Ferrosilicon has many properties essential to a metal or alloy powder that is to be used as a heavy medium, some of the more important being the following:

- resistance to abrasion,
- resistance to corrosion,
- high specific gravity,
- magnetism, which allows easy magnetic recovery with subsequent easy demagnetization, and
- low ccst.

Ferrosilicon containing between 14 and 16 per cent silicon is found to have the optimum combination of these properties<sup>1</sup>. If the silicon content is lower than 14 per cent, the specific gravity and magnetic properties are improved, but resistance to corrosion decreases rapidly. Above 16 per cent silicon, the corrosion resistance of the alloy is not significantly improved, but the magnetic properties and specific gravity deteriorate.

## THE PRODUCTION OF FERROSILICON POWDERS

At present there are basically two types of ferrosilicon available in South Africa to the operators of heavy-medium plants. These are milled and spherical grades.

### Milled Ferrosilicon

The standard method is to melt steel scrap, quartz, and a reductant in a submerged-arc furnace. The molten alloy is tapped into a sandbed, allowed to cool, and then broken into lumps, after which it is crushed in two stages and milled to the required size range.

At the Kookfontein Works of Amcor, a 7,5 MVA submerged-arc furnace is used for the production

of milled ferrosilicon. The following are the characteristics of this furnace:

Shell diameter	6400 mm
Hearth diameter	4000 mm
Electrode diameter	890 mm
Secondary voltage	90 to 120 v
Resistance	0,85 m $\Omega$
Reactance	1,0 m $\Omega$ .

The power consumption (including auxiliaries) for 1 tonne of ferrosilicon (15 per cent silicon) amounts to 2100 kWh. The furnace is charged on a semi-continuous basis and is usually tapped into a ladle every two hours. The temperature of the melt on tapping is 1600°C.

The liquid ferrosilicon from the ladle is granulated into small particles in a high-pressure water jet. This granulation process, developed

TABLE I  
SPECIFICATIONS FOR MILLED FERROSILICON 14 TO 16 PER CENT SILICON  
Size Analysis

Tyler mesh	48D	65D	100D	150D	270D
+ 65	5	0,5	0	0	0
+100	15	3,0	0,2	0	0
+150	30	8,0	1,2	0,5	0
+200	50	20,0	5,0	2,0	0,2
+325	75	55	35	25	10
- 325 (typical)	25	45	65	75	90
- 325 (limits)	20-30	42-49	60-70	70-80	90+

### Chemical and Physical Specification:

Silicon	14-16%
Carbon	1% max.
Sulphur	0,05% max.
Phosphorus	0,10% max.
Rust Index	1,0% max.
Non-magnetics	0,75% max.
Specific gravity	6,7-6,95

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by Iscor, eliminates the breaking and crushing stages and is believed to have the added advantage of preventing segregation in the alloy on cooling. The granulated material is recovered by spiral classifier and dried in a gas-fired rotary dryer.

The final powder is obtained by milling in a ball mill in closed circuit with an air classifier, which is set to yield a product of required size analysis.

A list of the grades of milled ferrosilicon available in South Africa, together with their chemical and size specifications, is given in Table I.

### Spherical Ferrosilicon

There are two methods for the production of spherical grades of ferrosilicon.

#### Atomized Ferrosilicon

Knapsack AG, a subsidiary of Hoechst AG, was the first to apply the atomizing process to the production of ferrosilicon for heavy-medium separation<sup>2</sup>. This process is now also used in the Hymat plant at Amcor's Kookfontein works.

Ferrosilicon of 75 per cent silicon is diluted with high-grade steel scrap in an induction furnace. Characteristics of this furnace are as follows:

Holding capacity 3 tonnes  
Electrical capacity 750 kW  
Power consumption 600 kWh/t  
Type Mains frequency.

By means of a tilting device, the furnace is tapped at approximately 3-hourly intervals at a charge temperature of approximately 1550°C. The molten material flows into a ceramic tundish, which ensures that the alloy stream entering the atomizing steam cone has a constant diameter and velocity.

In the atomizing nozzle, the stream of molten ferrosilicon comes into contact at its apex with a cone of steam, and the melt is immediately broken into fine particles, which are quenched in water.

The resultant ferrosilicon pulp is filtered in a drum filter, dried in a gas dryer, then screened for the removal of oversize material. This oversize fraction (approximately 3 to 10 per cent of the atomized ferrosilicon) is milled in the ball mill.

A list of the grades of atomized ferrosilicon available in South Africa, together with their chemical, physico-

TABLE II  
SPECIFICATIONS FOR ATOMIZED FERROSILICON 14 TO 16 PER CENT SILICON

#### Size Analysis

Tyler mesh	Sishen Coarse	ISCOR Coarse	Coarse	Fine	Cyclone 60 *	Cyclone 40 †
+ 65	3	4	3	1	0	0
+100	13	13	11	8	0	0
+150	30	31	28	18	2	0
+200	49	44	40	33	7	2
+325	74	67	62	55	27	10
-325 (typical)	26	33	38	45	73	90
-325 (limits)	23-30	30,1-35	35,1-40,5	40,6-50	65-75	—
-400 (typical)	—	—	—	—	65	85

\* Cyclone 60: +100 mesh 0,02% max.  
+200 mesh 12% max.

† Cyclone 40: Is not produced at this stage because there is no local demand.

#### Chemical Specification

	Normal Grades	Special Grades	Cyclone Grades
Si	14-18%	14-16%	14-16%
C	± 1%	± 0,5%	1,5% max.
S	0,05% max.	0,05% max.	0,05% max.
P	0,1% max.	0,1% max.	0,1% max.
Al.	± 0,8%	0,5% max.	0,5% max.
Ma	0,75% max.	0,75% max.	0,75% max.
Cu	0,8% max.	0,5% max.	0,5% max.
Cr.	0,5% max.	0,5% max.	0,5% max.

#### Physical and Physicochemical Specification:

Content of spheres:	Normal grades	: ± 50%
	Cyclone and special grades:	: ± 90%
Magnetic content		: 99%+
Pyknometer density		: 6,6-7,0 g/cm <sup>3</sup>
Bulk density		: 3,5-4,2 g/cm <sup>3</sup>

al, and size specifications, is given in Table II.

#### Spheroidized Ferrosilicon

A second method for the production of spherical ferrosilicon was developed by Iscor<sup>1</sup>. Tests have shown that in many respects this material is identical to that produced by the Knapsack method.

Spheroidized ferrosilicon is produced initially in the same induction furnace. However, the stream of molten alloy is broken up in a series of concentric cones of high-pressure water. Clearly, the energy available in this system is not as great as in steam atomizing, and consequently the water-granulated product is coarser.

In fact, only a fraction of this material (about 30 per cent) constitutes the final product. The granulated product is dried and screened at 48 mesh, and the screen oversize (about 70 per cent) is milled to the required size in a ball mill in closed circuit with an air classifier. The milled fraction is then spheroidized, and the two fractions are combined in the desired proportions. The spheroidized powder constitutes the

fine fraction of the final product.

In spheroidizing, the milled powder is allowed to fall through a flame that has an oxidizing centre and a reducing outer zone, which permits each individual particle to be melted without being oxidized. The surface tension and fluidity of ferrosilicon are such that each particle contracts into a sphere. The design of the burner prevents agglomeration, and, after spheroidizing, the powder is quenched in waste gas to prevent oxidation.

It is claimed that the water-granulated fraction of the final product is superior to the corresponding fraction of the atomized product, making it possible to operate at higher pulp densities<sup>1</sup>.

### THE PROPERTIES OF FERROSILICON 14 TO 16 PER CENT SILICON

Premier Mine installed the first heavy-medium separation plant in South Africa in 1948, the complete specification for the ferrosilicon used in that plant being 25 per cent minus 325 mesh. Since then, considerable progress has been made both in the

production and quality control of milled ferrosilicon.

Notwithstanding these advances, the use of milled ferrosilicon is limited. The production of atomized ferrosilicon was a welcome development because it made possible the heavy-medium separation of certain ores that could not be treated with milled ferrosilicon.

### Particle Shape

There is a marked difference in both the shape and nature of the particles of ferrosilicon powders produced by grinding and by atomizing. Particles produced by grinding are rough and angular in shape, whereas particles produced by atomizing are smooth and largely spherical or rounded. This difference in the individual particle shape has marked effects on the rheological properties of aqueous suspensions of the two types of ferrosilicon.

### Rheological Properties

The rheological properties of heavy-medium suspensions play an important part both in the heavy-

medium separation itself and in the handling of the medium with regard to pumping and storage. The rheology of fast-settling suspensions of this kind can best be described by two properties of the suspension: viscosity and stability.

#### Viscosity

The viscosity of a ferrosilicon suspension directly affects the separating efficiency of the simplest form of heavy-medium separator—the static bath—by influencing the terminal velocity of ore particles settling in the medium in a manner akin to that described by Stokes law for Newtonian fluids<sup>3</sup>. One investigator succeeded in deriving a direct relationship between plastic viscosity and the probable error of the separation (defined by the Tromp Curve) in tests on coal separations<sup>4</sup>. The influence of medium viscosity on dynamic separators such as the cyclone or Dyna Whirlpool is less certain. Many authorities maintain that the effect is negligible in relation to the high dynamic forces exerted on the ore particles. One study<sup>5</sup>, however, has suggested that viscosity

does affect the performance of a heavy-medium cyclone, and this view has been supported recently by some limited plant studies of cyclone operations within the diamond industry.

The measurement of medium viscosity is made difficult by the necessity of maintaining the solid particles in homogeneous suspensions while the measurement is being made. A number of investigators have approached this problem with varying degrees of success, and a number of ingenious instruments have been developed for the purpose<sup>6</sup>, including flow-rate or capillary-type consistometers<sup>7,8</sup>, a pressure-diaphragm viscometer<sup>9</sup>, concentric cylinder devices<sup>4,10,11</sup>, and other rotational instruments such as the modified Stormer viscometer<sup>12-15</sup>, which is used by Knapsack<sup>16</sup> and is widely used in South Africa.

Unfortunately, most of these instruments are able to provide only a relative measure of the viscosity of a sample based on calibration with liquids of known viscosity such as glycerine. Accordingly, the detailed shear-rate and shear-stress characteristics of ferrosilicon suspensions are still not well understood, although some attempts have been made to obtain this information by suitable calibrations and interpolation<sup>12</sup>.

It is generally agreed, however, that the rheological characteristics of ferrosilicon suspensions, as of most unstable suspensions, are non-Newtonian<sup>3</sup>. The main types of rheological fluid are well categorized, and their flow curves are shown in Fig. 1. However, it is by no means clear to which class ferrosilicon suspensions belong. Some work<sup>10</sup> on various types of heavy media using a rotational viscometer, reported in 1957, suggests that ferrosilicon suspensions show pseudoplastic charac-

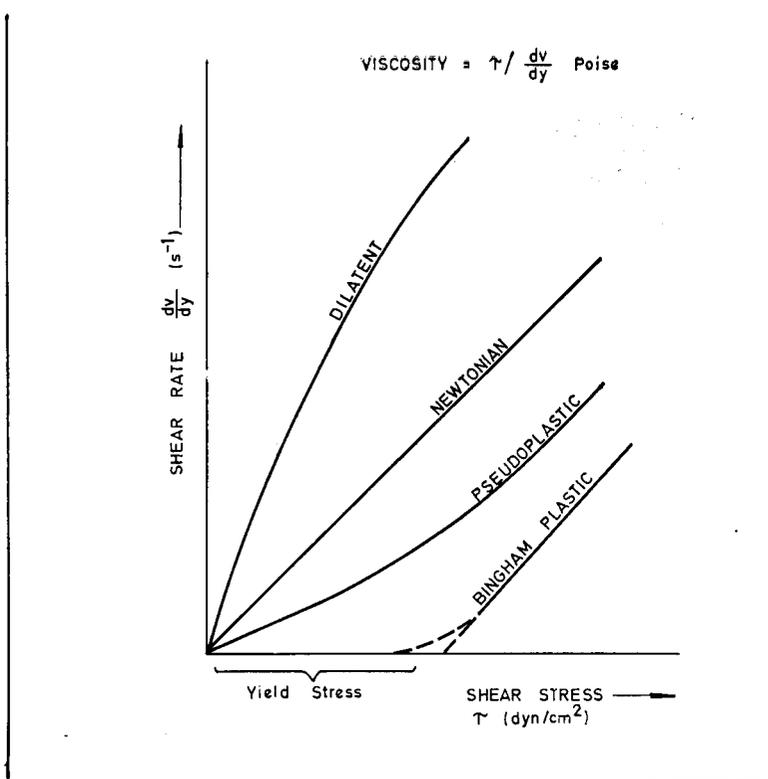


Fig 1—Generalized flow curves for main rheological types

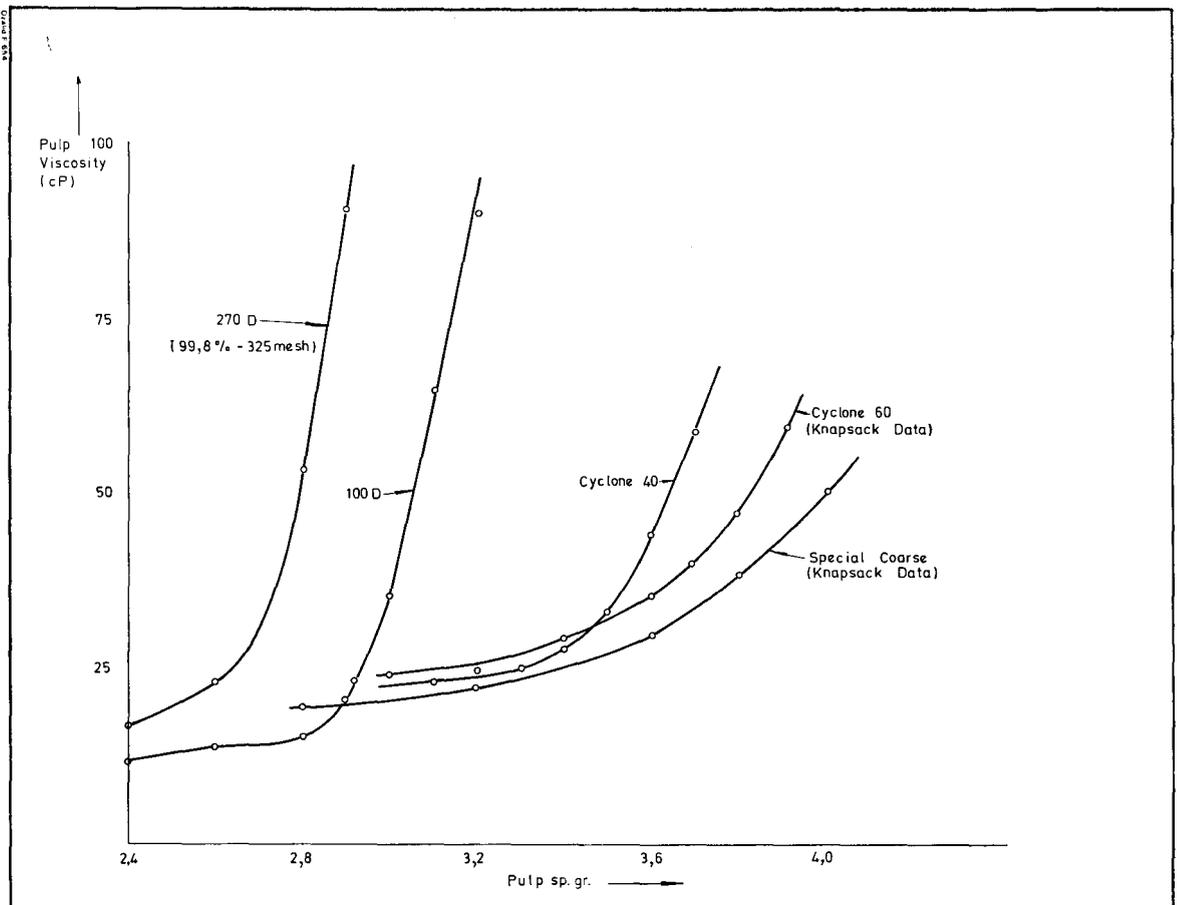


Fig. 2—Pulp specific gravity versus viscosity for various grades of ferrosilicon

teristics at low shear rates (up to about  $300 \text{ s}^{-1}$ ) and dilatent characteristics at high shear rates. This could have implications in heavy-medium cyclone operations where relatively high shear rates are experienced. A study<sup>5</sup> of the influence of medium viscosity on Driessen Cone separations did suggest that an increase in viscosity leads to an increase in the proportion of ore reporting to the underflow.

All investigators agree on the general shape of the curves for the pulp density versus viscosity of ferrosilicon suspensions, e.g. Eveson<sup>6</sup> Fig. 2 shows curves for selected grades manufactured by Amcor in South Africa. In each case, a critical value of pulp density (or volume proportion of solids) is reached beyond which the viscosity rises sharply. In general, it is inadvisable to use any given grade in any application in the region beyond this critical point, since small increases in density or the presence of small quantities of fine non-magnetic contaminants can cause

large increases in viscosity, with deleterious effects on separation and pumping characteristics.

The critical value of pulp density for the atomized grades is shown to be much higher than for the milled grades, and not as clearly defined. Unlike the viscosity of the atomized grades, that of milled ferrosilicon is shown to increase with fineness or grade of the ferrosilicon. Fig. 3 shows that the relationship between viscosity and percentage minus 325 mesh is in fact almost linear.

At densities above 3.0, the viscosities of suspensions of atomized ferrosilicon are significantly lower than those of the milled grades owing to the greater friction of collision of the irregularly shaped milled particles, which requires a larger energy input to achieve a given deformation of the suspension<sup>18</sup>.

This superior property of atomized ferrosilicon allows very high pulp densities to be obtained (up to 3.8), which has made possible the heavy-medium separation of certain ores that were not previously amenable

to the treatment.

In general, it is not usual to employ milled ferrosilicon at a pulp density much in excess of 3.0.

#### Stability

The stability of a suspension can be defined as the reciprocal of the settling rate.

As with viscosity, a number of techniques have been developed for the measurement of stability. The simplest method is to agitate a sample of the medium, allow it to stand, and time directly the settling rate of the clear water interface<sup>7</sup>. However, in many cases, particularly where excessive fines are present, no clear demarcation line is visible. Another method developed by the Diamond Research Laboratory, and used by Knapsack<sup>16</sup>, employs a differential-pressure technique, in which air is bubbled through the settling medium and the change in pressure at a point in the suspension is timed by use of a manometer<sup>19</sup>.

A more sophisticated technique, an advanced version of which is currently under test at the Diamond

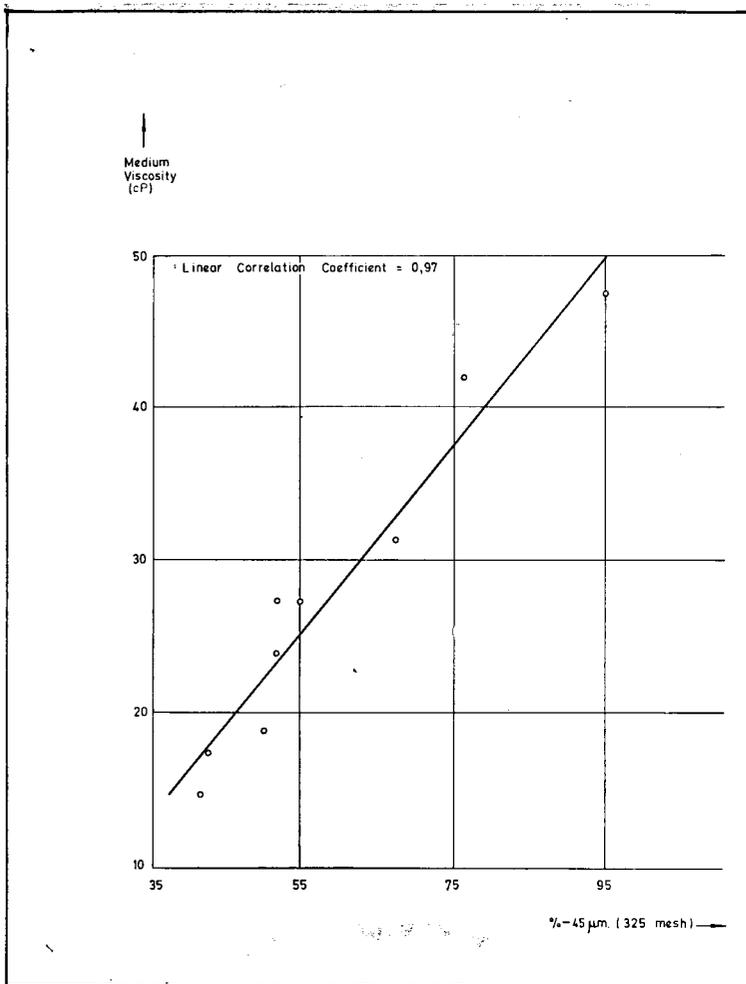


Fig. 3—Apparent viscosity versus fines content of milled ferrosilicon—pulp density 2,80 g/cm<sup>3</sup> (after Wilson<sup>17</sup>)

Research Laboratory, was developed at the Fuel Research Institute. This involves the measurement, by an optical method, of the rate of change in specific gravity at a point in the settling medium<sup>20</sup>. The change in specific gravity over a timed interval has also been measured by a gamma-ray attenuation method<sup>21</sup>.

Another simpler, though less precise, method of timing the change in specific gravity (slightly modified from that described by Geer *et al.*<sup>9</sup>) is as follows. A perspex tube, about 1 cm in diameter and 30 cm high, closed at the lower end, with a hole drilled in the side about one-third of the distance from the top and fitted with a bung, is placed vertically. The medium is then introduced into the tube so as to fill it completely, the top is closed, and the whole is shaken vigorously so as to ensure homogeneity of the suspension. The tube is then allowed

to stand for 60 seconds, after which the bung in the side is removed and the top portion of the suspension is drained off. The tube is weighed before and after this procedure, and, from the dimensions and dry mass of the apparatus, the change in density of the medium in the top portion of the tube relative to the initial density is easily calculated. The method, though relative and arbitrary with respect to the dimensions of the apparatus and the time allowed for settling, is particularly suitable for rapid plant measurements. In the present case, the stability index  $S$  is given by

$$S = 1 - \left( \frac{D_1 - D_2}{D_1 - 1} \right) \times 100\% \\ = \left( \frac{D_2 - 1}{D_1 - 1} \right) \times 100\%$$

where  $D_1$  = initial density of the medium (g/cm<sup>3</sup>), and  $D_2$  = final density in the top portion of the tube.

This provides a relative scale from 100 per cent (no settling) to 0 per cent (total settling of the ferrosilicon solids to below the level of the tap-off hole).

Stability data<sup>21</sup> for certain grades of ferrosilicon manufactured in South Africa are given in Fig. 4. It is clear that, as in the case of viscosity, stability increases with both the fineness of the ferrosilicon and with pulp density.

For both static and dynamic separations, the desired conditions are those of minimum viscosity with maximum stability. A low stability, due for example to the use of too coarse a grade of ferrosilicon, will result in a large differential between the specific gravities of the overflow and underflow media from the separator, whether it be static bath or cyclone. This in turn will lead to the artificial creation of a large body of middlings material, and consequently a poor separation will be achieved.

As might be expected, grades of milled ferrosilicon show greater stability than grades of atomized ferrosilicon of equivalent size analysis. Generally, it is necessary to use a grade of atomized ferrosilicon that is finer than the milled ferrosilicon that might be used under the same conditions. This entails no disadvantage, however, as the viscosities of suspensions of the atomized grades are not significantly dependent on their fineness.

#### Modification of Rheology

The modification of the rheological properties of ferrosilicon suspensions can be achieved in three main ways:

- (1) by addition of polymeric compounds or other reagents,
- (2) by addition of ore slimes or clays, or
- (3) by demagnetization of the circulating medium.

Considerable work has been carried out on the stabilization of heavy-medium suspensions for static-bath separators by the addition of polymers. It is claimed that significant improvement in stability (with a corresponding increase in viscosity) can be achieved by the addition of as little as 0.1 per cent by mass of solids of certain polymers. This allows the use of coarser (and

cheaper) grades of medium, easier start-up due to reduced settling, and other advantages<sup>11</sup>. Reductions of viscosity by the addition of peptizing agents have also been reported<sup>22</sup>. This effect is found to be highly pH-dependent.

The addition of small quantities of ore slimes or clays has been found to increase significantly the viscosity and stability of ferrosilicon suspensions. In some cases, the slimes represent an undesirable constituent of the ore being treated, and a proportion of the circulating medium has to be continuously removed and cleaned through magnetic separators. In other cases, natural slimes can be used to stabilize a relatively coarse grade of medium<sup>23</sup>.

The degree of magnetization of the ferrosilicon particles, induced by their passage through magnetic separators during normal recovery, has

been found to influence significantly the viscosity of the medium. In order to reduce viscosity, most static-bath processes include a demagnetization coil on the pipe that returns medium from the magnetic separators to the main circuit. Up to now this has not normally been considered necessary for cyclone plants<sup>23</sup>.

The design of the coil with regard to attenuation characteristics and field strength is of considerable importance<sup>24</sup>. A recent exercise at the Premier Mine<sup>25</sup> established an inverse relationship between coil field strength and the viscosity of the circulating medium in the heavy-medium cone circuits (Fig. 5).

In general, atomized ferrosilicon requires a field strength for demagnetization that is four times higher than that for milled ferrosilicon.

## Size Distribution

Apart from the primary classes of atomized and milled ferrosilicon, the various manufactured grades are distinguished and classified exclusively by their size distribution. Specifications for the size distributions of the various grades manufactured by Amcor are given in Tables I and II.

Sizing for quality control is carried out by conventional screening down to 400 mesh (38 microns) and by sub-sieve methods thereafter to about 5 microns; sub-sieve techniques employed successfully in this country and overseas include the Bahco air elutriator, the Alpine suction/sieve apparatus, and the Cyclosizer.

The size distributions of both manufactured ferrosilicon and ferrosilicon taken from operating heavy-medium circuits have been found to be well represented by the Rosin-Rammler distribution, which is given by

$$W_R = 100 e^{-(x/a)^b}$$

where  $W_r$  = % mass retained,  
 $x$  = size (determined by nominal sieve aperture), and  
 $a, b$  = constants.

This expression can be linearized as follows:

$$\ln \ln \frac{100}{W_R} = b(\ln x - \ln a).$$

By the plotting of  $\ln \ln (100/W_R)$  versus  $\ln x$ , a straight line is obtained with gradient  $b$ . The characteristic size of the distribution is generally defined as the size at which  $x=a$ . This gives  $W_R = 100 e^{-1} = 36,8$  per cent.

It has been found that, for ferrosilicon distributions, the linear correlation coefficient for straight lines fitted in this way is normally in excess of 0,95. Fig. 6 shows the Rosin-Rammler plots for samples taken from a number of Amcor grades. The ability of ferrosilicon size distributions to be represented in this way is extremely useful both for specification purposes and in the evaluation of research and plant tests.

## Absolute Density

The absolute density of a ferro-

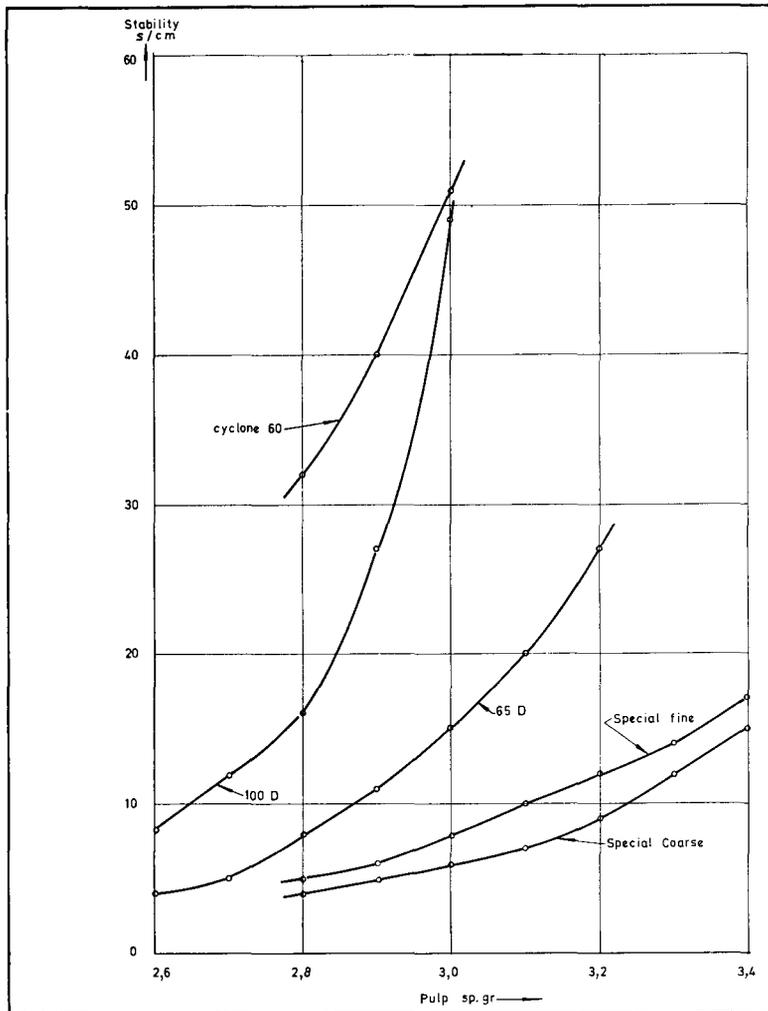


Fig. 4—Stabilities of various grades of ferrosilicon (data from Nesbitt and Loesch<sup>19</sup>)

silicon alloy is governed essentially by its metallurgical constituents, and varies within relatively narrow limits depending on the exact proportions of the elements present. The high density of the powder (6,7 to 7,0) allows much higher pulp densities to be achieved than with other conventional heavy-medium materials.

The measurement of density is usually carried out with specific gravity bottles or pycnometers. The determination must be made with great care because of the extreme fineness of the powder. To wet the particles completely, paraffin is usually preferred to water as the wetting medium, and the bottles are usually evacuated, by use of a water vacuum pump, for 2 to 4 hours, being gently tapped from time to time to remove all entrained air. All weighing is done to 0,0001 g. The density of the paraffin is critical, since an error of only 0,005 g/cm<sup>3</sup> (about 0,6 per cent) in the measurement of the paraffin density will lead to an error of about 20 per cent in the estimate of the ferrosilicon density. The determinations have therefore to be made at an accurately controlled temperature. With care, a standard deviation of 0,02 g/cm<sup>3</sup> in the estimate of ferrosilicon density is usually possible, based on three replicate determinations.

### Magnetic Properties

Being an iron alloy, ferrosilicon is inherently magnetic. This property of the medium permits easy recovery and cleaning of the medium in circuit. A certain residual magnetism is induced in the medium by passage through a magnetic separator during normal operation. As noted earlier, excessive residual magnetism can have a deleterious effect on the viscosity of the medium. In addition, if a magnetic ore is being treated, this residual magnetism in the medium will lead to excessive losses of the medium by adhesion. The agglomeration effects due to residual magnetism can be observed directly under a binocular microscope; an investigation of residual magnetism with a sedimentation photometer has been reported<sup>26</sup>.

The study of inherent ferromagnetism is more complex. In

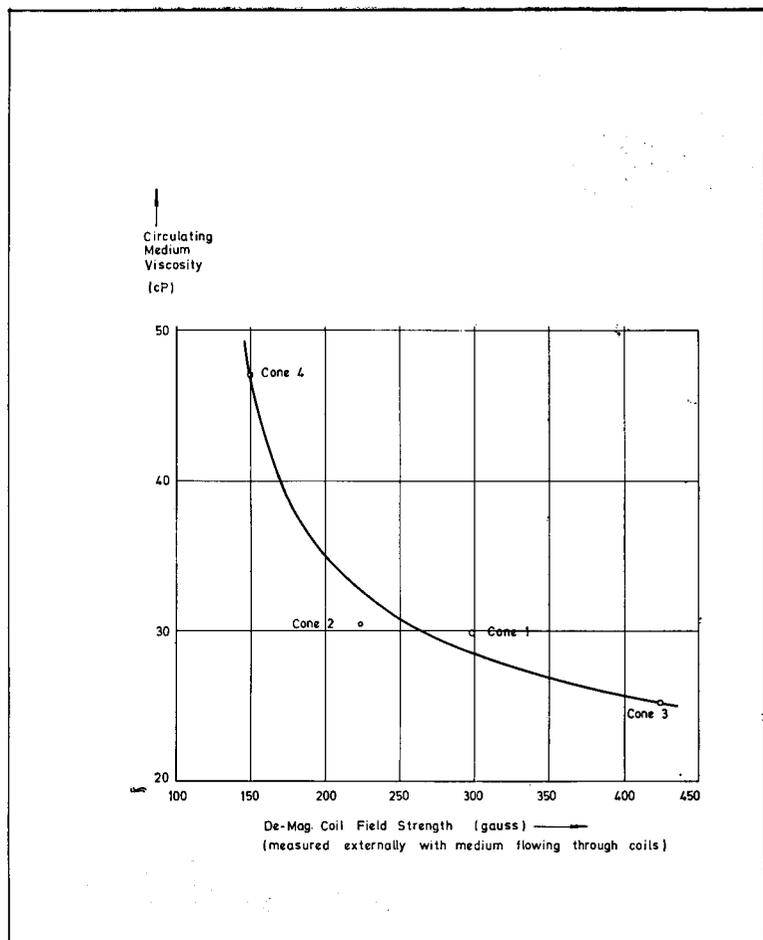


Fig. 5—Demagnetized coil field strength versus medium viscosity for Premier Mine heavy-medium cones (after Napier-Munn and Wilson<sup>25</sup>)—field strength: mean of two parallel coils

most of the investigations reported (e.g. that by Schmeiser *et al.*<sup>27</sup>), some form of magnetic balance was used. This type of device is used to measure the magnetic moment of a ferromagnetic sample when saturated in a strong magnetic field. A commercial instrument of this type is the Satmagan balance, manufactured by Outokumpu Oy of Finland, and originally designed for the determination of magnetite in ores and slags.

Tests on the application of the Satmagan to ferrosilicon analysis at the Diamond Research Laboratory have shown that, although the instrument gives an indication of the proportion of magnetic iron present in the alloy, the reading is also influenced by the metallurgical species present and by size distribution. It is probable, however, that the results obtained can be related directly to the probability of the sample<sup>25</sup> being recovered by a mag-

netic separator. From this point of view it is interesting to note that the minus 400 mesh fraction of any ferrosilicon sample always gives a lower reading than the plus 400 mesh, and that atomized ferrosilicon always gives a significantly higher reading than the milled material. This is in accordance with plant experience that the fines in the medium are lost preferentially from the magnetic separators. It is also usual to find that readings are lower from dried samples obtained from an operating circuit, even after fine non-magnetic contamination has been removed, probably owing to the presence of an oxidized surface on the ferrosilicon as a result of corrosion.

During the manufacturing process of milled ferrosilicon, a small proportion of non-magnetic material becomes mixed with the ferrosilicon. This is mainly graphite, which can often be seen as a black scum

floating off when fresh medium is added to a heavy-medium circuit.

Manufacturing specifications state that the proportion of non-magnetics should not exceed 0,75 per cent by mass, but in practice it is found that the proportion rarely exceeds 0,1 per cent.

### Corrosion Resistance

The inclusion of 14 to 16 per cent silicon in the alloy results in a relatively high resistance to corrosion or rusting. This is important for three reasons.

1. Corrosion leads to loss of ferrosilicon.
2. The finely-divided products of corrosion tend to increase the viscosity of the medium and thus impair the separating efficiency of the process.
3. Corrosion *in situ* can lead to the cementing of ferrosilicon particles when they stand in water, which results in difficulties in starting up a heavy-medium process after a long shut down.

Corrosion is a surface phenomenon<sup>28</sup> and results from the electrochemical oxidation of the ferrosilicon surface to produce non-magnetic iron oxides. Under static conditions, a passive layer is rapidly built up on the surface, which effectively prevents the progress of further corrosion. Under plant conditions, however, this passive layer is continually being removed by abrasion, which tends to accelerate the corrosion process.

The irregular-shaped particles of milled ferrosilicon have a greater surface area than the rounded atomized particles, and are therefore more susceptible to rusting. In addition, the sharp points and crevices of the milled particles make ideal nucleation points for the corrosion process. The resistance to rusting of the atomized material is extremely high owing to a passivity imparted to it during the quenching process<sup>2</sup>.

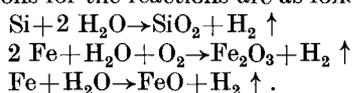
The provision of adequate corrosion resistance becomes more important in plants operating under abnormal conditions such as at high density (or in other words at the limit of acceptable viscosity),

high temperature, and acid or saline water.

Quality-control techniques for the assessment of corrosion resistance are based on the rusting of ferrosilicon samples under controlled conditions, and measurement of the effect of the rusting. In the case of milled ferrosilicon, the sample is repeatedly wetted with distilled water and dried for a fixed period at 110°C. The resultant increase in mass due to oxidation is then expressed as a percentage, termed the Rust Index (R.I.).

In the past, the manufacturer's specification for the ground material has stated that the R.I. should not exceed 0,4 per cent for a three-cycle wetting and drying procedure. Tests at the Diamond Research Laboratory, however, have shown that, if sufficient cycles are carried out, the R.I. always reaches a constant value due to the formation of the passive oxide layer (Fig. 7). The number of cycles required has been found to vary from about two to ten depending on the sample, although no correlation was found between the number of cycles required and the fineness of the ferrosilicon. A new specification maximum of 1 per cent has therefore been adopted, subject to each analysis being carried to the end-point. It has also been proposed that the rate of corrosion measured in this way could be used as a more realistic indicator of corrosion resistance, in view of the fact that under normal conditions of operation the passive layer is continually being removed.

The superior corrosion properties of the atomized material precludes the use of the R.I. as a measure of corrosion resistance, because the R.I. for atomized ferrosilicon measured in this way rarely exceeds 0,01 per cent. An alternative method used by Knapsack<sup>2,16</sup> involves the measurement of the volume of hydrogen evolved over a period of 100 hours from a fixed volume of stirred medium at a given density in an acid environment. The equations for the reactions are as follows:



The phenomenon of hydrogen evolution is frequently encountered

on a large scale in heavy-medium plants<sup>21</sup>, particularly after a settled medium has stood for some time in a storage vessel such as a spiral densifier.

Some investigators have questioned the validity of these methods for the assessment of corrosion resistance<sup>23</sup>, and indeed it has not been possible to relate laboratory data directly with the rusting behaviour of the medium in an operating plant.

One alternative that has been advocated is a plant test of the medium on pilot-plant scale in order to fully simulate production conditions, although clearly it would not be practical to employ such a method for the regular quality control of manufactured batches.

### Adhesion Losses

One of the major sources of loss of ferrosilicon from a production plant is by adhesion to the processed ore due to inadequate washing. The extent of adhesion is partly a function of the surface characteristics of both the ore and the ferrosilicon, and it has been shown<sup>2</sup> that adhesion loss is less with atomized ferrosilicon than with the milled material. As mentioned earlier, adhesion loss can be significantly increased by the presence of magnetic constituents in the ore.

### SELECTION OF THE MOST SUITABLE FERROSILICON GRADE FOR A GIVEN APPLICATION

A wide range of grades of ferrosilicon is now marketed in South Africa, and one of the first problems involved in designing a new heavy-medium plant is to select the correct grade of medium for the particular separating conditions. The selection must be based on a consideration of the following in relation to the viscosity and stability characteristics of the medium:

- (1) density of separation required,
- (2) size of ore to be treated,
- (3) sharpness of separation required, and
- (4) costs.

### The Tromp Curve

The distribution curve introduced by Tromp is generally accepted as a

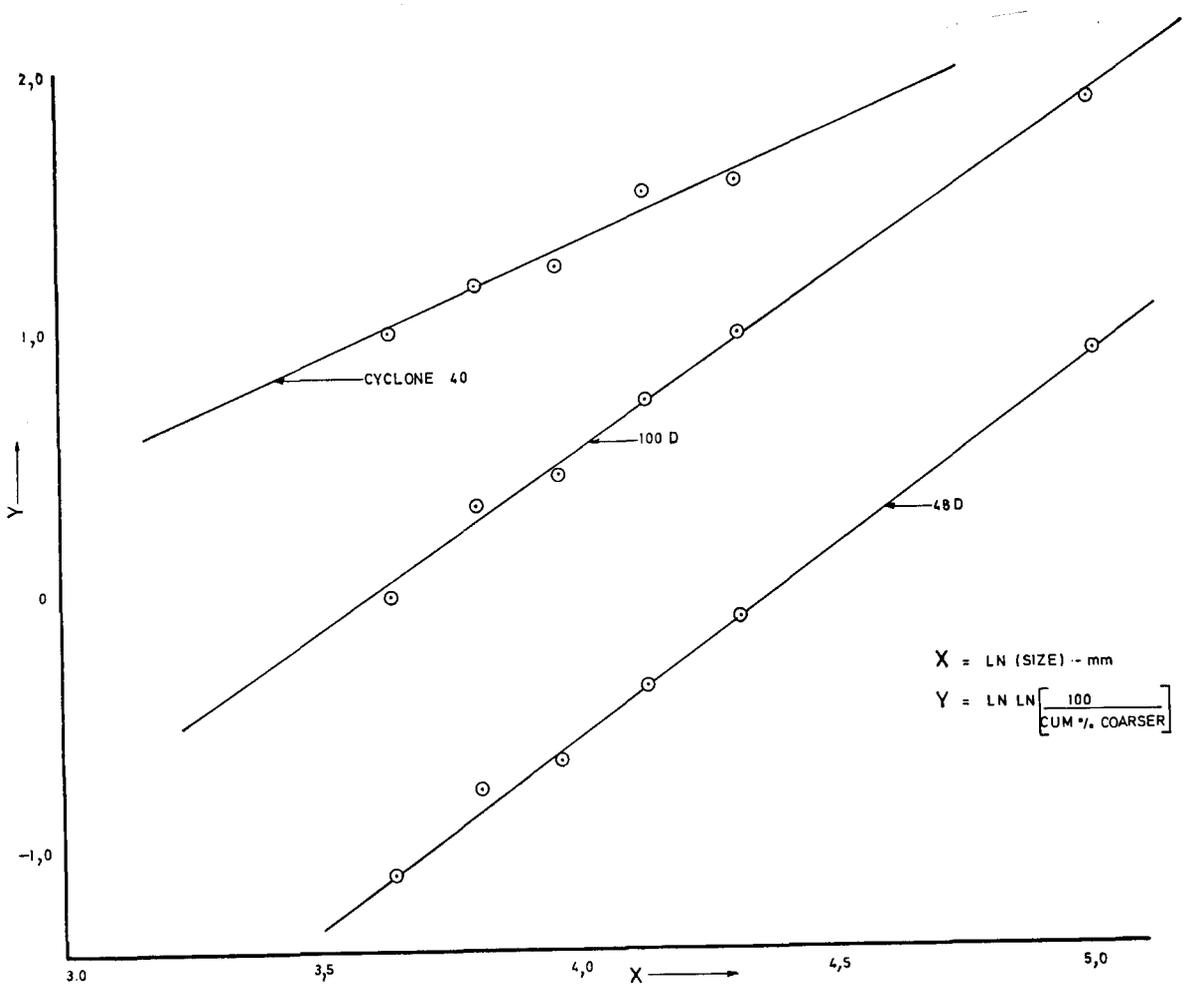


Fig. 6—Rosin-Rammler plots of size distributions of various grades of ferrosilicon

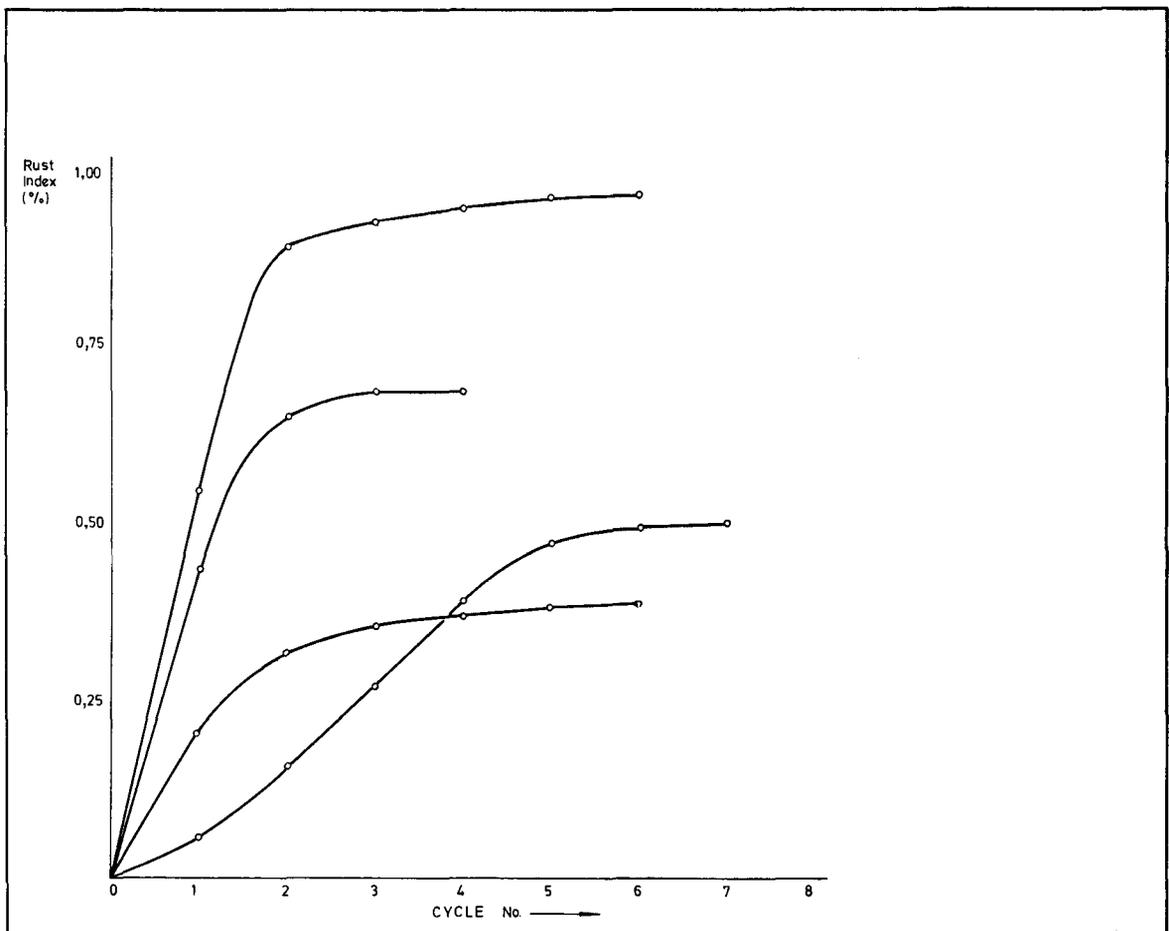
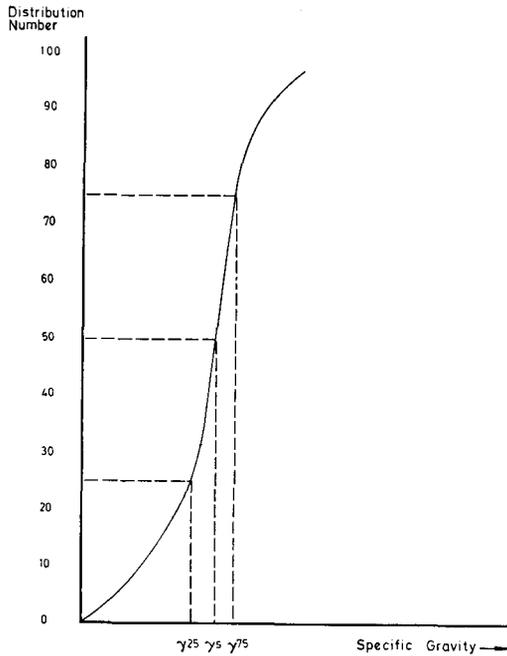


Fig. 7—Rust Index versus number of cycles for various samples of milled ferrosilicon



**Fig. 8—The Tromp Curve**

$\gamma_s$  = specific gravity of separation

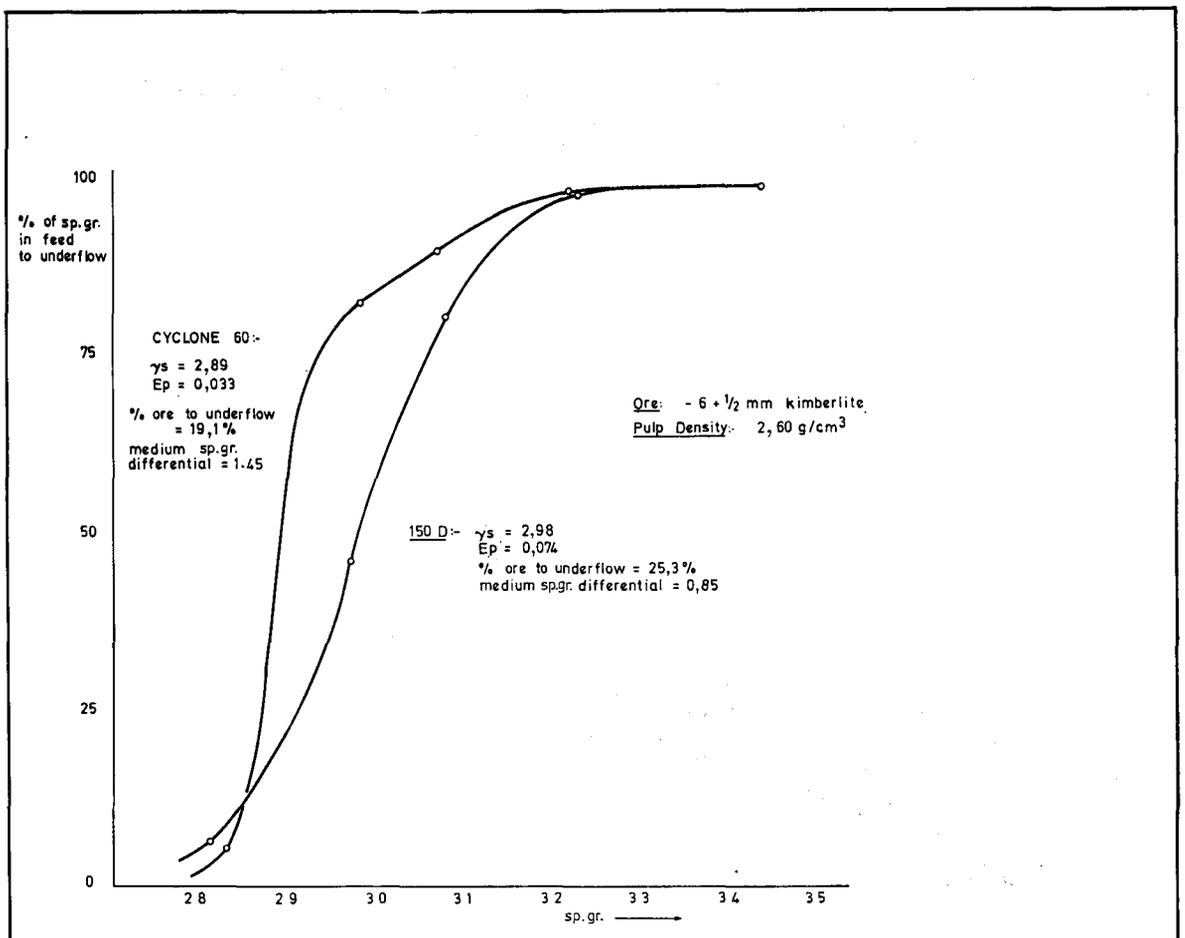
$$Ep = \frac{\gamma_{75} - \gamma_{25}}{2}$$

measure of the efficiency of separation in any heavy-medium system. The distribution number, defined as the mass percentage of the feed ore in a specific gravity interval reporting to the concentrate, is plotted against specific gravity (Fig. 8).

The specific gravity of separation ( $\gamma_s$ ) is defined as the specific gravity at which the distribution number is 50. The probable error ( $Ep$ ) is defined as half the specific gravity at a distribution number of 75 minus the specific gravity at a distribution number of 25. In this way a vertical line would indicate perfect separation at a particular specific gravity, whereas a horizontal line would indicate no separation at all.

### Density of Separation

In general, for actual separations above about 3,0 for static baths and 3,2 for cyclones, the use of atomized ferrosilicon is necessary, because above a true pulp density of about



**Fig. 9—Tromp Curves for separation in a 100mm cyclone using 150D and Cyclone 60 ferrosilicon**

3,0 the viscosity of the milled material has been shown to increase rapidly to unmanageable proportions (Fig. 2). At higher densities it is a question merely of selecting a grade of atomized ferrosilicon that exhibits adequate stability in a suspension of the required density.

### Size of Ore

The size of the ore to be treated generally determines the type of separating vessel to be used. Ore pieces larger than 25 mm cannot be handled in a dynamic separator. This in turn affects the choice of medium because a more stable medium is required in dynamic separation. A finer medium is necessary for dynamic separations than for static separations, because the higher forces involved in dynamic separation increase the tendency for the medium to thicken and create high differentials.

In dynamic separations, the size distribution of the medium must

also be considered in relation to the size of the separating vessel itself; smaller vessels engender higher separating forces owing to the smaller radius of rotation, and thus increase the tendency for the medium to thicken. Finer medium is therefore required for smaller cyclones. For example, in the tests reported here, which were carried out on a 100 mm cyclone (the results are shown in Figs. 8 and 9), of all the grades of medium currently manufactured by Amcor, only 100D, 150D, 270D, Cyclone 40, and Cyclone 60 could be used owing to the excessive specific-gravity differentials experienced with the coarser grades (often greater than 2,0), resulting in the bulk of the ore reporting to the underflow product.

### Sharpness of Separation

In the lower density ranges, either milled or atomized ferrosilicon may be used. Milled ferrosilicon is generally preferred because it is

cheaper. However, where a particularly accurate separation is required or where severely corrosive conditions are encountered, the use of atomized ferrosilicon may be justified.

Fig. 9 illustrates the results of treating a kimberlite sample in a 100 mm cyclone using 150D milled and Cyclone 60 atomized ferrosilicon. The atomized ferrosilicon is shown to provide a sharper separation. The density of separation, the  $E_p$  value, and the proportion of concentrate produced are lower for the atomized than for the milled material, although recoveries at the higher densities are almost identical.

It should be noted that 150D and Cyclone 60 grades have an almost identical size distribution. From the specific-gravity differentials it can be seen that the milled grade is more stable than the atomized grade. In practice, to achieve the same stability of the medium, a grade of atomized ferrosilicon would

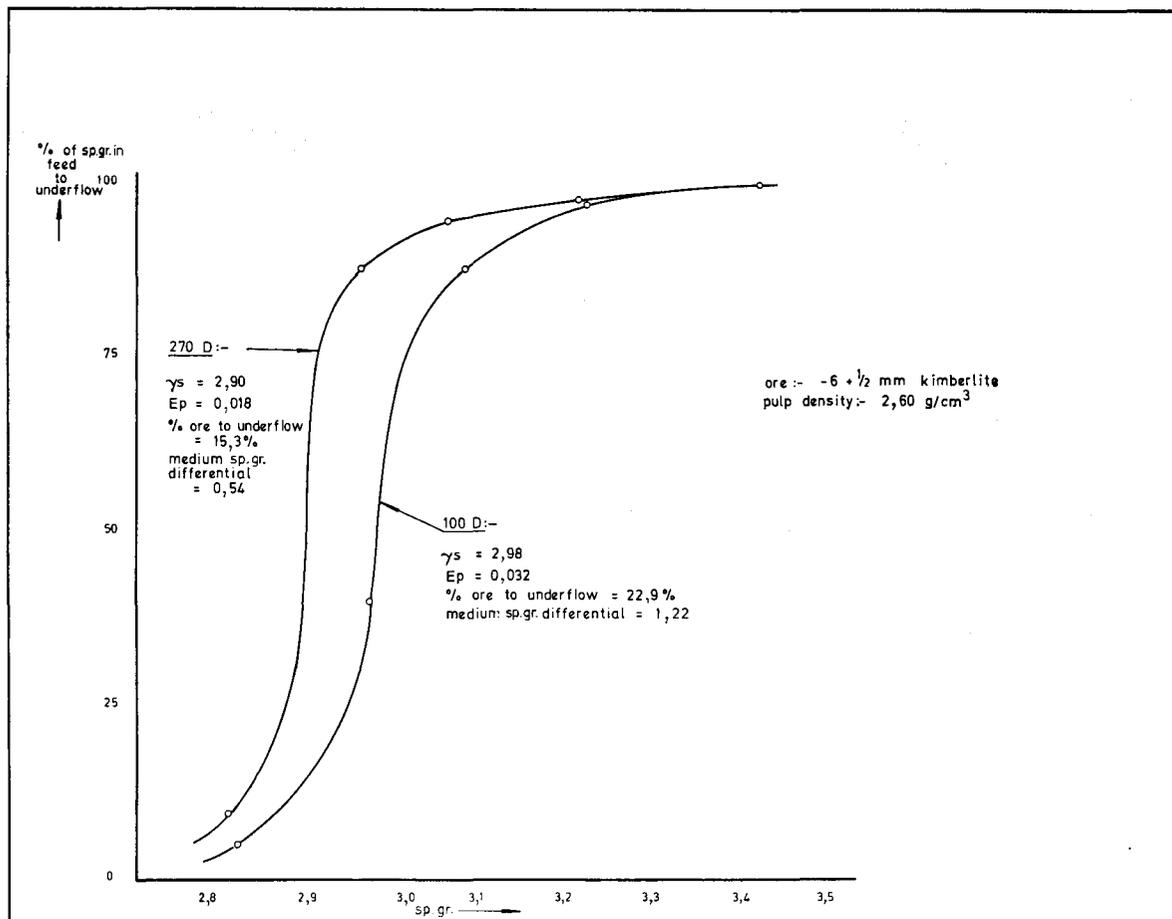


Fig. 10—Tromp Curves for separation in a 100mm cyclone using 270D and 100D ferrosilicon

be selected that is finer than the required grade of milled ferrosilicon. In this way an even better separation would be expected because the viscosities of suspensions of atomized ferrosilicon have been shown to be independent of size distribution in the lower density ranges (Fig. 2).

In cases where it has been decided that milled ferrosilicon will provide an adequate separation, it is essential that the medium employed should possess adequate stability. Fig. 10 shows the Tromp curves for the treatment of an identical kimberlite ore in a 100 mm cyclone using grades 270D and 100D at low density. The 100D medium is shown to be unstable at this density by the high specific-gravity differential. As a result, a sharper cut with a lower cut-point specific gravity and a lower proportion of ore reporting to the underflow is obtained with the finer, more stable 270D medium.

As noted earlier, it is often possible to use extremely coarse grades of ferrosilicon with static-bath separators in processes where the medium is stabilized by slimes generated by the feed or added artificially. This practice is not to be recommended, however, because it inevitably leads to an increase in medium viscosity to the detriment of separating efficiency.

### Costs

At present, the price of atomized ferrosilicon is more than double that of milled ferrosilicon. When a choice is being made between the milled and atomized material, it is not enough simply to compare prices. The overall economic advantages of atomized ferrosilicon should be taken into account. These include lower consumption due to lower corrosion, adhesion, and magnetic-separator losses; greater efficiency of separation; and a smaller bulk concentrate, reducing subsequent treatment costs. An accurate cost comparison can be made only by full-scale plant tests, but unfortunately this is not always convenient.

### A NOTE ON THE HANDLING OF MEDIA

Finally, aspects of handling the selected grade of medium should

also be considered. When the ferrosilicon is added to an opening circuit, care should be taken to ensure that the fines are not lost by flotation. Some plants include a mixing circuit for wetting the particles thoroughly before they are added to the main heavy-medium circuit: laboratory tests have shown that atomized ferrosilicon is less prone to loss in this way, since it appears to be more wettable. The settling characteristics of the selected grade are also important in relation to static densifiers. For example, a plant-scale test of Cyclone 40 at Consolidated Diamond Mines of South West Africa Ltd had to be abandoned because it was found that the ferrosilicon would not settle adequately in the spiral densifiers used on the plant, even though preliminary indications were that an improved separation was being obtained in the 600 mm heavy-medium cyclones using this medium.

### CONCLUSION

It is hoped that this paper has shown that ferrosilicon is a simple and effective material for heavy-medium separation, subject to the proviso that the correct grade is selected for the particular application; to assist potential users, some guidelines have been provided for the correct choice of grade for any given duty.

The technology of ferrosilicon manufacture is now well established, and it seems unlikely that any major advance in this field is either possible or warranted at this stage. However, the literature review undertaken for the paper has clearly shown that the field of research into the rheological properties of ferrosilicon suspensions, although relatively old in years, is nevertheless in its infancy as regards progress and achievement. Important contributions have been made by a number of investigators, particularly in this country, but many fundamental questions remain unanswered. The solution to these problems is likely to have an important bearing both on grade selection and on the optimization of the performance of heavy-medium separators. In particular, the rheological behaviour and characteristics of ferrosilicon

suspensions in dynamic separators are not well understood, and it may be that significant improvements in performance could be achieved either by changes in operating conditions or by modification of the characteristics (particularly size distribution) of the ferrosilicon powder itself.

To this end, further research is planned at the Diamond Research Laboratory on the stability and viscometric properties of ferrosilicon suspensions and their modification, in order to promote a greater understanding of the fundamental principles of heavy-medium separation using this material, and thus to optimize performance.

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## Discussion of the above paper

T. B. BEETON\*

### Introduction

The authors are to be congratulated on a very fine paper. It is immensely gratifying to see the obvious co-operation and consensus of opinion evidenced in this paper by the manufacturer, the seller, and a major user of ferrosilicon. As a pioneer in the manufacture of, and research into, this interesting material here in South Africa, I earnestly wish that this co-operation will continue in the future, as such an almost unique situation can lead only to the eventual benefit of all parties concerned.

I should now like to comment briefly and expand a little on a few selected aspects of this paper.

### Fundamental Properties

The authors have listed a number of fundamental properties of the ferrosilicon alloy that are vital to the success of the material as a heavy-medium powder. I should, however, like to draw your attention to two further properties that are of great importance to the successful production of atomized material.

#### *The Fluidity of the Melt Just Above the Freezing Point*

The fluidity is important in its effect on the shape of the resulting particles. The alloy should freeze straight from the liquid into a single-phase component, and should not go through a 'mushy' or 'misch kristal' stage. In this respect, ferrosilicon of 14 to 16 per cent silicon is very suitable, but additions of other metals may interfere with this rapid freezing. Small quantities of fluidizers such as sulphur and phosphorus can be added with some advantage, but we must be careful of their effect on the second and more important property, which is dealt with below.

#### *Surface Tension Just Above the Freezing Point*

The surface tension of the alloy just above the freezing point, like the fluidity, should be as high as possible.

In theory, the surface tension of the solid alloy should be directly proportional to the free electron-atom ratio of the alloy. Work carried out at ISCOR many years ago confirmed that, in most cases, this theory holds true for liquid alloys at a temperature close to the freezing point. Therefore, the addi-

tion of small quantities of substances that will increase this electron-atom ratio should yield an improvement in the particle shape.

It is interesting to note how rapidly the surface tension of ferrosilicon drops as the silicon content rises, and then how it takes a sudden plunge as the alloy reaches the stage of the first intermetallic compound and the electron-atom ratio drops to a theoretical zero.

I am mentioning these facts because I feel that, although a good deal of theoretical work has been done along these lines, it has been accompanied by very little practical experimentation. I am sure there is scope for more basic research work in this field.

### Properties of the Heavy-medium Material

One of the properties of the material itself not mentioned by the authors is the basic one of hollow particles, the so-called 'hollow balls', with which I would now like to deal briefly.

#### *Hollow Particles*

I was led into this subject by the mention of the ISCOR process in the paper.

One of the reasons for our claim that the water-atomized product

\*ISCOR

was superior to the steam-atomized was the virtual absence of hollow particles in the former. Why hollow particles are produced, or not produced, under certain conditions remains an enigma.

We know from experimental work on the production of large granules that the hollowness is produced by the liberation of gas from the molten material during the formation of a solid crust on the outside of the particle. The percentage of hollow particles produced under given conditions usually increases with increasing particle size, and appears to depend on the carbon and manganese content of the alloy.

These hollow particles, apart from lowering the specific gravity of the material, tend to break open during usage and thereby cause severe corrosion and other problems. They must be taken seriously in the production of a superior-quality heavy-medium, but we do not really know enough about the detailed conditions under which they are produced.

The material produced in an induction furnace always has fewer hollow particles than that produced in an arc furnace, and I often wonder what kind of material would be produced if we were to vacuum de-gas a ladle of ordinary material from the arc furnace prior to atomization.

#### *Corrosion Properties*

Once again the dangers of accepting any laboratory corrosion result as a criterion of possible plant performance cannot be overstressed. But I should like to deal briefly with one aspect of corrosion resistance not mentioned by the authors, and this is the influence of the carbon content of the material on corrosion. Our experience for many years past has indicated that, in general, the higher the carbon content, the greater the risk of corrosion problems.

Corrosion inhibitors can be, and have been, used in some of our alloys. Materials such as copper, nickel, or chromium have been added in small quantities, and even some of the more exotic metals such as uranium. Once again an abundance of laboratory work has been done in this field, but not much

practical field work. One thing, however, is sure, and that is that an increase in carbon content will adversely affect the specific gravity and the corrosion resistance of the material, but this is the cheaper method of producing ferrosilicon. Can we not find some inexpensive additions that will offset this effect of carbon?

Corrosion resistance during storage of the wet medium can be countered by the addition of inhibitors to the storage tank or, even if freely available, by freezing of the bath with liquid nitrogen just sufficiently to keep the temperature down before the next start-up of the plant. Cooling of the medium is an effective method of combating corrosion.

#### *Magnetic Properties*

Time will allow comment on only one more property of the material, namely the magnetic property. We did a great deal of work on the magnetic properties of various ferrosilicon alloys some years ago at ISCOR, and eventually came to the conclusion that any ferrosilicon alloy of 14 to 16 per cent silicon has magnetic properties that are so superior to other materials, such as magnetite, that virtually any reputable make of magnetic separator or demagnetizer would be adequately effective (providing, of course, that it was in good working condition).

We never measured magnetic attractability, but did measure the hysteresis loop under high field strengths. We found very little difference between atomized and milled ferrosilicon.

In this regard, I should like to ask the authors some questions.

- (1) At what field strength is ferrosilicon saturated?
- (2) Are the differences in attractability not related to particle size and shape, and to packing density in the sample?
- (3) Is the loss of fines in any practical magnetic separator not due to the fact that, when dealing with very small particles, the relative drag forces in the fluid medium become greater than the magnetic attraction force and mechanically prevent the small particles from being pulled out of the liquid flow? If this is the case, then the

loss of fines would not be due to any inherent magnetic property of the material itself.

#### **Conclusion**

In conclusion, I should once more like to thank the authors for a most informative and well set-out paper, which has more than adequately covered the three aspects referred to in the title. However, before closing I should like to stress the point made in this paper regarding the selection of the correct grade of ferrosilicon for the requirements of the job. This is most important if the maximum benefits of the use of ferrosilicon, which is after all not a cheap material, are always to be obtained.

#### **J. B. SEE\***

In his discussion, Dr Beeton indicated that the high surface tension<sup>†</sup> of ferrosilicon 14 to 16 per cent silicon was important in ensuring that spherical powders could be produced by steam atomization of the liquid alloy. The aim of this contribution is to discuss in more detail the influence of surface tension on the morphology of particles produced during the atomization of a liquid metal by a gas.

The final shape of a metal particle formed by the disintegration of a liquid-metal stream by a gas jet is determined by the relative magnitudes of the time required for solidification and the time required for surface tension forces to restore the particle to a spherical shape. Thus, all other atomization variables being constant, a higher value of surface tension means that there is more likelihood that spheres will be formed before sufficient heat transfer from the particle has occurred to 'freeze in' an intermediate shape between that of the primary particles and a sphere. Such intermediate shapes have been observed for the atomization of iron and iron-nickel alloys by air and nitrogen<sup>2,3</sup> as well as for the atomization of ferrosilicon by air<sup>4</sup>.

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†At 1550 °C, the surface tension of this alloy should be closer to that of iron<sup>1</sup> (about 1750 to 1870 dyn/cm) than that of silicon<sup>1</sup> (720 dyn/cm).

Investigations of the atomization of lead and tin by nitrogen jets<sup>5,6</sup> indicate that these intermediate shapes are formed by a particular type of disintegration mechanism. This mechanism requires filming of the liquid stream by the gas to form a sheet of liquid that breaks up into unstable ligaments from which drops are formed.

The studies cited above indicate that, under some circumstances, sufficient heat transfer can occur from liquid-metal particles for them to solidify during a time ( $t_{sol}$ ) that is less than the time required for the particle to spheroidize ( $t_{sph}$ ). Since spherical particles of ferrosilicon are produced by the Knapsack process described in the paper, the atomization conditions must be such that  $t_{sph}$  is less than  $t_{sol}$ .

Formulae<sup>7</sup> are available for the calculation of both  $t_{sol}$  and  $t_{sph}$ . However, before these formulae can be used, it is necessary to determine experimental details such as the relative velocity between the particles and the gas, and the precise shape of the particles immediately after their formation from the bulk liquid.

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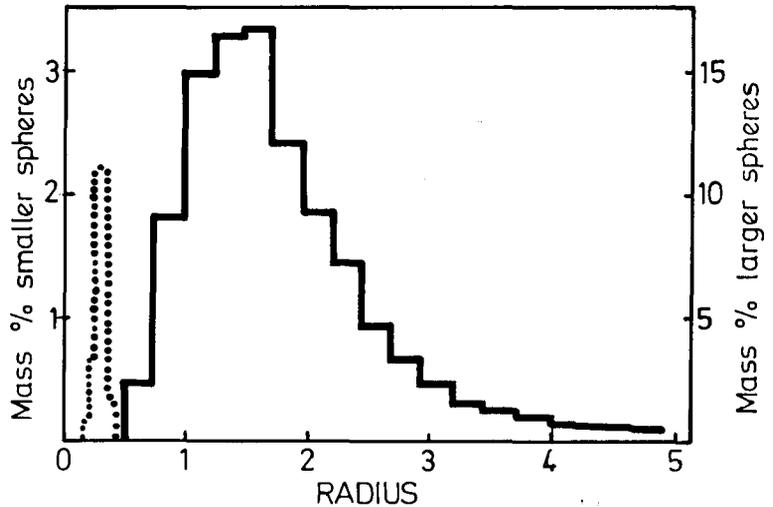
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## A. W. BRYSON\*

In this paper, the authors indicate that the particle size of manufactured ferrosilicon can be well represented by the Rosin-Rammler distribution, which has a unimodal density function. It would be of interest to investigate properties such as slurry density, viscosity,

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Type of bed	Void fraction	Density of ferrosilicon suspension
Dense random bed of equal spheres	0,4	4,6
25% expanded bed of equal spheres	0,52	3,9
Dense random bimodal distribution of spheres	0,2	5,8
25% expanded bed of bimodal distribution of spheres	0,36	4,8



and stability of a bimodal distribution of spheroidized ferrosilicon. The figure above shows a log-normal distribution of spheres (solid line), with a superimposed distribution of smaller spheres that just fit into the interstices of the larger ones (dotted line). The table summarizes the theoretical void fractions and slurry densities that would be expected in beds of equal spheres and in beds with the proposed bimodal distribution of spheres. It will be noted that the theoretical slurry densities of 25 per cent expanded beds increases from 3,9 to 4,8 when the bimodal distribution is used.

## J. DE KOK\*

Mr Collins and his co-authors have given an excellent survey of the production and properties of ferrosilicon powders and their use in heavy-medium separation.

It may be useful at this stage to look more closely at some of the fundamentals of the rheology of suspensions and to discuss their application to these operations.

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## Particle-size Distribution and Stability

As described in the paper, the settling velocity is a very convenient parameter for expressing the stability of a heavy-medium suspension. Accurate correlations have been established for the hindered settling of uniformly sized rigid particles, and a particularly useful equation is that of Richardson and Zaki<sup>1</sup>:

$$u = u_t \epsilon^n,$$

where  $u$  is the settling velocity of a particle in a suspension of voidage fraction  $\epsilon$ , and  $u_t$  is the velocity that the same particle would have in free fall.  $n$  is a function of  $Re_t$ , the Reynolds number based on  $u_t$ . When  $Re_t$  is small,  $n$  is equal to 4,7, and it decreases to 2,4 for large values of  $Re_t$ . For our purposes, the equation can be simplified to

$$u = \frac{gd^2(p_s - p_f)}{18\mu} \epsilon^{4,7},$$

where  $d$  and  $p_s$  are the particle diameter and density, and  $\mu$  and  $p_f$  the fluid viscosity and density.

This equation explains in a qualitative way why the stability of a suspension is improved by smaller particle sizes and lower voidage

fractions. Unfortunately, the quantitative agreement is not good when applied to the data in Fig. 4 of the paper.

The calculated exponents for the various grades are as follows:

Special coarse	7,7
Special fine	8,3
Cyclone 60	9,1
65D	12,6
100D	17,5.

These high values of  $n$  indicate a more rapid change in stability with pulp specific gravity than would be expected from the Richardson and Zaki equation. The discrepancy is due to the wide range of particle sizes in each grade. It is well known that size segregation occurs during hindered settling, and that density gradients are established in such cases<sup>2</sup>. Because of this, the zone of medium of the original starting specific gravity can thus fall appreciably faster than indicated by the sedimentation velocity, and it could be argued that the medium is less stable than indicated by this test. The segregation effect is more pronounced at higher voidage fractions, and the gradients are greatest at the top of the bed, which is the region in which sedimentation velocity is usually measured.

No quantitative information appears to be available on this phenomenon, and it seems that it would be worth some further study, as the simple sedimentation velocity may not always be an adequate measure of stability.

#### The Effect of Shear Rate on Viscosity

As pointed out in the paper, much work has been done on the viscosity of unstable suspensions. It has been fairly well established that such suspensions are usually pseudo-plastic or shear-thinning, i.e., the apparent viscosity increases with decreasing rates of deformation. Now, we are particularly interested in the behaviour of slowly moving near-gravity particles, and the viscous resistance of the medium to these. It can readily be shown<sup>3</sup> that the maximum shear rate in the vicinity of a falling spherical particle is equal to  $\frac{3u}{d}$ , and the effective value would be somewhat lower. This

would mean, for instance, that the effective shear rate for a particle of 1 cm diameter travelling at 1 cm/s is less than  $3 \text{ s}^{-1}$ . Unfortunately, because of experimental difficulties, most measurements of viscosity have been done at shear rates in the range 30 to 300  $\text{s}^{-1}$ , and these would tend to underestimate the viscosity.

A test on a mixed ferrosilicon sample with a modified Brookfield viscometer has, for instance, given the following result<sup>4</sup>:

Shear Rate ( $\text{s}^{-1}$ )	Apparent Viscosity (Cp)
32,0	36
16,0	52
6,5	98
3,1	141

More information on viscosities at low shear rates would therefore be required before we could hope to make predictions of the behaviour of static-bath separators from medium properties.

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#### K. KOMORNICZYK\*

As a contribution to the discussion of atomized versus milled ferrosilicon, I submit the findings of one of our clients, who was last year in the position to make a one-year comparison of two parallel-working Wemco drums. The feed of iron ore to each drum was 400 t/h, and the feed per month to each drum was 103 000t. The pulp density was 3,0 to 3,2 g/ml. The average consumption of atomized ferrosilicon was 5,8 tonnes per month, and of milled ferrosilicon 10,1 tonnes per month.

#### AUTHORS' REPLY

The authors would like to thank the contributors for their constructive and authoritative discussion of this paper. The points submitted are thought-provoking and worthy of

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careful consideration, and in some cases the necessity for further research in this field is clearly indicated.

Dr Bryson's suggestion that significantly higher pulp densities could be achieved by use of a ferrosilicon size distribution having a bimodal, instead of a unimodal, density function is of particular interest. The possibility of modifying ferrosilicon size distributions so as to improve the performance of the medium has been considered in the past; for example, it has been proposed that the exclusive use of that size of ferrosilicon having the maximum residence time in a heavy-medium cyclone could improve performance by increasing medium stability without unduly increasing viscosity. All such proposals, however, would undoubtedly be difficult to achieve in practice since the manufacturing process does not allow the easy modification of the *width* of the size distribution in each case.

Dr Bryson's suggestion could no doubt be accommodated by selective blending procedures, although the high level of control required to achieve the exact fitting of the two accurately produced unimodal distributions would probably result in prohibitive manufacturing costs. In addition, it seems likely that the reduction of the void fraction by this procedure would lead to an increase in viscosity for a given pulp density. Nevertheless, both the production of the desired distributions and the investigation of the properties of the resultant medium would be relatively easy on a laboratory scale, and Dr Bryson's comments are of sufficient interest to warrant further investigation.

Dr De Kok rightly points out that Zaki's equation has been found useful in describing the hindered settling of uniformly sized particles. The equation can also be expressed as

$$\frac{u}{u_t} = (1 - C)^n,$$

where  $u$  = settling velocity of a particle in a medium of volume concentration  $C$ ,  
 $u_t$  = equivalent Stokesian settling velocity, and

$n$  = an exponent, which only approaches 4,7 for Reynold's numbers of less than  $10^{-2}$ .

However, the quantitative validity of Zaki's equation is seriously tested under the conditions quoted in the paper, for the following reasons.

- (1) The equation refers only to perfect spheres; for irregular-shaped particles, the value of  $n$  should be increased by 50 per cent.
- (2) The equation is not really valid for volume concentrations above about 10 per cent. A ferrosilicon suspension of density  $3,0 \text{ g/cm}^3$  has a volume concentration of about 35 per cent.
- (3) As Dr De Kok points out, the equation refers to uniformly sized particles, whereas a ferrosilicon suspension contains particles of a very wide range of sizes.
- (4) The substitution in the equation of settling velocities calculated from the differential-pressure stability-measuring method quoted in the paper must be fraught with danger, since in no way can the method be assumed to provide direct quantitative data on particle-settling velocity, but rather on the rate of change of pulp density at an arbitrary level in the pulp.

In fact, at high volume concentrations, the properties of polydisperse systems cannot be predicted with any confidence. Dr De Kok's remarks concerning size segregation and the establishment of density gradients are valid at low volume concentrations (less than 10 per cent) but cannot really be substantiated at high volume concentrations. Any attempt to quantitatively correlate sedimentation velocity with such an

arbitrary definition of stability would seem to be a pointless exercise, since, as Dr De Kok rightly emphasizes, the important variable from a practical viewpoint is pulp-density change rather than settling rate.

As noted in the paper, work is currently being planned at the Diamond Research Laboratory on medium 'stability' as characterized by the rate of change of density, and it is hoped that reliable quantitative data, which Dr De Kok suggests would be worth acquiring, will result from this work.

Dr De Kok's comments on the effect of shear rate on viscosity are of interest in view of the dearth of reliable data on this subject. There certainly is evidence to indicate that unstable suspensions in general are pseudoplastic, although there are few direct data available on ferrosilicon suspensions specifically. To this characteristic must be added the indirect indication of the presence of a yield stress in some such suspensions, a characteristic of the Bingham Plastic class of materials.

A knowledge of the relationship between shear rate and viscosity for a particle of known dimensions and a medium of known viscosity can be used to calculate the smallest size of particle that can be effectively treated in a static-bath separator of known geometry and dimensions. This was in fact done some years ago at the Diamond Research Laboratory, where it was estimated that the Premier Mine 16 ft diameter heavy-medium cones were likely to lose any diamonds smaller than 7 mesh (2,8 mm) in size owing to the high viscosity and resultant low settling rates prevalent for that size of stone (these units are fed with

a material larger than 3 mm in size).

By use of a specially designed Haake viscometer recently acquired by the Diamond Research Laboratory, it is hoped to carry out studies of the viscometric characteristics of ferrosilicon suspensions at shear rates as low as  $2 \text{ s}^{-1}$ .

As noted in the paper, there remains significant lack of understanding of the rheological behaviour of ferrosilicon suspensions under dynamic flow conditions (e.g. in a cyclone), in which the behaviour of the particle being separated is complicated by the shear of the medium itself caused by its rotational flow in the vessel. This represents almost virgin territory for any potential investigator.

With regard to Dr Beeton's queries concerning the magnetic properties of ferrosilicon, Schmeiser *et al.* (reference 25 of the paper) quotes a figure of 4000 A turns/cm for the field intensity required to saturate ferrosilicon. Although the manufacturers of the Satmagan magnetic balance specifically state that differences in packing density of the sample are automatically compensated for, there is evidence to suggest that, over a wide range of size distributions, this may not entirely be so. The significant drop in magnetic susceptibility consistently noted for particles below 38  $\mu\text{m}$  in size (compared with relatively consistent readings above this size) is nevertheless interesting in relation to the probable size of the magnetic domains present in alloys of this kind. This suggests that, although there is little doubt that mechanical forces are indeed partly responsible for the observed preferential loss of fines from magnetic separators, a low magnetic susceptibility may also be a cause.