Size segregation in filling and emptying of a Paul-Wurth bin

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SIZE SEGREGATION IN FILLING AND EMPTYING OF
A PAUL-WURTH BIN

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by

Ali Kilic

Supervisor:-
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SYNOPSIS

In-bin segregation and the discharge segregation of a 17:1 scale model of the Paul-Wurth bin at the Port Kembla No.5 Blast Furnace was investigated.

In-bin segregation was studied using two different materials (ore and coke), and two different sampling procedures, namely in-bin sampling method and freezing technique. Comparison of these methods show that in-bin sampling could be used instead of freezing technique for practical purposes.

The experimental results also show that in-bin segregation shows notable change with the nature of material and the material height on the bin.

Using RTD method the flow in the Paul-Wurth bin was studied. The results show that the flow model of the Paul-Wurth bin contains a volume of plug flow ($V_p$) in series with parallel mixed flow volumes ($V_{m1}$, $V_{m2}$) and doud volume ($V_d$). Calculated values of volumes and volumetric flow rates ($v_{m1}$, $v_{m2}$) are as follows:

$$V_{m1} = 0.12, V_{m2} = 0.37$$
$$V_p = 0.27, V_d = 0.24$$
$$v_{m1} = 0.91, v_{m2} = 0.09$$

Also the measured flow patterns of ore and coke were found to be exactly the same during the discharge of the bin.

Discharge experiments were also conducted to study discharge segregation phenomenon of ore and coke of different sizes (large = -8.0 + 6.3mm, medium = -5.0 + 4.0mm, and small = -2.0 + 1.0mm). Sieve analysis was performed for each experiment and the results were used for establishment of power relationships.
between \((\text{Li}/\text{Lo})\) Vs \((\text{Wi}/\text{Wo})\), \((\text{Mi}/\text{Mo})\) Vs \((\text{Wi}/\text{Wo})\) and \((\text{Si}/\text{So})\) Vs \((\text{Wi}/\text{Wo})\) where \((\text{Li}/\text{Lo}) = \text{normalized percentage values of large size particles, (Mi}/\text{Mo}) = \text{normalized percent values of medium size particles, (Si}/\text{So}) = \text{normalized percent values of small size particles and (Wi}/\text{Wo}) = \text{normalized discharge values.}

These relations are as follows:-

\[
(\text{Li}/\text{Lo}) = K(\text{Wi}/\text{Wo})^{1/5} M \leq MC
\]

\[
(\text{Li}/\text{Lo}) = K(\text{Wi}/\text{Wo})^{-1/5} M \geq MC
\]

and

\[
(\text{Si}/\text{So}) = K(\text{Wi}/\text{Wo})^{-1/5} M \leq MC
\]

\[
(\text{Si}/\text{So}) = K(\text{Wi}/\text{Wo})^{1/5} M \geq MC
\]

where \(M = \text{material}\)

\(MC = \text{material critical}\)

\(K = \text{constant}\)

Discharge segregation results revealed that medium sized particles were biased towards the particle size with the lowest percentage content in the feed mixture. The discharge segregation patterns of ore and coke were found to be the same. The results of this investigation also revealed that the calculated in-bin segregation pattern, using a simple discharge model, is in reasonable agreement with experimentally obtained results.

The comparison of results of this investigation show good agreement with the theoretically expected patterns, and with the discharge segregation results under industrial conditions.
ACKNOWLEDGEMENT:

The research work reported in this thesis was carried out in the laboratories of the Department of Metallurgy, The University of Wollongong, under the supervision of Associate Professor N. Standish.

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1.0 INTRODUCTION

For many years iron-making has played an active role in the development of nations and their advancement. Though today's iron-making production is not as primitive as it used to be, the unsolved problems of this industry still continue. Though the details of these problems are out of the scope of this investigation, the size segregation is a very important phenomenon when dealing with filling and emptying of bins or material handling in general.

When a mixture of solid particles of different properties is set in motion, such as in the filling and emptying of bins, the particles of similar characteristics tend to separate themselves from the rest of the mixture. This tendency is called Segregation. Numerous factors affect the segregation to a lesser or greater extent. These are:

1. size
2. specific gravity
3. geometrical shape of the particle
4. flowability of the particles
5. surface properties of the particles
6. geometry of the hopper
7. composition of the mixture
8. elasticity of the particle, etc.

For many years the type of top used for a blast furnace was the bell top as shown in Figure 1.1(a). It is only within the last decade that the iron-making industry has shown preference for a bell-less blast furnace top (see Figure 1.1(b)). This
preference is based upon three advantages that the Paul-Wurth top offers over the traditional bell-top. These advantages are:

i. a significant reduction in top-gas pressure loss both during charges and between charges;

ii. significant time saving on furnace top maintenance; and

iii. greater control over the furnace stockline.

Because these advantages can readily be shown to be the case, and because their benefits can be easily estimated in terms of cost savings, they have been seen by iron-making management to be sufficient justification of the Paul-Wurth system. However, it is probable that greater benefits accrue from the last advantage, which manifests itself in the compositional characteristics of the burden. A greater control over the furnace stockline means greater control over both the chemical non-uniformity and the structural non-uniformity of the burden. Hence the blast furnace iron-maker is entitled to expect a corresponding increase in metallurgical efficiency and production efficiency. In other words, increased production at decreased production cost.

Referring to the stockline profile in Figure 1.1 it is of interest to note that the rotary chute top is capable not only of placing charge material differentially across the stockline, but also of placement of different charge materials at different segmental sections of the burden surface (stockline area). These capabilities allow the following advantages:

i. The Ca/Co₂ ratio as a function of furnace radius can be kept constant;
(a) Bell Top

(b) Paul-Wurth Bell-less Top

Figure 1.1
ii. Control of temperature distribution over the burden surface;

iii. Wall temperature corrections can be made by ore or coke layer position shifting;

iv. The burden surface (stockline) can be made flat;

v. Increased stock refractory life; and

vi. The coke rate may be reduced towards the theoretical limit together with production.

It is very important to understand that the total of the particle size segregation occurring between the top supply and the stock line is the sum of the discrete segregation events. These are the "piling" segregation which occurs on charging the feed bin, and the "coring" segregation which occurs as the bin is discharged. Both of these size segregation events are completely controlled by physical principles and are functions of separate sets of variables. So far no action is taken by furnace operators to control or influence either of these segregation events in the Paul-Wurth system.

The first of these segregation events is associated with filling of the feed bin. The stream of solid particles flowing on to a surface gives rise to the phenomenon of piling. The angle of the sloping sides of the conical pile, the angle of repose, is a function of many variables of which the principal ones are particle density, particle shape, size distribution, direction of impact, impact velocity, particle elasticity, and the elasticity or rigidity of the pile structure.

In the case of the Paul-Wurth bin, the bin geometry can modify the angle of repose. Segregation by the angle of repose mechanism magnifies any size distribution in a material sample.
because the fines bounce at a higher angle of repose than the coarser particle fractions. Because the coarsest particles have the lowest angle of repose, they tend to roll to the outside of the pile, as shown in Figure 1.2. The segregation of constant specific gravity materials is dependent upon the difference between the momenta of the impacting particles. Larger particles, by virtue of their higher momentum, tumble further down the free face of the pile.

If a bin is filled by pouring material consisting of a mixture of particle sizes, the material will pile up in response to the prevailing forces and conditions. If the flowing point is centrally located then the segregation pattern will be similar to (a) in Figure 1.2. If the pouring point is offset but still vertical then the segregation pattern will be similar to that shown in Figure 1.2(b), except that in both cases due to vertical walls the central core of fines will be a tube. For free-flowing materials the basic principle governing the emptying of bins can indeed be easily stated thus: the material will discharge only if the pressure at the discharge end is less than above it. Similarly, the basic principle governing the rate at which the material will discharge can also be easily stated thus: the rate of discharge is proportional to the difference in pressure, the area of the discharge opening and the coefficient of discharge.
Figure 1.2(a) Piling Segregation - pouring onto a surface

Figure 1.2(b) Piling Segregation in a Paul-Wurth bin
(Central core of fine)
2.0 THEORETICAL CONSIDERATIONS

2.1 SEGREGATION AS A PART OF THE COMPLEX BEHAVIOUR OF BULK GRANULAR MATERIALS

While feeding and discharging bulk materials into and from storage systems of any kind, there is a number of important variables whose effect on the whole complex should be known in order to design storage systems which will work satisfactorily.\(^1\)

It is necessary to have the correct size and form of hoppers and bins suited to the special material to be handled and satisfactory arrangements for feeding and discharging, to ensure continuous flow.

It is a common, every-day sight, where a free flowing stream of granular solids - for instance ore, coke or gravel - forms a cone-shaped pile on the ground. It is known that the sloping sides of the pile represents the angle of repose of the material. It is also known that when the material stream contains at least two different sizes of particles or consists of particles of various specific gravity, the solid particles tend to segregate on a size or specific gravity basis when they are fed into and later discharged from storage.

When a storage bin is filled from a single pour point on the axis of the bin there is a core of fines at the centre and a ring of the coarser or coarsest material - if there are more than two components of different size - at the outside wall. While handling material of different specific gravity, the heavier particles will stay at the centre and the lighter will move to the bottom edge.
Consider a cylindrical flat-bottomed storage bin with a concentric circular surface. When a bunker like that has been filled, and bottom discharge flow is started, there will generally be no appreciable movement of the particles at the wall of the bin until the inverse angle of repose has developed at the centre. It can easily be shown that the first material from the bin will be from the core of fines, and after movement at the wall has begun, a more or less uniform material will be discharged, depending on the height of the material in the bin, and the diameters of the bunker and the orifice. If the bin is emptied completely, the last material will consist to a great extent of coarse particles (see Figure 2.1).

It was observed that, by feeding a mixture of two components of different-sized granules axially into a bin so that a cone is formed, the number of small particles that reach the periphery of the cone is less as the bunker is made wider. These small particles that get to the edge will move into the empty space between the bigger particles along the wall while the material is discharged through a central orifice.

The literature contains many references to the problems of solid-solid mixing and some of these, because of a close similarity between the mechanisms involved in particle mixing and in bin segregation, also refer to segregation. These factors on which segregation depends will be discussed later.

Jenike described the phenomenon of segregation in a freely falling stream of particles. He explains that in free fall each particle is acted upon by two forces - its weight and air resistance to motion. In vertical free fall, both forces are vertical and while the terminal velocities of various particles
Figure 2.1 Segregation pattern by plotting sample orders vs percentage of weight
may vary, their trajectories do not, and therefore there is no significant segregation. This appearance changes when an initial horizontal component of velocity is introduced. The two forces are no longer aligned and, as their ratios differ for the various particles, so do the trajectories of the particles. That would result, for example, when a material is discharged from the end of a conveyor belt.

2.2 THE POSSIBLE EFFECT OF DIFFERENT VARIABLES ON THE RATE AND DEGREE OF SEGREGATION

Segregation is only a part of the complex behaviour of bulk materials in bunkers. If one tries to find a more or less exact mathematical formula describing the amount of segregation that will take place within a given material or container, it is necessary to find the very complicated interrelationship between those factors that cause segregation and those that deal with other aspects of solid flow. It is clearly impossible to take all such factors into consideration.

There are, for instance, the grain size and grain size distribution, as well as particle shape, particle density, bulk density, flowability, angle of repose, resistance to agglomeration, surface characteristics, the shape and diameter of the bunker and its orifice, the height of material in a bin, wall friction, the method of feeding and discharging, and other factors.

The most prevalent segregation mechanism when handling a mixture containing various particle sizes is the sifting of fines through the voids of the larger particles. For this mechanism to be effective, there must be inter-particle motion such as 'down
THICKNESS, $T$ OF SLIDING
LAYER OF MOVING
SHEARING MATERIAL

ANgle OF REPOSE, $\alpha$

CROSS-SECTION OF PILE

STATIONARY
MATERIAL

Figure 2.2 Sliding on a pile causes sifting of fines into stationary material
the surface of the pile, as illustrated in Figure 2.2. The fines shifting into the stationary layer below are left behind.

Studies on segregation by Stephens and Foster\textsuperscript{3} using corn with 6\% fines in a 21ft. diameter bin showed that, under the central charge point, the fines content increased to 20\% and that virtually no fines occurred on the edge of the pile. Studies by the author in which corn with 6\% fines was loaded into a model of a ship's hold also illustrated the severity of segregation from a single point charging. From their work it is evident that 50\% of the total material has 92\% of total fines (by weight) and that 50\% of the fines are located in 22\% of the total material. The highest fines concentration occurred directly under the charge point and was about 40\% by volume of 32\% by weight. This shifting mechanism is not limited to piles; shifting can be very significant wherever there is horizontal/shear movement.

2.3 DIFFERENCES IN ANGLE OF REPOSE

Significant segregation can occur when uniformly sized particles of the individual elements of a mixture have different angles of repose. The material with the steeper angle of repose tends to be concentrated on the outside. In this case both the white and black materials have about the same particle size. The black, however, has an angle of repose of 38° while the white has an angle of repose of 30°. The deposited mixture has a 30° angle at the base of the pile where the white is concentrated and a 33° angle on the mid-section.
Figure 2.3  Impact effect on a pile of material
2.4 DYNAMIC EFFECTS

As solids are deposited on a pile with a significant impact velocity, there is a flat spot or crater formed on the top of the pile as shown in Figure 2.3. The size of this crater can be approximated by equating the impact force to the weight of the volume of the material missing at the top of the pile. For a conical pile the diameter \( d \), of the flat spot is approximated by:

\[
d^3 = \frac{24Wv}{\gamma g \tan \alpha}
\]

where:
- \( \gamma \) = bulk density of the material
- \( g \) = gravitational constant
- \( W \) = weight flow rate onto the pile
- \( v \) = vertical component of impact velocity
- \( \alpha \) = angle of repose of the solid.

This flat spot or crater will tend to catch particles that are not resistant enough to bounce out. If all of the particles have about the same resilience, there will be little effect on segregation, however, if resilience is significantly different among particles, the more resilient particles will tend to be on the outside of the pile. Since fines tend to be less resilient than coarse, this mechanism will tend to accentuate a central fines concentration. The direction of larger particles can also be a factor in segregation. For example, in a mixture of 75% iron ore pellets and 25% larger briquettes, it was found that unless the briquettes had initial velocity component down the pile, they would stay on the pile where they initially fit.
However, with an initial downward component of velocity the briquettes would slide over the pellets to the bottom of the pile, causing significant segregation.

2.5 FLOW PATTERN OF PARTICLES IN A BIN

Figure 2.4 shows a typical example of tracer layer pattern of an internal observation cross section after a preset amount of material was discharged.

Near the vicinity of the surface the particle layer has an angle of inclination nearly equal to that of the surface of sintered ore layer but showing slightly larger inclination; all the particle layers run towards the centre and angled down. Though it is not shown in the figure, this region becomes broader if the particle size is bigger.4

Figure 2.5 shows different schematical material flows in bins with and without a rectifying board. When there is no rectifying board, the central flow is extremely strong. In contrast to this, when there is a rectifying board, the region of central flow is enlarged and the flow is more uniform. Figure 2.6 shows the retention time distribution of particles when 53% of the capacity of the bin was charged with sintered ore and discharged, and when the charge and discharge were repeated. When there was no rectifying board, as shown in Figure 2.6(a), the central elliptical part was discharged first, then the particles at the periphery of the bin were discharged slowly and uniformly. In contrast to this, when there is a rectifying board, as shown in Figure 2.6(b) a region of doughnut shape centred at the surrounding edge of the rectifying board was discharged first, the discharged region was then enlarged from this region towards the periphery of the bin.
Figure 2.4 A typical example of flow pattern of sinter in a model bin

Figure 2.5 Schematic material flow in bins with or without a flow control insert
Figure 2.6 Retention time distribution of particles in ore bins (a) without or (b) with a flow control insert.

Figure 2.7 Variation of particle size of sinter discharged and from surge hopper
In the case of raw material charged from the centre, the variation in the size of discharged particles from the surge hopper is shown in Figure 2.7. From this, if the amount of discharge is about 30-50%, the fine particles at the centre are discharged and if the amount of discharge is about 60-90%, the coarse particles near the wall of the bin are discharged, the result is a variation in particle size (as shown in Figure 2.7(b)).

The retention time distribution (RTD) method was found to be quite useful to study the flow model of the Paul-Wurth bin from this investigation's point of view.

2.6 **SEGREGATION KINETICS OF PARTICULATE SOLID SYSTEM INFLUENCE ON PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION**

Mixture of solids is involved in many processes of industrial and technical importance. The glass, ceramic, paint, powder, metallurgy, cement and pharmaceutical industries are among those in which control of systems of solid particles is essential for the production of an acceptable end product. Such general characteristics as particle size distribution, "average shape", pore size, tendency to flow, and uniformity of composition are of prime importance.

Solid mixing as a unit operation has received attention in the literature in connection with specific types of mixers. Rate equations allowing approximate calculations of the line of moving necessary to achieve a complete mix have been derived by several workers. Again these studies primarily reflected the character of a specific mixer rather than the nature of the mechanism of
mixing and unmixing in general. It is, however, the mixing proceeds to state wherein processes (convection, shear and diffusion) leading to random mix balance the tendency to segregate.

Since no fundamental studies have been undertaken to determine the mechanism of segregation or the factors which influence it, this mechanism work has been carried out by James L. Olsen and Edward G. Rippie\textsuperscript{5} for the first time.

2.7 MEASUREMENT OF SEGREGATION

The first detailed study of the mechanism of segregation was reported by Donald and Roseman\textsuperscript{6} who investigated the effect of placing a mixture of particles of different size and density in a rotating horizontal drum, and showed that under certain circumstances almost complete separation of the components could occur. First radial segregation was observed, the finer or denser material being concentrated in a central core, parallel to the axis with the larger or less dense particles around it. This can be explained by reference to the "heap pouring" effect, the finer or denser particles being sieved out from the highly sheered surface layer and accumulating in the comparatively static and undeformed central region.

Campbell and Bridgewater\textsuperscript{7} carried out a series of experiments in which the aim was to isolate the effect of a shear field in a flowing powder mass as cause of segregation. This bed of particles was contained between vertical walls of float glass, the horizontal dimensions being 13.5 x 16.35cm. The bed rested on a piston which was driven downwards at a controlled speed to produce movement of the bed and one was of the container was
roughened by attaching to it 120 grit sand paper, thus introducing a failure zone in the moving powder near the rough wall. The bed consisted of a 4mm drum, glass spheres of other sizes were introduced as tracer and their movement was followed photographically.

When the tracer particles were larger than 4mm, no percolation was detected, but for tracer particles smaller than 4mm percolation was observed for diameter ratios more than two, the width of the zone in which percolation occurred was about seven, particle diameter (7 x 4mm), the width of the shear zone was velocity dependent, varying from 5 to 15 particle diameter.

It may be noted that in the above experiments the shear planes of the direction of percolation were both vertical. It would be expected that more marked percolation would occur, if the shear planes were horizontal. Scott and Bridgewater have studied the rate of percolation of a small particle through a bed of closely-sized larger particles in a simple shear cell in which the bed is subjected to a uniform shear strain. By reversing the direction of movement of the cell unlimited strain can be applied. They found that difference in particle size was the most serious cause of percolation. The effect of diameter ratio being as shown in Figure 8. When the smaller particles were more than half the diameter of the bed particles repeatable results were not obtained, but measurable percolation rates were observed when the difference in particle diameter was only about 3%.

If the percentage of ore component in these four samples are proportional to 1, 2, 3 and 4 where \(1 + 2 + 3 + 4 = 100\) then:
The value of \( S \) varies from 0 (when all samples have the same composition) to 150 (when only one sample contains the component).

Hence the above formula is not true for general cases. It is quite clear that samples must have either the same composition or one of the samples should contain the component. For binary mixtures of constant particle size, it was found that the coefficient of segregation increased as the diameter ratio of the components increased up to a value of 4.3, and therefore remained constant (see Figure 2.9).

The most recent work of J.C. Williams\(^9\) seems to be appropriate for the binary sizes, but in any case that theory could not be useful for the study of multi-size segregation.

Sugimoto and Yamamoto\(^10\) used a method similar in principle to that of Campbell and Bridgewater, in which a bed of particles was allowed to move downwards in a vertical channel of rectangular cross-section. In this case however, all the walls were smooth and the flow was observed. A layer of tracer particles was placed on top of the bed and after allowing flow, the bed was examined to find the position of the tracer particles. The results obtained do not appear to be consistent with those of Campbell and Bridgewater.
Figure 2.8 Effect of particle diameter ratio on percolation velocity in a simple shear cell.

Figure 2.9 Variation of coefficient of segregation with particle diameter ratio.
2.8 MIXTURE QUALITY IN MIXTURE OF PARTICULATE SOLIDS

Poole et al.\(^2\) assumed a linear relationship between the log of the coefficient of variation and the log of the sample size and over the range of sample sizes they used, found that the assumption was valid on the slope of the curve taken as a measure of the mixture's approach to randomness. Mirza\(^3\) made similar findings. Bourne\(^1\) pointed out the connection between the slope of this relationship.

Bourne\(^1\) emphasised that the above considerations involved non-randomness over relatively short distances, whereas in some particulate systems longer-range structure may be present, due to segregation or dead space.

The clustering of particles causing a departure from a random mixture was used by Dukes,\(^15\) who proposed that although a mixture may not be random as far as the individual particles are concerned, it may be random with respect to agglomerates of particles of the separate powders.

Baylik\(^16\) introduced a similar concept in his so-called universal homogeneity and mixing index (Hi). The index is the negative logarithm of the sample weight that would be required to obtain a standard deviation of 1%. The practical determination of Hi would necessitate either interpolation from repeated sampling at different sample size measurement and an assumption concerning the variance sample size relationship.

Dukes\(^15\) criticised Buslik's method for the practical difficulty in its assessment and also for its seemingly arbitrary selection of 1% standard deviation.
2.9 THE PRACTICAL SAMPLING OF MIXTURES OR SEGREGATION

The various methods discussed above for describing the state of mixedness of a mixture all require the measurement of composition in samples of relatively small and uniform size at a large number of locations throughout the mixture. It is somewhat surprising how little effort has been directed to this exercise, compared with that which have applied to the mathematical aspects discussed above. In the end the method for describing mixture quality is only as good as the sampling method.

In a very few instances the complete mixture has been divided into small samples by solidifying a fluid introduced into it and then cutting into blocks, or partitioning in a tray. These methods have the advantage that the sampling is complete and the composition of adjacent samples can be combined to give the variance/sample size relationship and, because the geometric locations of the samples are known, autocorrelation methods can be applied for the results.

Williams and Khan, in an investigation of the mixing of segregating materials, found that a side-sampling thief gave completely misleading results, and developed a tube-sampling method which, in fact, removed a core of material which was subsequently divided by dividing the tube.

The analysis of samples from the outlet stream of the mixer has been suggested by Harnby as being more relevant to practical applications, because account is taken of any change in mixture quality that might occur during discharge. Adams and Baker used a similar method in assessing mixture quality on discharge of plastic granules from the mixer. Various other
methods have been used to assess mixture quality and they merit brief discussion either because of their novelty or because of some special applications.
3.0 EXPERIMENTAL

3.1 APPARATUS

Throughout this investigation the main apparatus was the 17:1 scale model of the Paul-Wurth top (bin), at the Australian Iron and Steel Company's Port Kembla No.5 Blast Furnace. The dimensions of the bin are shown in Figure 3.1 and the actual photograph of the experimental apparatus is shown in Figure 3.2.

The system consisted of four primary components: funnel, bin, the sampling system and the adjustable beam device. The plastic funnel was attached to a movable beam for the production of the filling profiles in desirable angles.

The sheet metals bin which was the most important part of the system, consisted of two components, namely a cylindrical portion and the outlet (chute). These were welded together. The out flow could be controlled by the gate device provided at the end of the outlet (chute). The sampling system consisted of a number of plastic cells (500cm$^3$) placed on a track, so they could be mixed easily when required. The adjustable beam was a device which could be used to set the funnel in the desired position (up or down, vertical, left or right).

Metler PC 16 Balance with the weighing capacity of 16 kg ($\pm$ 0.1 gr) and Hover and Boeker EML 200 sieve shaker were used for the precise sieve analysis.
Figure 3.1 Feed bin Model Bell-less top
Figure 3.2 Actual Photograph of apparatus (Paul-Wurth bin)
Figure 3.3 Line diagram of in-bin sampling
3.2 MATERIALS

The materials chosen fall into three categories:

(i) Ternary size ore

(ii) Ternary size coke

(iii) Ternary size sinter (as a tracer)

(i) Ternary Sized Ore:

The sizes used were in the range of -8.0 + 6.3mm, -5.0 + 4.0mm and -2.0 + 1.0mm.

Feed compositions used were as follows:

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<th>-8.0 + 6.3mm</th>
<th>-5.0 + 4.0mm</th>
<th>-2.0 + 1.0mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>33.33%</td>
<td>33.33%</td>
<td>33.33%</td>
</tr>
<tr>
<td>(2)</td>
<td>14%</td>
<td>30%</td>
<td>56%</td>
</tr>
<tr>
<td>(3)</td>
<td>56%</td>
<td>14%</td>
<td>30%</td>
</tr>
<tr>
<td>(4)</td>
<td>30%</td>
<td>56%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Apparent density of ore: $\rho = 3.986 \text{ g/cm}^3$.

(ii) Ternary Sized Coke:

The sizes used were in the range of -8.0 + 6.3mm, -5.0 + 4.0mm and -2.0 + 1.0mm.

Feed compositions used were as follows:

<table>
<thead>
<tr>
<th></th>
<th>-8.0 + 6.3mm</th>
<th>-5.0 + 4.0mm</th>
<th>-2.0 + 1.0mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>33.33%</td>
<td>33.33%</td>
<td>33.33%</td>
</tr>
<tr>
<td>(2)</td>
<td>14%</td>
<td>30%</td>
<td>56%</td>
</tr>
<tr>
<td>(3)</td>
<td>56%</td>
<td>14%</td>
<td>30%</td>
</tr>
<tr>
<td>(4)</td>
<td>30%</td>
<td>56%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Apparent density of coke: $\rho = 1.188 \text{ g/cm}^3$. 
(iii) **Ternary Sized Sinter (Tracer Material):**

Weights and composition were always kept constant throughout the investigation, and these were as follows:

weight of tracer = 900 g

Composition of tracer consisted of 33.33% of each size. Particle sizes were in the range of -8.0 + 6.3mm, -5.0 + 4.0mm and -2.0 + 1.0mm.

Apparent density of tracer: \( \rho = 4.11 \text{ g/cm}^3 \).

**Table 1. Material weights and heights in the bin**

<table>
<thead>
<tr>
<th>Material height in the bin (mm)</th>
<th>weight of coke at each height + tracer (g)</th>
<th>weight of ore at each height + tracer (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>240</td>
<td>2390</td>
<td>6115</td>
</tr>
<tr>
<td>290</td>
<td>3194</td>
<td>8600</td>
</tr>
<tr>
<td>331</td>
<td>3940</td>
<td>11100</td>
</tr>
<tr>
<td>357</td>
<td>4685</td>
<td>13600</td>
</tr>
<tr>
<td>390</td>
<td>5430</td>
<td>16100</td>
</tr>
</tbody>
</table>
3.3 METHOD

During the study of filling and emptying of the Paul-Wurth bin, the apparatus shown in Figure 3.2 was used. Throughout the investigation the method of filling was kept constant (central filling).

Initially two in-bin sampling methods were compared (in-bin sampling and freezing technique). In order to do that 33.33% of each size of ore was carefully mixed and carefully hand charged into a bucket then simply poured into the bin through the funnel. After the completion of filling the material in the bin was thoroughly wetted. During the wetting process great care was taken not to disturb the material profile in the bin and also to make sure that material was wetted fully. After leaving the charged bin in the freezer for a few days, the bin was warmed gently from outside to release the frozen model. The model was then cut into the two halves by a diamond cutter. The cross-section of the frozen model was photographed as shown in Figures 4.8 and 4.9.

The same experiment was carried out for coke, repeating the same procedure as in the case of ore. For each experiment, samples were collected in the required manner. The bin was filled at required heights then in-bin sampling was carried on as shown in Figure 3.3. During this sampling great care was taken not to disturb the material in the bin. The experiments were repeated for ore and coke.
By conducting discharge segregation experiments separately for ore and coke the flow patterns in the Paul-Wurth bin were measured by simply measuring the flow patterns after every 1 kg of material had discharged (see Figure 4.10; for ore and coke).

After filling the bin with the required composition to a required height, a tracer was poured in the same way as the main material. The required amount of material was then poured on top of it (it was approximately 2.7 kg each time). The bin was emptied and the material was sampled by using intermittent sampling procedure. Tracer particles were separated by using a permanent magnet. When the tracer was used two processes were employed, namely continuous process and batch process.

Finally, discharge experiments were conducted at the required heights and with the required feed compositions. Again two different materials were used separately (ore and coke). The discharge experiments were conducted by pouring the carefully mixed feed material into the bin then sampled. During in-bin sampling, tracer sampling and discharge sampling at fixed constant heights were used. Discharge samplings were always done by an intermittent sampling method.

For each experiment samples were collected in the required manner and a sieve analysis performed. These results were used in the calculation and the resultant data tabulated. The data were also plotted as required, and the material balances performed.
4.0 RESULTS

4.1 IN-BIN SEGREGATION

Many industrial problems arise from particle segregation. The most obvious is that occurring when free-flowing particles of different size are being mixed. Since the aim of this study is to inter-relate in-bin and discharge particle segregation, the importance of first understanding the in-bin segregation is obvious.

Because of its accuracy as shown by Mirza\(^{13}\), the freezing technique was employed to study the in-bin segregation. By using the tabulated sieve analysis results of the freezing technique in Tables 1 and 2, the in-bin segregation for ore and coke was drawn as shown in 4.5 and 4.6.

When the quantitative results of the freezing technique of ore and coke were compared in the light of detailed data in Tables 1 and 2, their in-bin segregation patterns for large and small particles with the 10% range follow the same path.

Because of the large size concentration at the walls the segregation patterns of large particles follow a u-shaped path. In the case of small particles for ore and coke the situation is reversed, less concentration of small particles at the centre. See the segregation mappings in Figures 4.5 and 4.6. Although the concentrations at different heights do not show significant discrepancy at the salls when the large particles are considered, this is not the same with the small particles in both cases (ore and coke). Concentration of small particles show considerable amount of spread in the right side of the bin (see Figures 4.5 and 4.6) compared with the left side.
This is mainly due to the geometry of the bin and the filling procedure employed during the experiment. Since the bin employed here is off-centred (see Figures 4.8 and 4.9) the distance between the left side of the bin and the pouring point is shorter than the distance between the right side of the bin and the pouring point. Hence, due to the height effect on segregation noted in the Theory Section, concentrations at different heights scattered.

However, in the case of medium particles the in-bin segregation patterns of ore and coke do not show any similarity. As exemplified in Figure 4.7 the concert ration of medium sized ore particles shows significant increase at the walls and decrease in the middle of the bin. See tabulated data in Tables 1 to 2 and in-bin mappings in Figures 4.5 and 4.6.

Their segregation patterns across the bin diameter tend to show similar behaviour to large particles.

However, a close inspection of Figure 4.7 and detailed data in Tables 1 and 2 show that, although the large particle (ore and coke), small particle (ore and coke) and medium sized particle ore follow the expected in-bin segregation behaviour, the medium sized coke particles seem to follow unexpected in-bin segregation behaviour, that is, more concentration in the middle of the bin and less concentration at the walls.

Since it is known that potential energy = Mgh = \( \frac{1}{2}Mv^2 \) = kinetic energy, it could be argued that the reversed in-bin segregation patterns of medium sized coke are due to their lower mass, compared to that of the medium sized ore particles.

Frozen cross-sections of ore and coke were photographed (Figures 4.8 and 4.9) and comparison can be made between...
quantitative (sieve analysis and mappings) results and qualitative results (photographs) for both ore and coke.

As it can be seen from Figures 4.8-4.9 and 4.5-4.6 both results quantitative and qualitative follow the same argument for ore and coke when the large and small sizes are considered. However it is very difficult to compare the medium particle behaviour since it is difficult to distinguish them from the rest at low magnification. The concentration of large and small particles is quite obvious in both cases (qualitatively and quantitatively).

The experimental results of this investigation show good agreement with the theoretical analysis of Matthee.1 The qualitative and quantitative results of this investigation show that when the different sizes of mixture are fed to the bin from a single pouring point the small particles (-2.0 + 1.0mm) mainly concentrates towards the centre while large particles (-8.0 + 6.3mm and -5.0 + 4.0mm) concentrate toward the walls, except in the case of medium sized ore (-5.0 + 4.0mm).

Since the freezing technique was extremely time-consuming and difficult, it was decided to evaluate in-bin sampling method to investigate the in-bin segregation. The in-bin sampling method employed during this study was similar to the method of Schofield21 as described in the Experimental Section.

The main reason for employment of this method was its practicality, from this investigation's point of view (see Figure 3.1). Experimental results of this method showed that samples taken across the bin diameter were reasonable enough to produce the segregation patterns of different sizes at different heights across the bin diameter. Detailed results are given in Tables 5
to 9 (Appendix) whilst the salient features of the results are exemplified in Figures 4.1 and 4.2 for the two extreme heights in the bin.

As can be seen from Figure 4.1 there is a notable segregation of the smaller particles in the centre as expected. However the segregation of the large sized particles is not very pronounced particularly when compared with that of the medium sized particles. In fact, the behaviour of these two sizes is reversed if one considers theoretical prediction. This apparent reversal is almost certainly caused by the end effect of this low height as the results at all other heights (Tables 5-9) show the expected behaviour exemplified in Figure 4.2.

The end effect of the low height referred to previously is explained by noting that significant size segregation only occurs after the core shaped pile has formed and that this was not the case at the lowest height considered here (Figure 4.1). At other heights, the core shaped pile was fully formed and segregation was therefore fully developed. It should be stated that in the ternary mixture investigated the medium sized and large sized particles behaved as a single large sized material. This can be clearly seen in Figure 4.2 for the -8.0 + 6.3mm and -5.0 + 4.0mm particles.

An explanation that may be suggested for this phenomenon is that the difference between the mean sizes of the large and medium sized particles (2.5mm) is insufficient to separate them while the difference between the medium and the small particles (3.5mm) is.

In order to compare and contrast the in bin segregation of different materials experiments 10 to 15 were conducted by using
some ternary sizes as in the case of ore (all other conditions being kept constant except the material). Figures 4.3 and 4.4 and tabulated data in Tables 10 to 15 (Appendix) show that although the large sized particles of coke follow the theoretical prediction, the medium and small sized particles followed completely different paths to these segregation patterns of ore at the height of 290mm, 331mm, 357mm and 390mm.

The segregation patterns of different sizes of coke in Figure 4.3 do not need to be explained since they have already been related to the end effect in Figure 4.1.

However the segregation patterns of medium and small sized coke particles as exemplified in figure 4.4 behave differently to those of ore at the various heights (except the lowest height). In the case of medium sized coke particles it has been explained in previous stages that it was due to the particle mass, and therefore the segregation pattern of small particles of coke should be affected by the medium particles, and this is clearly seen in Figure 4.4.

Though the size segregation of different materials (ore and coke) in the bin were studied, the effects of initial material composition were not examined.

To examine these effects experiments were conducted with the different feed composition by using the same experimental procedures as before. When the experiments 16 to 24 were conducted at three different heights (290mm, 331mm and 357mm) with different mixture compositions, the results in Tables 16 to 24 show that in-bin segregation patterns of large (-8.0 + 6.3mm) and small (-2.0 + 1.0mm) particles were exactly the same as those obtained during experiments 4 to 9, that is, large
particle concentration towards walls (w), small particle concentration towards centre (c).

It was concluded that this phenomenon was independent of feed mixture. The mean size difference (5.7mm) between large (-8.0 + 6.3mm) particles and small particles (-2.0 + 1.0mm) seems to be extreme enough to cause this phenomenon.

In the case of medium size particles (-5.0 + 4.0mm) the segregation pattern was always biased towards the size of less percentage in the mixture. This is due to the mean size difference that medium size particles make by large and smaller particles. Therefore its size together with its mass effect the segregation pattern of its own.

By referring to previous explanations one can always guess from feed mixture (with the same size ranges used here) what the material concentration will be in the bin, after the filling.

The results of this study show that the quantitative results of freezing technique in both cases (ore and coke) were similar in the case of large and small sizes (their segregation patterns follow the same path) but they were not identical. Medium size ore tends to follow the segregation pattern of large particles, but in the case of medium size coke particles the situation was reversed (see Figure 4.7).

On the other hand the results of the in-bin sampling method show the similar results as discussed previously.

Therefore it is concluded that although in-bin sampling is not as accurate as the freezing technique it could be used as a substitute for the freezing technique.

The difference between freezing technique results and in-bin sampling results is almost 10%. See detailed data in Tables 1 to 15.
The experimental results also show that in-bin segregation is a function of material and show significant change by the height in the bin.
Figure 4.1 In-bin segregation patterns of different sizes of ore at the height of 240mm.
Figure 4.2 In-bin segregation patterns of different sizes of ore at the height of 390mm.
Figure 4.3  In-bin segregation patterns of different sizes of coke at the height of 240mm
Figure 4.4 In-bin segregation patterns of different sizes of coke at the height of 390mm
Figure 4.5 In-bin segregation mapping of the Paul-Wurth bin when the ore was used.
Figure 4.6 In-bin segregation mapping of the Paul-Wurth bin when the coke was used
Figure 4.7 Segregation patterns of medium size ore and coke when the freezing technique was used.
Figure 4.8  Cross-sectional view of in-bin segregation when the ore was used
Figure 4.9 Cross-sectional view of in-bin segregation when the coke was used
4.2 FLOW PATTERN

Bins, silos and hoppers always play a very important role in the material handling industry. Though a lot of investigation has been carried out on various kinds of bins and bunkers, very little has been done on the Paul-Wurth bin.22 During this investigation the material aspect of the bin was mainly studied.

When the Paul-Wurth 17:1 bin was centrally filled to the height of 390mm for ore and coke separately the material profiles were recorded while discharging. The measured flow patterns for both ore and coke were exactly the same. See the schematical flow pattern in Figure 4.10. Each number corresponds to material top head profile in the bin, after the same number of samples were taken.

Consequently it can be concluded that material profile in the bin is not the function of material, but must be a function of bin geometry. The experimental flow patterns of this investigation also show general agreement with the experimental results of Fukutake.5 Due to bin geometry employed during this investigation these material profiles were off centred which caused rapid decrease of material head on the left side of the bin, while the material head movement was very slow on the right side of the bin.

This is a strong indication of the nature of material flow in the bin. From the measured flow patterns in Figure 4.10, it is quite clear that material head on the right side of the bin
only starts to move approximately after the discharge of samples 7-8 were taken (see the corresponding sample numbers in Figure 4.10). This seems not to be in accordance with the flow pattern definition of Nguyen.23

Instead of the usual classification into mass and core flow, Nguyen defines three flow patterns: type A in which all the materials are in motion (this is synonymous with mass flow); type B where there is a stagnant zone which does not extend as far as the top surface; and type C in which the stagnant zone reaches the top surface.

But he also states that the transitions between these types is found to depend on the particle properties, the hopper angle and the height of the top surface. Therefore from the measured flow patterns in Figure 4.10 it can be concluded that there is a stagnant pont on the right side of the bin.

Although flow patterns were measured in the Paul-Wurth bin, this method was not effective in observing whether different sizes of material in the same region of the bin comes out at the same time.

Hence experiment 3 was repeated by simply replacing seven different colours of tracer (sinter) in seven different regions in the bin while charging (main material was ore). Tracer particles consisted of seven different size ranges between -10.0 + 8.0mm and -2.0 + 1.0mm.

Results of this experiment (see Figure 4.11) show that different sizes of particles in the same region come out at the same time. Therefore RTD is not a function of the size of the material. Results of this experiment were used as a basic knowledge during in-bin segregation mappings in section 4.0.
Despite its complications this technique was very useful for establishing the discharge order of regions in the bin (see Figure 4.11). Because of colour differences between the tracer particles, they were readily visible, therefore experimental errors were reduced.

Tracer technique was also used to study the flow model of the Paul-Wurth bin. Therefore using the tracer technique experiments 25 to 26 were conducted.

The response curves obtained (for batch and continuous process) during this investigation were of the type shown in Figure 4.12.

From these curves in Figure 4.12 it was possible to calculate $\sigma^2_{\theta} E^4$ (Figure 4.13). Hence it was possible to compare the variances ($\sigma^2_{\theta}$) of the two processes. Comparison of the variances show that they were different (see Appendix 8.3). However the curves initially show similar behaviour for both continuing and batch processes, until about 60% of the material has been discharged.

Therefore because of their similar behaviour of response curves, the continuous process was employed to investigate flow model in the Paul-Wurth bin. In order to reduce any experimental errors both processes were repeated three times. See the tabulated data in Tables 25 and 26.

When $\ln E_{\theta}$ values vs dimensionsless time $\theta$ are plotted (Figure 4.14 the results show linear relationships, and this is a very strong indication that there must be parallel mixed flow in the bin. A big difference in $\bar{t}$ calculated and $\bar{t}$ experimental (see Appendix 8.4) appeared indicative of the dead volume which existed on the right side of the bin as shown in Figure 4.10.
From Figure 4.14 the following values were calculated:

where: \[ v_{m_1} = 0.91 \]
\[ v_{m_2} = 0.09 \]
\[ V_{m_1} = 0.12 \]
\[ V_{m_2} = 0.37 \]
\[ V_p = 0.27 \]
\[ V_d = 0.24. \]

In order to study the effect of the nature of material on flow in the bin, Experiments 27 to 34 were conducted at different heights (290mm, 331mm, 357mm and 390mm) by using the two different materials (ore and coke).

When the experiment at the lowest height was conducted (290mm) the tracer response curves of two different sizes (-2.0 + 1.0mm and -8.0 + 6.3mm) show similar behaviour. They both show bi-modality. Since the material height in the bin was very low the tracer particles came out simultaneously with the main material (ore; see Figures 4.15 and 4.16) and their peak heights were not in agreement with prediction. This is merely due to the end effect as explained previously in Section 4.0.

At the different heights as exemplified in Figure 4.17 and 4.18, the different sizes of tracers behaved as expected. They all started to come at the same time but until nearly 50% of bin discharged there was more small particle concentration, less large particle concentration and concentration of medium size particles (-5.0 + 4.0mm) was between the two, that is, lower than the small particles and higher than the large particles. This pattern was reversed after nearly 65% of material discharged. See detailed data in Tables 27 to 30 when the ore was used.

When these experiments were conducted in exactly the same
way by using the coke, the tracer response curves showed similar behaviour to those of ore (see Figures 4.19 and 4.20, and detailed data in Tables 31 to 34). The significant discrepancy however was between their first and second peak heights. In the case of ore the second peaks were always higher than the first peaks whereas in the case of coke the situation was reversed. Since the density of tracer (sinter) material is very close to ore and different to coke, it could be argued that the peak differences in both cases could be due to the material density differences.

In order to do quantitative analysis between the flow behaviours of ore and coke, the Figures 4.21 and 4.22 were plotted by using the detailed data in Tables 35 and 36, which were extracted from the graphical results of Tables 27 and 34 when total concentration Vs cumulative net values were plotted. The calculated slopes of straightness were as followed when the ore was used:

Line No.1 = 2.40
Line No.2 = 1.12

The slopes of straight lines when the coke was used:

Line No.1 = 2.58
Line No.2 = 1.05

Hence when the slope of some lines are compared for different intervals, they seem to be very close (as shown above). Therefore Figures 4.21 and 4.22 show $t$ increases with the tracer height in the bin. This linear relationship shows that $t$ is directly proportional to the height in the bin.

These results also illustrate that the density difference of sinter (tracer) did not effect the flow of coke in the bin.
despite their density differences.

Therefore experimental results show that flow model of the bin in all probabilities will be the same for different materials and the bi-modulaltiy of tracer response curves in both cases (when the ore or coke was used) is a good indication that there is a two mixed dispersed parallel flow in the Paul-Wurth bin.

Hence it can be concluded that the flow in the Paul-Wurth bin consists of plug in series with parallel mixed flow, plug flow into the core of the bin, mixed flow between the core and the walls of the bin, and stagnant zone on the right side of the bin as shown in Figure 4.10.
Figure 4.10 Material profile of ore and coke in the bin, while discharging.
Figure 4.11 Initially declared flow regions in the Paul-Wurth bin
Figure 4.12 Tracer response curves of batch and continuous process
Figure 4.13 Relationship between D/UL and the dimensionless C curve for small extends of dispersion.
Figure 4.14 Plot of $E_n$ vs $Q$ for continuous discharge.
Figure 4.15 Discharge segregation pattern of small size of tracer when the ore was used as a main material at the height of 240mm.
Figure 4.16 Discharge segregation pattern of large size tracer (-8.0 + 6.3mm) when the ore was used at the height of 240mm
Figure 4.17 Discharge segregation pattern of different sizes when the ore was used at the height of 331mm
Figure 4.18 Discharge segregation pattern of tracer material when the ore was used at the height of 390mm
Figure 4.19 Discharge segregation pattern of tracer material of different sizes, when the coke was used at the height of 331mm.
Figure 4.20 Discharge segregation pattern of tracer of different sizes, when the coke was used at the height of 390 mm
Figure 4.21 Relationship between the material height and the t when ore was used.
Figure 4.22 Relationship between the material height and the time when coke was used.
4.3 **DISCHARGE SEGREGATION**

From the previous study\textsuperscript{25} it is known that the discharge segregation patterns of sinter and coke were substantially identical, despite large differences in their densities.

When the experiments were conducted during this study, their experimental results also show complete agreement, with the experimental results of previous study (see Figure 4.23 and 4.24 and tabulated data in Tables 37 to 44) for different feed composition at the height of 357mm.

The segregation patterns in Figure 4.23 and 4.24 (ore and coke) appear in remarkable agreement with the experimental discharge results of Clague.\textsuperscript{26} Experimental results of other workers for the Paul-Wurth bin are rare. When a bunker such as the conical-bottomed Paul Wurth bin has been filled and bottom discharge flow is started, there will generally be no appreciable movement of the particles at the wall of the bin until the inverse angle of repose has developed at the centre.

The experimental results of this investigation in Figure 4.23 and 4.24 also in Tables 37 to 44 show complete agreement with the theoretical prediction. Discharge segregation patterns of large sizes always show negative segregation up to nearly 50% of bin discharged with % weight Vs cumulative discharge weight plotted (see Figure 4.23 and 4.24), whereas the small size particles behave almost in the opposite way (positive segregation first then the negative segregation).

Quantitative results of this investigation show that the first material from the bin will be from the core of fines then followed by the material at the walls.

Comparison of discharge segregation patterns of ore and coke
show substantial agreement (see exemplified in Figures 4.23 and 4.24, and tabulated data in Tables 37 to 44). Therefore it was concluded that the discharge segregation patterns of different sizes is independent of the nature of material.

Effect of feed composition in general on discharge segregation patterns of large and small particles seems to be negligible within the percentage limits used during this investigation. However fluctuations of discharge segregation patterns are effected by the feed composition. See tabulated data of different feed composition of different sizes in Tables 37 to 44.

As can be seen from the exemplified Figures 4.23 and 4.24, the discharge segregation patterns of large size always show less concentration until about half of the material has discharged from the bin, then concentration of large particles increases when the rest of the material is discharged from the bin.

Whereas in the case of small particles this phenomenon is reversed for both materials (ore and coke). This is merely due to the in-bin segregation during the bin charging.

However close inspection of Figures 4.23 and 4.24 and detailed data in Tables 35 to 40 show that the medium size particles do not follow the same discharge segregation pattern for different feed composition when ore or coke was used. Due to iats mean size difference with large and small size particles, the discharge segregation pattern of medium size particles (-5.0 + 4.0mm) always tend to behave like particles with the less feed composition.
Hence it can be concluded that the discharge segregation patterns of large and small particles are not the function of material feed composition (within the composition ranges used, during this study). Within all probabilities the discharge segregation patterns of different sizes of ore and coke will be the same, whereas discharge segregation patterns of medium size particles is influenced by the feed composition. Therefore its discharge segregation pattern is a function of feed composition.

The experimental results also show that the exemplified discharge segregation patterns of this study show substantial agreement with those of industrial results of British Steel Corporation (see Figure 4.23 and 4.24, and the detailed data in Tables 37 to 39).

Because of the shape of the discharged segregation patterns of large and small particles in the case of ore and coke, it was decided to search for a mathematical relationship of discharge patterns of different sizes.

In order to do an effective comparison between different sizes and different material it was appropriate to normalize the sieve analysis. By using the tabulated data in Tables 35 to 40 the normalized curves of Figures 4.25, 4.26 and 4.27 were plotted separately for different sizes (large, medium and small) or ore and coke.

Then by simply keeping the fraction discharge constant at three instances of discharge (at the 30%, 60% and 90% of fraction discharge) the logarithmic graphs were plotted from these normalized graphs.
From these logarithmic graphs various mathematical relations were investigated. Consequently the power relationship between the normalized fraction of Li/Lo and the normalized fraction of Si/So coming out of the Paul-Wurth bin, with the initial normalized composition were \((Wi/Wo)\) were established in a useful way (see Appendix 8.6).

The relationship was found to be:

\[(Li/Lo) = K(Wi/Wo)^{1/5}\]

where \(K = -0.67\)

\[(Li/Lo) = K(Wi/Wo)^{1/5} M \leq MC\]

where \(K = 1.75\)

and

\[(Si/So) = K(Wi/Wo)^{-1/5} M \leq MC\]

where \(K = 1.73\)

\[(Si/So) = K(Wi/Wo)^{+1/5} M > MC\]

where \(K = 0.54\)

In the case of medium size particles the power relation found to be zero since it is known that:

when \(x^0\) the \(x = 1\)

Hence

\[(Mi/Mo) = K(Mi/Mo)^{0}\]

\[= K \times 1\]

\[\therefore (Mi/Mo) = K\]
When the \((n)\) values of \((Si/So)\) for coke were calculated they showed notable differences to the rest. This is due to the experimental errors (see repeat result of coke in Figure 4.29). This experiment was a repeat of experiment 40. A close inspection of the discharge segregation patterns of these two experiments (Experiment 43 and Experiment 40) show a notable difference of about 8% (see detailed data in Tables 44 and 47). But when experiment was repeated for ore, the reproducability was excellent (see Figure 4.30 and detailed data in Tables 45 and 46).

Therefore the experimental results show that reproducability of coke experiments are difficult compared to those of ore. Consequently increase in the possibility of experimental error is more likely in the case of coke.

When \(Li/Lo\) and \(Si/So\) values Vs \(Wi/Wo\) were plotted separately for two different materials (ore and coke) it was quite easy to compare and contrast the discharge segregation patterns of these two materials for some sizes (large or small) (see Figures 4.28 and 4.29).

As can be seen from Figure 4.28 the concentration of large particles of different feed compositions increases with the increase of \(Li/Lo\) values, with respect to their feed composition. In other words higher feed composition gives higher concentration.

This is so until about half of the material has discharged, then the situation is reversed.

However in the case of coke the situation is slightly
changed compared to that of the ore when half of the bin has discharged (see Figure 4.29). Initially there was a higher concentration of the 30% large particles, followed by the 56% large and then the 14% large (the first graph readings should be ignored, since they are due to the end effects). When the experiment was repeated with the 30% large feed composition it showed a different segregation pattern. This is almost consistent with the segregation pattern of 56% large particles. But the segregation pattern of 14% large is in agreement with the segregation pattern of 14% ore.

The second half of the discharge segregation patterns of 56%, 30% and 14% large particles show good agreement with those of ore particles. Therefore the segregation pattern discrepancy of 30% large coke could be due to experimental error.

The other salient feature is the end spread in both cases. Although the discharge segregation patterns of different feed mixture particles show consistency up to nearly 70% of discharge, after 70% there is salient end spread. That is also caused when the feed mixture contains 14% large particles in both cases (ore and coke).

At this stage it is very important to refer to Figure 4.23 and 4.24. These figures clearly show that when the feed mixture contains only 14% of large particles (-8.0 + 6.3mm), the discharge segregation pattern of large particles almost shows no segregation in both cases (ore and coke) until about 75% of material discharged, then it shows significant segregation.

It could be argued that this phenomenon is due to the feed
composition of material. Since the feed composition contains only small amounts of large particles some of these mixed with the other two sizes, but some of the large particles concentrated in the stagnant zone of the bin. Since there was not a sufficient amount of large particles to hold up the smaller particles, the smaller particles penetrate through the larger ones, leaving large and medium particles together. Also, medium size particles mostly segregated from the larger particles, due to the mean size difference between these two. Finally readily segregated particles discharges from the bin and that gives a sudden increase of large particle concentration which causes the spread effect.

The concluded experimental results of discharge segregation of this study should be of considerable interest to those dealing with filling and emptying of hoppers. The literature survey revealed that little work has been specifically done on investigation of discharge segregation when the feed composition is considered.

In order to combine the discharge segregation with the in-bin segregation the discharge order in the Paul-Wurth bin was drawn, by using the information measured by the flow patterns in Figure 4.10 and the RDT results in Figures 4.6, 4.18 and 4.19. The resultant discharge order of the Paul-Wurth bin can be envisaged as shown in Figure 4.31.

Using Figure 4.31 together with the measured in-bin segregation in Figure 4.5, the calculated discharge segregation for large particles is given in Figure 4.32, which includes the
experimental discharge segregation pattern of large particles in Table 3 (similar procedure should show the discharge segregation of medium and small particles but for the sake of brevity corresponding graphs are omitted).

Although these two segregation patterns (experimental and calculated) are not exactly the same, they both follow the same expected pattern. The discrepancy of degree of segregation is of the order of 2-7%, which is not a substantial difference considering the simple nature of the calculations.

It may therefore be suggested that, for all practical purposes Figure 4.31 could be used to estimate the discharge segregation from the similar in-bin segregation as shown in Figure 4.5.
Figure 4.23  Discharge segregation patterns of different sizes when 14%L, 30%M and 56%S ore was used at the height of 357mm.
Figure 4.24 Discharge segregation patterns of different sizes (L, M and S) when the coke was used at the height of 35 mm
Figure 4.25  Total normalized results in the case of ore and coke
Figure 4.26 Normalized discharge segregation patterns for medium size ore and coke of different percentages.
Figure 4.27 Normalized discharge segregation patterns for small size ore and coke of different percentages
Figure 4.28 Normalized discharge segregation patterns for large size ore of different percentages
Figure 4.28 Normalized discharge segregation patterns for large size ore of different percentages
Figure 4.29 Discharge segregation patterns of large size coke of different percentages
Figure 4.30 Reproducability of results when the ore was used at the height of 357mm
Figure 4.31 Discharge order in Paul-Wurth bin
Figure 4.32 Experimental and calculated discharge segregation patterns of large particles.
5.0 CONCLUSIONS

The results of this investigation have shown that:

(1) In-bin segregation is dependent on the nature of material.

(2) In-bin segregation shows significant change with the material height in the bin.

(3) In-bin segregation patterns of large and small size particles are not functions of feed composition but the medium size particles are.

(4) Although in-bin sampling is not as accurate as the freezing technique, it could be considered as a substitute in some applications.

(5) Tracer method can be used to study flow model of the Paul-Wurth bin.

(6) The flow model of the Paul-Wurth bin is plug flow in series with two dispersed mixed flows and contains dead volume.

(7) The flow models of the bin for ore and coke are exactly the same.

(8) The discharge segregation of ore and coke is the same.

(9) The medium size particles are biased towards the particles size with the lowest content in the feed mixture.

(10) Large particles always show negative then positive segregations, while the smaller particles show positive then negative segregation.

(11) Discharge segregation is a function of the initial composition of the mixture.

(12) Calculated and experimental discharge patterns are similar.
6.0 NOTATIONS

TM = top material
BM = base material
L = large
S = small
M = medium
\( \rho \) = density
\( t \) = mean time
RDT = Residence Time Distribution
Wi = weight of each sample
Wo = total weight of samples
Si = w.t. % of small particles in each sample
So = total weight of small particles
Li = w.t. % of large particles in each sample
Lo = total weight of large particles
C = centre
B = between
W = wall
7.0 REFERENCES


(6) DONALD, M.B. and ROSEMAN, B., British Chemical Engineering, 7 (1962), T49.


(18) N. HARNBY, *Powder Technology* 1, (1967), 94.


### 8.1 Sieve Analysis

Table 1. Sieve analysis of Freezing technique when 33.33% of L, M and S ore was used

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>% wt of -8.0 + 6.3 mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0 mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0 mm ore particles (g)</th>
<th>Total wt of each sample (g)</th>
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Table 2. Experiment 2. Sieve analysis of Freezing technique when 33.33% of L, M and S coke was used

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<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
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<td>% wt of -8.0 + 6.3mm ore particles (g)</td>
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Table 4. Experiment 4. Sieve analysis of in-bin sampling at the height of 240mm when 33.33\% of each size of ore was used

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<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
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Table 5. Experiment 5. Sieve analysis of in-bin sampling when the 33.33\% of each size of ore were used at the height of 290mm

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<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
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Table 6. Experiment 6. Sieve analysis of in-bin sampling of ore at the height of 331mm

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<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
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### Table 7. Experiment 7. Sieve analysis of in-bin sampling at the height of 357mm

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<th>Total wt of each sample (g)</th>
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### Table 8. Experiment 8. Sieve analysis of in-bin sampling at the height of 390mm

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<td>301.2</td>
<td>35.59</td>
<td>32.33</td>
<td>17.72</td>
</tr>
</tbody>
</table>

### Table 9. Experiment 9. Sieve analysis of in-bin sampling at the height of 290mm (Repeat)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>263.3</td>
<td>37.37</td>
<td>19.04</td>
<td>3.89</td>
</tr>
<tr>
<td>2B</td>
<td>268.2</td>
<td>31.73</td>
<td>25.13</td>
<td>26.73</td>
</tr>
<tr>
<td>3C</td>
<td>275.3</td>
<td>21.61</td>
<td>14.78</td>
<td>22.12</td>
</tr>
<tr>
<td>4B</td>
<td>339.6</td>
<td>22.55</td>
<td>18.69</td>
<td>37.77</td>
</tr>
<tr>
<td>5W</td>
<td>241.9</td>
<td>22.11</td>
<td>24.84</td>
<td>17.23</td>
</tr>
</tbody>
</table>
Table 10. Experiment 10. Sieve analysis of in-bin sampling when the 33.33% coke was used at the height of 240mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>120.1</td>
<td>10.48</td>
<td>7.65</td>
<td>7.48</td>
</tr>
<tr>
<td>2B</td>
<td>122.3</td>
<td>12.75</td>
<td>13.57</td>
<td>5.06</td>
</tr>
<tr>
<td>3C</td>
<td>174.6</td>
<td>10.59</td>
<td>6.41</td>
<td>5.55</td>
</tr>
<tr>
<td>4B</td>
<td>124.6</td>
<td>17.89</td>
<td>10.03</td>
<td>5.77</td>
</tr>
<tr>
<td>5W</td>
<td>117.6</td>
<td>17.94</td>
<td>9.26</td>
<td>8.16</td>
</tr>
</tbody>
</table>

Table 11. Experiment 11. Sieve analysis of in-bin sampling when the 33.33% coke was used at the height of 290mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>143.1</td>
<td>15.30</td>
<td>14.60</td>
<td>14.88</td>
</tr>
<tr>
<td>2B</td>
<td>137.3</td>
<td>17.69</td>
<td>18.49</td>
<td>9.39</td>
</tr>
<tr>
<td>3C</td>
<td>222.1</td>
<td>7.29</td>
<td>8.05</td>
<td>6.88</td>
</tr>
<tr>
<td>4B</td>
<td>131.1</td>
<td>20.59</td>
<td>16.93</td>
<td>9.61</td>
</tr>
<tr>
<td>5W</td>
<td>161.4</td>
<td>18.83</td>
<td>9.54</td>
<td>8.73</td>
</tr>
</tbody>
</table>

Table 12. Experiment 12. Sieve analysis of in-bin sampling when the coke was used at the height of 331mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>162.0</td>
<td>22.90</td>
<td>11.72</td>
<td>6.85</td>
</tr>
<tr>
<td>2B</td>
<td>157.2</td>
<td>14.82</td>
<td>15.83</td>
<td>15.01</td>
</tr>
<tr>
<td>3C</td>
<td>213.0</td>
<td>6.68</td>
<td>7.39</td>
<td>9.49</td>
</tr>
<tr>
<td>4B</td>
<td>161.5</td>
<td>17.58</td>
<td>19.62</td>
<td>19.87</td>
</tr>
<tr>
<td>5W</td>
<td>143.7</td>
<td>27.83</td>
<td>13.56</td>
<td>4.38</td>
</tr>
</tbody>
</table>
Table 13. Experiment 13. Sieve analysis of in-bin sampling when the coke was used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>154.1</td>
<td>27.77</td>
<td>15.83</td>
<td>10.31</td>
</tr>
<tr>
<td>2B</td>
<td>175.5</td>
<td>13.39</td>
<td>17.72</td>
<td>17.83</td>
</tr>
<tr>
<td>3C</td>
<td>230.8</td>
<td>2.98</td>
<td>4.46</td>
<td>6.75</td>
</tr>
<tr>
<td>4B</td>
<td>148.1</td>
<td>12.01</td>
<td>17.75</td>
<td>17.82</td>
</tr>
<tr>
<td>5W</td>
<td>122.4</td>
<td>26.71</td>
<td>15.68</td>
<td>8.66</td>
</tr>
</tbody>
</table>

Table 14. Experiment 14. Sieve analysis of in-bin sampling when the coke was used at the height of 390mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>132.0</td>
<td>31.21</td>
<td>19.16</td>
<td>5.75</td>
</tr>
<tr>
<td>2B</td>
<td>165.9</td>
<td>13.68</td>
<td>22.00</td>
<td>21.51</td>
</tr>
<tr>
<td>3C</td>
<td>219.4</td>
<td>6.15</td>
<td>6.79</td>
<td>10.89</td>
</tr>
<tr>
<td>4B</td>
<td>161.6</td>
<td>13.67</td>
<td>19.36</td>
<td>18.37</td>
</tr>
<tr>
<td>5W</td>
<td>133.3</td>
<td>32.48</td>
<td>16.95</td>
<td>6.15</td>
</tr>
</tbody>
</table>

Table 15. Experiment 15. Sieve analysis of in-bin sampling when 14%L, 30%M, and 56%S ore was used at the height of 290mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>266.0</td>
<td>15.22</td>
<td>41.65</td>
<td>42.06</td>
</tr>
<tr>
<td>2B</td>
<td>248.0</td>
<td>5.87</td>
<td>21.34</td>
<td>70.11</td>
</tr>
<tr>
<td>3C</td>
<td>203.1</td>
<td>12.90</td>
<td>29.29</td>
<td>55.58</td>
</tr>
<tr>
<td>4B</td>
<td>282.5</td>
<td>7.46</td>
<td>23.78</td>
<td>67.29</td>
</tr>
<tr>
<td>5W</td>
<td>271.9</td>
<td>25.89</td>
<td>39.79</td>
<td>33.13</td>
</tr>
</tbody>
</table>
### Table 16. Experiment 16. Sieve analysis of in-bin sampling when 56%L, 14%M, 30%S ore was used at the height of 290mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>283.5</td>
<td>86.10</td>
<td>15.09</td>
<td>17.38</td>
</tr>
<tr>
<td>2B</td>
<td>358.2</td>
<td>47.62</td>
<td>17.56</td>
<td>33.72</td>
</tr>
<tr>
<td>3C</td>
<td>256.4</td>
<td>42.62</td>
<td>15.63</td>
<td>40.87</td>
</tr>
<tr>
<td>4B</td>
<td>326.5</td>
<td>51.94</td>
<td>18.37</td>
<td>28.79</td>
</tr>
<tr>
<td>5W</td>
<td>304.5</td>
<td>80.36</td>
<td>12.11</td>
<td>6.50</td>
</tr>
</tbody>
</table>

### Table 18. Experiment 18. Sieve analysis of in-bin sampling when 30%L, 56%M and 14%S ore was used at the height of 290mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>288.0</td>
<td>36.11</td>
<td>52.74</td>
<td>10.41</td>
</tr>
<tr>
<td>2B</td>
<td>323.3</td>
<td>18.49</td>
<td>61.21</td>
<td>19.27</td>
</tr>
<tr>
<td>3C</td>
<td>285.6</td>
<td>24.54</td>
<td>52.59</td>
<td>21.70</td>
</tr>
<tr>
<td>4B</td>
<td>306.4</td>
<td>29.76</td>
<td>53.29</td>
<td>16.05</td>
</tr>
<tr>
<td>5W</td>
<td>257.3</td>
<td>52.00</td>
<td>40.65</td>
<td>6.17</td>
</tr>
</tbody>
</table>

### Table 19. Experiment 19. Sieve analysis of in-bin sampling when 14%L, 30%M and 56%S ore was used at the height of 331mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>311.4</td>
<td>26.42</td>
<td>36.57</td>
<td>36.19</td>
</tr>
<tr>
<td>2B</td>
<td>322.8</td>
<td>9.51</td>
<td>23.57</td>
<td>65.79</td>
</tr>
<tr>
<td>3C</td>
<td>313.5</td>
<td>11.25</td>
<td>24.30</td>
<td>63.03</td>
</tr>
<tr>
<td>4B</td>
<td>281.7</td>
<td>9.86</td>
<td>21.33</td>
<td>67.34</td>
</tr>
<tr>
<td>5W</td>
<td>271.8</td>
<td>21.92</td>
<td>30.86</td>
<td>46.13</td>
</tr>
</tbody>
</table>
Table 20. Experiment 20. Sieve analysis of in-bin sampling when 56%L, 14%S, 30%S ore was used at the height of 331mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>306.1</td>
<td>75.26</td>
<td>13.23</td>
<td>9.60</td>
</tr>
<tr>
<td>2B</td>
<td>359.2</td>
<td>34.15</td>
<td>18.20</td>
<td>46.49</td>
</tr>
<tr>
<td>3C</td>
<td>302.1</td>
<td>39.45</td>
<td>14.00</td>
<td>45.74</td>
</tr>
<tr>
<td>4B</td>
<td>326.1</td>
<td>37.19</td>
<td>15.45</td>
<td>46.05</td>
</tr>
<tr>
<td>5W</td>
<td>299.1</td>
<td>82.61</td>
<td>12.13</td>
<td>4.61</td>
</tr>
</tbody>
</table>

Table 21. Experiment 21. Sieve analysis of in-bin sampling when 30%L, 56%S and 14%S ore was used at the height of 331mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>280.2</td>
<td>38.39</td>
<td>52.42</td>
<td>8.52</td>
</tr>
<tr>
<td>2B</td>
<td>366.0</td>
<td>13.03</td>
<td>60.71</td>
<td>25.38</td>
</tr>
<tr>
<td>3C</td>
<td>292.7</td>
<td>23.67</td>
<td>50.49</td>
<td>24.83</td>
</tr>
<tr>
<td>4B</td>
<td>367.5</td>
<td>23.07</td>
<td>53.08</td>
<td>22.82</td>
</tr>
<tr>
<td>5W</td>
<td>283.2</td>
<td>53.00</td>
<td>40.64</td>
<td>6.14</td>
</tr>
</tbody>
</table>

Table 22. Experiment 22. Sieve analysis of in-bin sampling when 14%L, 30%S and 56%S ore was used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>298.3</td>
<td>22.22</td>
<td>42.37</td>
<td>34.76</td>
</tr>
<tr>
<td>2B</td>
<td>383.1</td>
<td>6.31</td>
<td>26.75</td>
<td>65.98</td>
</tr>
<tr>
<td>3C</td>
<td>366.2</td>
<td>14.82</td>
<td>22.74</td>
<td>61.08</td>
</tr>
<tr>
<td>4B</td>
<td>360.2</td>
<td>8.05</td>
<td>23.34</td>
<td>67.60</td>
</tr>
<tr>
<td>5W</td>
<td>399.7</td>
<td>30.22</td>
<td>34.57</td>
<td>34.42</td>
</tr>
</tbody>
</table>
Table 23. Experiment 23. Sieve analysis of in-bin sampling when 56%L, 14%M and 30%S ore was used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>309.0</td>
<td>70.38</td>
<td>16.34</td>
<td>12.29</td>
</tr>
<tr>
<td>2B</td>
<td>336.0</td>
<td>34.73</td>
<td>16.09</td>
<td>48.21</td>
</tr>
<tr>
<td>3C</td>
<td>328.8</td>
<td>41.78</td>
<td>13.80</td>
<td>42.60</td>
</tr>
<tr>
<td>4B</td>
<td>345.3</td>
<td>51.78</td>
<td>15.53</td>
<td>32.29</td>
</tr>
<tr>
<td>5W</td>
<td>312.2</td>
<td>88.30</td>
<td>8.39</td>
<td>2.14</td>
</tr>
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</table>

Table 24. Experiment 24. Sieve analysis of in-bin sampling when 30%L, 56%M, and 14%S ore were used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W</td>
<td>337.0</td>
<td>41.39</td>
<td>51.63</td>
<td>5.99</td>
</tr>
<tr>
<td>2B</td>
<td>340.1</td>
<td>14.61</td>
<td>54.95</td>
<td>30.93</td>
</tr>
<tr>
<td>3C</td>
<td>320.4</td>
<td>26.74</td>
<td>51.18</td>
<td>22.65</td>
</tr>
<tr>
<td>4B</td>
<td>325.7</td>
<td>23.05</td>
<td>54.34</td>
<td>21.58</td>
</tr>
<tr>
<td>5W</td>
<td>392.4</td>
<td>48.34</td>
<td>45.36</td>
<td>5.42</td>
</tr>
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</table>
Table 25. Experiment 25. Sieve analysis of continuing process when the tracer technique was used

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>cumulative weight of samples (g)</th>
<th>% weight of tracer (concentration)</th>
<th>Repeat 1</th>
<th>cumulative weight of samples (g)</th>
<th>% weight of tracer (g)</th>
<th>Repeat 2</th>
<th>cumulative weight of samples (g)</th>
<th>% weight of tracer (g)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>1614.7</td>
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<td>0</td>
<td>564.2</td>
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<td>0</td>
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Table 27. Experiment 27. Sieve analysis of discharge sampling of tracer at the height of 290mm when ore used

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Table 28. Experiment 28. Sieve analysis of discharge sampling when 33.33% of each size of ore and tracer were used at the height of 331mm

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Table 29. Experiment 29. Sieve analysis of discharge sampling at the height of 357mm when 33.33% of each size of ore and tracer were used

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Table 30. Experiment 30. Sieve analysis of discharge sampling segregation at the height of 390mm when 33.33% of each size of ore and 900g of tracer were used

<table>
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<tr>
<th>Sample Number</th>
<th>cumulative wt of each sample (g)</th>
<th>% wt of -8.0 + 6.3mm tracer particles (g)</th>
<th>% wt of -5.0 + 4.0mm tracer particles (g)</th>
<th>% wt of -2.0 + 1.0mm tracer particles (g)</th>
<th>Total % wt of tracer particles</th>
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<td>0.0</td>
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<tr>
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<td>0.0</td>
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<td>6.85</td>
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</table>
Table 31. Sieve analysis of discharge sampling when 33.33% of each size of coke and tracer were used at the height of 290mm

<table>
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<tr>
<th>Sample wt of each</th>
<th>cumulative</th>
<th>% wt of</th>
<th>% wt of</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number sample</td>
<td>wt</td>
<td>-8.0 + 6.3mm</td>
<td>-5.0 + 4.0mm</td>
<td>-2.0 + 1.0mm</td>
</tr>
<tr>
<td></td>
<td>(g)</td>
<td>tracer particles (g)</td>
<td>tracer particles (g)</td>
<td>tracer particles</td>
</tr>
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</tr>
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</tr>
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Table 32. Sieve analysis of discharge sampling when 33.33% of each size of coke and tracer were used at the height of 331mm

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<th>cumulative</th>
<th>% wt of</th>
<th>% wt of</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number sample</td>
<td>wt</td>
<td>-8.0 + 6.3mm</td>
<td>-5.0 + 4.0mm</td>
<td>-2.0 + 1.0mm</td>
</tr>
<tr>
<td></td>
<td>(g)</td>
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<td>tracer particles (g)</td>
<td>tracer particles</td>
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Table 33. Experiment 33. Sieve analysis of discharge sampling when 33.33% of each size of coke and tracer were used at the height of 357mm

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<th>Sample wt of each sample (g)</th>
<th>% wt of tracer particles</th>
<th>% wt of tracer particles</th>
<th>% wt of tracer particles</th>
<th>Total % wt of tracer particles</th>
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Table 34. Experiment 34. Sieve analysis of discharge sampling when 33.33% of each size of coke and tracer were used at the height of 390mm

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<th>Sample wt of each sample (g)</th>
<th>% wt of tracer particles</th>
<th>% wt of tracer particles</th>
<th>% wt of tracer particles</th>
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<td>4.31</td>
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</tr>
<tr>
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<td>6.56</td>
<td>15.76</td>
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Table 35. Extracted data of discharge analysis of experiments 26-29

<table>
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<th>Exts.</th>
<th>Tracer height in the bin (mm)</th>
<th>Occurrence reading for peaks 1st peaks</th>
<th>Occurrence reading for 2nd peaks</th>
<th>Wt of material at different tracer heights in the bin (g)</th>
</tr>
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Table 36. Extracted data of experiments 30-33

<table>
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<th>Exts.</th>
<th>Material height in the bin (mm)</th>
<th>Wt of material at each height</th>
<th>Occurrence reading from cumulative axis. 1st peaks</th>
<th>Occurrence reading of 2nd peaks</th>
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<td>1.0</td>
<td>2.95</td>
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<td>(12-13)</td>
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<td>1.45</td>
<td>2.65</td>
</tr>
<tr>
<td>(14-15)</td>
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Table 37. Experiment 35. Sieve analysis of discharge sampling when 14%L, 30%M and 56%S was used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of ore particles (-8.0 + 6.3mm) (%)</th>
<th>% wt of ore particles (-5.0 + 4.0mm) (%)</th>
<th>% wt of ore particles (-2.0 + 1.0mm) (%)</th>
<th>Li/Lo</th>
<th>Wi/Wo</th>
<th>Mi/Mo</th>
<th>Si/So</th>
</tr>
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<tbody>
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Table 38. Experiment 36. Sieve analysis of discharge sampling when 56%L, 14%M and 30%S ore was used at the height of 357mm

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<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
<th>Li/Lo</th>
<th>Wi/Wo</th>
<th>Mi/Mo</th>
<th>Si/So</th>
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</thead>
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Table 39. Experiment 37. Sieve analysis of discharge sampling when 30%L, 56%M and 14%S ore was used at the height of 357mm

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of -8.0 + 6.3mm ore particles (g)</th>
<th>% wt of -5.0 + 4.0mm ore particles (g)</th>
<th>% wt of -2.0 + 1.0mm ore particles (g)</th>
<th>Li/Lo</th>
<th>Wi/Wo</th>
<th>Mi/Mo</th>
<th>Si/So</th>
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<td>0.98</td>
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<td>0.60</td>
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### Table 40. Normalized values of ore when 33.33% of each size was used, at the height of 357mm

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<th>Sample Number</th>
<th>Li/Lo ore 33.33% Lo</th>
<th>Wi/Wo fraction discharge ore</th>
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<td>0.27</td>
</tr>
<tr>
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<td>0.47</td>
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</tr>
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<tr>
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### Table 41. Normalized values of coke when 33.33% of each size was used, at the height of 357mm

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<th>Wi/Wo fraction discharge ore</th>
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<td>0.19</td>
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Table 42. Sieve analysis of discharge sampling when 14%L, 30%M and 56%S coke was used at the height of 357mm

<table>
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<tr>
<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
<th>Wi/Lo fraction of discharge</th>
<th>Li/Lo</th>
<th>Mi/Mo</th>
<th>Si/So</th>
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Table 43. Experiment 39. Sieve analysis of discharge sampling when 56%L, 14%M and 30%S coke was used at the height of 357mm

<table>
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<tr>
<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of coke particles -8.0 + 6.3mm (g)</th>
<th>% wt of coke particles -5.0 + 4.0mm (g)</th>
<th>% wt of coke particles -2.0 + 1.0mm (g)</th>
<th>Wi/Wo fraction</th>
<th>Li/Lo discharge</th>
<th>Mi/Mo</th>
<th>Si/So</th>
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Table 44. Experiment 40. Sieve analysis of discharge segregation when 30%L, 56%M and 14%S coke was used at the height of 357mm

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<th>Sample Number</th>
<th>Cumulative weight of samples (g)</th>
<th>% wt of -8.0 + 6.3mm coke particles (g)</th>
<th>% wt of -5.0 + 4.0mm coke particles (g)</th>
<th>% wt of -2.0 + 1.0mm coke particles (g)</th>
<th>Wi/Wo fraction discharge</th>
<th>Li/Lo</th>
<th>Mi/Mo</th>
<th>Si/So</th>
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Table 45. Experiment 41. Sieve analysis of discharge sampling when experiment 35 was first repeated

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<th>% weight of -8.0 + 6.3mm particles (g)</th>
<th>% weight of -5.0 + 4.0mm particles (g)</th>
<th>% weight of -2.0 + 1.0mm particles (g)</th>
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Table 46. Experiment 42. Sieve analysis of discharge segregation when experiment 35 was repeated the second time

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<th>% weight of -8.0 + 6.3mm particles (g)</th>
<th>% weight of -5.0 + 4.0mm particles (g)</th>
<th>% weight of -2.0 + 1.0mm particles (g)</th>
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Table 47. Experiment 47. Sieve analysis of discharge sampling when experiment 40 was repeated

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<th>% wt of -5.0 + 4.0mm particles (g)</th>
<th>% wt of -2.0 + 1.0mm particles (g)</th>
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<th>Wi/Wo</th>
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8.2 MATERIAL CALCULATIONS OF EXPERIMENTS 1-11

WHEN THE ORE WAS USED

Tracer w.t. = 900g - kept constant for all experiments.

At the height of 240mm
Base material (BM) = 5215.5g

Percentages
Sizes:  -8.0 + 6.3mm  33.33%
        -5.0 + 4.0mm  33.33%
        -0.20 + 1.0mm  33.33%

Material size and percentages were kept constant for above experiments.

At the height of 290mm
Base material = 7700g

At the height of 331mm
Base material = 10200g

At the height of 357mm
Base material = 12700g

At the height of 390mm
Base material = 15200g
Material calculations when the coke was used:

The appropriate material calculations for coke at different heights were made by using the formula

\[ V = m \times \rho \]

At same heights where:
- \( V \) = volume
- \( m \) = mass
- \( \rho \) = density

8.3 CONTINUOUS PROCESS

1. Calculation of 0.61 of its height
   
   \[ \text{height x 0.61} \]
   
   \[ 16.8 \times 0.61 = 10.25 \text{mm} \]
   
   \[ \therefore \text{its value at that point} = 33\text{mm} \text{ and } y = 39\text{mm} \]

   From the \( \left( \frac{x}{y} \right)^2 = 2 \quad 2D/UL = \sigma^2 \theta \)
   
   \[ = \left( \frac{x}{y} \right)^2 \times \frac{1}{8} \]

   \[ \left( \frac{33}{39} \right)^2 \times \frac{1}{8} = \sigma^2 \theta \]

   \[ \therefore \sigma^2 \theta = 0.089 \]

Batch Process

2. Height of the peak = 15
   
   \[ \therefore 15 \times 0.61 = 91.5\text{mm} \]

   \[ x \text{ at that height} = 7.5\text{mm} \]

   \[ y = 55\text{mm} \]

   \[ \therefore \left( \frac{7.5}{5.5} \right)^2 \times \frac{1}{8} = \sigma^2 \theta \]

   \[ \therefore \sigma^2 \theta = 0.232 \text{ (dimensionless)} \]
8.4 **CALCULATION OF $t_{\text{EXPERIMENTAL}}$ AND $t_{\text{CALCULATED}}$**

\[ v = \frac{\text{material w.t.}}{\text{total time taken}} \]

w.t. of total material = 16400g

total time taken = 21 (samples) x 5 (time increments)

\[ \therefore v = \frac{16400}{105} \]

\[ v = 156.19 \text{ g/sec.} \]

tracer = 400g

\[ \therefore \tilde{t} \text{ calculated} = \frac{\text{time} \times \text{tracer w.t.}}{100} \]

\[ = \frac{105 \times 400}{100} \]

\[ = 420 \text{ sec.} \]

\[ \therefore \tilde{t} \text{ calculated} = 420 \text{ sec.} \]

\[ \bar{t} \text{ experimental} = \frac{\text{weight of material used}}{\text{flow rate}} \]

\[ = \frac{16400}{156.19} \]

\[ \bar{t} \text{ experimental} = 105 \text{ sec.} \]
8.5 CALCULATION OF SLOPES WHEN THE PEAK VALUES VS MATERIAL
HEIGHT IN THE BIN WAS PLOTTED

When the ore was used

a) Slope of No.1 when the 1st peak heights were used

\[ \text{slope of No.1 line} = \frac{20}{8.33} \]

\[ = 2.40 \]

\[ \text{slope of No.2 line} = \frac{16}{14.32} \]

\[ = 1.12 \]

b) Slopes of lines when the coke was used

\[ \text{slope of line No.1} = \frac{2.33}{0.9} \]

\[ = 2.58 \]

\[ \text{slope of line No.2} = \frac{3.33}{3.15} \]

\[ = 1.05 \]
8.6 CALCULATION OF SLOPES
LARGE ORE

Slope of a:-

\[
\frac{\log 1.5 - \log 1.3}{\log 0.39 - \log 0.20} = \frac{0.17 - (0.11)}{-0.40 - (-0.69)} = 0.20
\]

Slope of c:-

\[0.06/0.29 = 0.20\]

and intercept \((K) = 1.78\)

Slope of b:-

\[
\frac{\log 0.94 - \log 0.80}{\log 0.60 - \log 0.32} = \frac{0.026 + 0.09}{-0.22 - (+0.49)}
\]

slope = \(0.064/0.27 = 0.22\)

\(K = 0.60\)

Slope of a:-

\[
\frac{\log 0.80 - \log 0.70}{\log 0.60 - \log 0.34} = \frac{-0.096 - (+0.15)}{-0.22 - (+0.47)} = \frac{0.054/0.25 = 0.21}{-0.22 - (+0.47)}
\]

\(\therefore n \quad 20 \quad 1/4 \quad K = 0.53\)
Slopes of large coke at three different points

Slope at portion a:

\[
\frac{\log (1) - .86}{\log 100 - .45} = \frac{0 - (0.065)}{0 - (0.35)}
\]

\[
0.065/0.35 = 0.20
\]

and \( K = 0.67 \)

Slope of b also approximately the same.

\[
\frac{\log 1.18 - 1}{\log .100 - .46} = \frac{0.07 - 0}{0 - (-.33)} = 0.21
\]

and \( K = 0.76 \)

Slope of c

\[
\frac{\log 1.34 - \log 1.2}{\log 0.36 - \log .20}
\]

\[
\frac{0.13 - (+0.079)}{-0.44 - (+0.69)} = \frac{0.051}{-0.25} = -0.20
\]

and \( K = 1.75 \)

\[
y = x^n
\]

\[\therefore \ n = 1/5\]
Small Ore:

Slope of a:

\[
\frac{\log 1.5 - \log 1.3}{\log 0.4 - \log 0.20}
\]

\[
0.17 - (+0.11) = 0.06 = -0.20
\]

\[
-0.39 - (+0.69) = 0.30
\]

and \( K = 1.73 \)

Slope of b:

\[
\frac{\log 1.09 - \log .90}{\log 0.60 - \log .22}
\]

\[
0.025 - (+0.045)
\]

\[
-0.22 - (+.65)
\]

\[
= 0.082/0.43 = 0.19
\]

and \( K = 0.79 \)

Slope of C:

\[
\frac{\log 0.76 - \log .62}{\log 0.60 - \log .24}
\]

\[
-0.12 - (+.20) = 0.08 = 0.20
\]

\[
-0.22 - (+0.61) = 0.39
\]

\[
= y = x^n
\]

\( n = 1/5 \)

and \( K = 0.54 \)
Si/So Coke

Slope of a: -
\[
\frac{\log 1.5 - \log 1.3}{\log .29 - \log 1}
\]

\[
0.17 - (0.11) = 0.06
\]

\[
-0.53 - (0.95) = 0.42
\]

\[
= 0.14
\]

and \( K = 1.50 \)

Slope of b: -
\[
\frac{\log 0.94 - \log 0.84}{\log 0.70 - \log 0.34}
\]

\[
= -0.026 - (+0.075) = 0.049
\]

\[
-0.15 - (-0.46) = 0.31
\]

\[
= 0.16
\]

and \( K = 0.70 \)

Slope of c: -
\[
\frac{\log 0.80 - \log 0.70}{\log 0.70 - \log 0.31}
\]

\[
= 0.096 - (+0.15)
\]

\[
-0.15 - (+0.51)
\]

\[
= 0.054
\]

\[
0.36 = 15
\]

and \( K = 0.59 \)

And slopes for a, b, and c found take zero for \( M_i/M_0 \) values when \( n = 0 \)

\[
y = K
\]

and \( K \) values for all varies between 0.8 and 1.0