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PNEUMATIC CLASSIFICATION OF FORT ST. VRAIN FUEL PARTICLES

by
DAVID deLESDERNIER

Prepared under
Contract AT(04-3)-167
Project Agreement No. 53
for the
San Francisco Operations Office
U. S. Energy Research and
Development Administration

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ABSTRACT

Closure of the High-Temperature Gas-Cooled Reactor (HTGR) fuel cycle necessarily involves the reprocessing of fuel. During the reprocessing sequence, it is necessary to separate the bred, 100% enriched (U-233) fertile fuel stream from the contaminated (U-235) fissile fuel stream which contains U-238 and the neutron poison U-236. Cross mixing of these fuel streams results in a proportionate cost penalty. For this reason separation of the fuel into its respective components was studied. The various methods of effecting a fertile-fissile fuel particle separation were considered and the method of pneumatic classification was selected for further experimentation. This report discusses a parametric study of pneumatic classification in which a commercial pneumatic classifier and an experimental pneumatic classifier were evaluated to determine the effect of height and feed composition on the efficiency of separation.

A model is proposed that can predict crossover of TRISO/TRISO fuel over a wide range of operating conditions once feed composition is known. The model offers potential for further economic evaluation of the fuel cycle. Recommendations are made for prototypical pneumatic classification equipment.

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1. INTRODUCTION

Closure of the High-Temperature Gas-Cooled Reactor (HTGR) fuel cycle is essential for successful introduction of the HTGR. General Atomic Company is currently funded under the Thorium Utilization Program of the U.S. Energy and Development Administration (ERDA) to develop the technology necessary for reprocessing spent HTGR fuel in a facility using unirradiated fuel materials. The reference process consists of the reduction of full-size HTGR fuel elements to $<3/16$ in. particles, which are then fluidized and burned to remove fuel element and matrix graphite from the fuel particles. After these two process steps, the fissile and fertile fuel particles are separated and continue throughout the remaining process steps as separate streams. As fuel cycle economic success depends in part on separation of the bred U-233 in the fertile particles from the U-236-contaminated U-235 in the fissile particles, it is important to achieve separation of the fertile from the fissile fuel particles as completely as is economically feasible in the Head-End Reprocessing System. This report describes a comprehensive year-long study of pneumatic classification of fuel particles.

Pneumatic separation was investigated in detail using an Alpine Multiplex Zigzag Air Classifier and a modular pneumatic classifier designed especially for this study. Effects of the following variables were determined:

1. Solids feed rate
2. Air velocity
3. Column height
4. Feed position
5. Particle size distribution
6. Ratio of fuel and graphite

For a comparison of separation methods, the fuel was also classified using a standard sieve and sieve shaker technique. In this analysis, the separation efficiency was related to charge size on the screen, rate of blinding of the screen opening, and screen throughput.

The pneumatic separation efficiency was applied to actual fuel particle size distributions to give the crossover of the fissile and fertile streams. (Crossover is defined as the percent loss of fissile heavy metal to the fertile stream and the percent loss of fertile heavy metal to the fissile stream.) Since the crossover of these two streams constitutes a cost penalty in the Thorium Fuel Cycle (Ref. 1), this mixing must be kept to a minimum. A model was developed that would predict the separation and crossover of the fissile and fertile streams. Using this model, the final crossover can be calculated for any size distribution of Fort St. Vrain (FSV) type TRISO/TRISO fuel. With this information, cost analyses and design decisions can now be made with greater accuracy and confidence.

2. FINANCIAL BACKGROUND

The cost penalty associated with the crossover of the fissile and fertile streams has been a major consideration in this research. The fissile stream is recycled once, then is disposed of because of the depletion of fissionable U-235 and the build-up of the neutron poison U-236. Loss of fertile material to the fissile stream results in either disposal of the bred U-233 or at best a minor improvement of the reactivity of the recycled fissile fuel. Loss of fissile material to the fertile stream contaminates the pure U-233 with other isotopes of uranium, one of which is a neutron poison - U-236. In the past, this cost penalty has been either ignored, assumed to be zero, or only treated generally for establishing the costs of the fuel cycle (Ref. 2). The main reason for this was that until Ref. 3 was published, no data were available on the crossover of the two streams. However, after that report led the way toward understanding the separation of TRISO/TRISO fuel, further information was obtained (Ref. 4) on the results of the Scrap Rod Program (Ref. 5), and this is now followed by the present detailed account of pneumatic classification. An accurate picture of the cost penalties resulting from crossover may now be drawn through the comparison of the results from these studies on separation with those from economic studies.

One study (Ref. 6) determined the cost penalties associated with the crossover of the HTGR fuel particles for a wide range of possible net crossover values (0 to 50%) and for various economic situations. The information from this broad range of data is summarized in this report in Figs. 2-1 and 2-2. These two figures (one for fissile, the other for fertile crossover) give the cost penalty as a function of crossover for two cases: (1) an average for 31 years of recycle operation; (2) a near equilibrium concentration of U-236 in the fertile particles. For both cases, three curves are given, each representing a different resale value associated with the residual makeup uranium. These figures permit the assignment of

Fig. 2-1. Fuel cost penalty resulting from crossover of bred fuel into retired stream

Fig. 2-2. Fuel cost penalty resulting from crossover of residual makeup uranium into recycle stream

cost penalties to known crossover values which can then aid in the design, economic, and process decisions governing HTGR fuel reprocessing. Using the average parameters of the second Scrap Rod Run, a fissile crossover of 13.3 wt % and a fertile crossover of 4.0 wt % are predicted using the model. These crossovers lead to a combined cost penalty of 0.044 mils/kWhr assuming the upper curves in Figs. 2-1 and 2-2 apply to this situation.

In the following sections, the results of various experiments on separation of the fissile and fertile streams are reported. In addition, a model that will permit the estimation of fissile and fertile crossover for a variety of process conditions and fuel compositions is proposed and refined. By coupling the model developed in the course of this investigation with Figs. 2-1 and 2-2, it is now possible to assess the cost penalties associated with the separation of TRISO/TRISO fuel in the head-end reprocessing.

3. THEORY

Pneumatic classification is based on a hydrodynamic force balance between the moving gas phase and the solid phase. In this force balance, the differences in size, in density, or in a combination of the two is used to separate the particles. The starting point for the theoretical consideration surrounding the pneumatic classification or separation of two particulate systems begins with the classic solution of the Navier-Stokes Equation (Ref. 7) for an incompressible fluid:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} = \frac{2}{\text{Re}} \nabla^2 \mathbf{V} - 1/2 \Delta P \quad (3-1)$$

(For definition of symbols see Appendix G.) For steady state flow the first term is zero, and from the equation of continuity

$$\nabla \cdot \mathbf{V} = 0 \quad (3-2)$$

The resulting equation of motion is nonlinear and as a result only approximate solutions can be found. The first solution to this equation was given by G. Stokes in 1851 (Ref. 8) when he assumed the inertial terms to be negligible. This solution gave

$$\bar{F} = 3\pi \mu dV \quad (3-3)$$

which is valid for Reynolds numbers less than 0.5. In the situation where a spherical particle is in a rising gas stream, the gravitational force is balanced by the viscous force (Eq. 3-3) and the buoyant force (see Fig. 3-1), giving the following equation:

$$V_f - V_p = V_t = \frac{g}{18} \frac{d^2}{\mu} (\rho_p - \rho_F) \quad (3-4)$$

$$\begin{aligned} \text{GRAVITATIONAL FORCE} &= \frac{1}{6} \pi d^3 \rho_p g \\ \text{BUOYANT FORCE} &= \frac{1}{6} \pi d^3 \rho_f g \\ \text{VISCOUS DRAG FORCE} &= 3\pi\mu d (v_f - v_p) \end{aligned}$$

Fig. 3-1. Free body force diagram

When the gas flow is such that the particle is suspended motionless, this velocity is equal to the terminal velocity of the particle falling in a stagnant gas. This force balance is useful in specifying an effective (Stokes) diameter for a nonspherical particle. This diameter is calculated from the experimentally determined terminal velocity and Eq. 3-4 and is useful in describing the interaction of a nonspherical particle and a fluid.

Other methods (Ref. 9) for solution to Eq. 3-1 have extended the applicable range of Reynolds number. In addition to these methods a friction factor chart (Fig. 3-2, Ref. 10) gives the relationship between a sphere and fluid over a wide range of Reynolds numbers. However, all of these solutions are only valid for low concentrations of particles in the fluid (Refs. 11-13). When the concentrations exceed 0.05 volume percent, the error exceeds 20%. Because normal operation of a pneumatic classifier has a concentration many times this value, these solutions cannot be used to describe the operation.

A pneumatic classifier is used to separate a mixture of particles into two fractions based upon the difference in size and/or density. In the ideal case of very low solids concentration, all of the larger and/or more dense particles will fall in the rising gas stream while all of the smaller and/or less dense particles will rise with the gas. This can be predicted via the above solutions to the Navier-Stokes equation if the solids concentration is low.

However, as the solids concentration increases, there are more and more particle to particle interactions which cause some of the large and/or more dense particles to be entrained with the rising less dense particles. The opposite also occurs. This results in contamination of the two fractions. For a binary system this leads to a percent purity of each stream. For a system which consists of particles having a spread of sizes and/or densities, the term separation efficiency is used and designated as

Fig. 3-2. Friction factor for spheres in relative motion to a fluid

ϕ . The separation efficiency is defined as the weight fraction of feed that is present in the coarse fraction for a certain size interval. Curve A in Fig. 3-3 represents the ideal case for separation. References 13 and 14 state this ideal separation can only be approached in classification since there will always be some degree of overlapping of distributions or entrainment. As the slope of the separation efficiency curve decreases from ∞ , the separation departs further and further from the theoretical maximum. For a measure of this departure from the ideal situation, the diameter with a 75% probability of falling into the coarse fraction is divided by that diameter with a 25% chance or

$$\phi_{25}^{75} = \frac{d_{25}}{d_{75}} \quad (3-5)$$

As this value approaches unity, the separation approaches theoretical efficiency.

The relationship of ϕ to diameter describes the separation process for a given set of conditions. Establishing the relationship between ϕ and d as a function of such variables as air velocity, solids feed rate, particle size distribution, and powder system components characterizes the separation process. With the process characterized with a mathematical model, the separation under any desired set of conditions may be determined. For manipulation of this model, it is convenient to use matrices (Ref. 15).

The particle size distribution of the feed is divided into consecutive equal size increments. The weight fractions of particles for each size increment comprise the elements of a column matrix which may be denoted as Y_i . As i increases the average diameter of the size increment increases. Also, the sum of Y_i for all i is equal to unity. To describe the process of classification, the elements of a diagonal matrix, Y_{ii} , are set equal to the fraction of feed in size increment i that goes to the coarse product

Fig. 3-3. Separation efficiency

($Y_{ii} = \phi_i$). Now with both the feed size distribution and the separation process described by matrices, the size distribution of the product may be found by simple matrix arithmetic or

$$o = f \cdot C \quad (3-6)$$

$$u = f - o \quad (3-7)$$

For example, suppose a feed had a size analysis as given in Table 3-1 and was separated by a classifier whose ϕ varied with size as given in Table 3-1. Then to find the size distribution of the products one needs only to substitute the above information into Eqs. 3-6 and 3-7 to obtain

$$o = \begin{vmatrix} 0.10 \\ 0.30 \\ 0.35 \\ 0.20 \\ 0.05 \end{vmatrix} \times \begin{vmatrix} 1.00 & 0 & 0 & 0 & 0 \\ 0 & 0.80 & 0 & 0 & 0 \\ 0 & 0 & 0.50 & 0 & 0 \\ 0 & 0 & 0 & 0.25 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0.10 \\ 0.24 \\ 0.18 \\ 0.04 \\ 0 \end{vmatrix}$$

$$u = \begin{vmatrix} 0.10 \\ 0.30 \\ 0.35 \\ 0.20 \\ 0.05 \end{vmatrix} - \begin{vmatrix} 0.10 \\ 0.24 \\ 0.18 \\ 0.04 \\ 0 \end{vmatrix} = \begin{vmatrix} 0 \\ 0.06 \\ 0.17 \\ 0.16 \\ 0.05 \end{vmatrix}$$

By having the elements of the diagonal matrix responsive to the operating parameters of the classifier, one may determine the products for a given set of operating conditions and for a given feed composition.

TABLE 3-1
PARAMETERS FOR AN EXAMPLE OF MATRIX MODELING

Size Range (microns)	Feed (Weight Fraction)	Separation Efficiency
+2000	0.10	1.00
+1000 -2000	0.30	0.80
+500 -1000	0.35	0.50
+250 -500	0.20	0.25
-250	0.05	0.00

4. EXPERIMENTAL: DEVELOPMENT AND ANALYSIS OF PNEUMATIC CLASSIFICATION TECHNIQUE

4.1. DESCRIPTION AND GENERAL OPERATING PROCEDURE WITH THE ALPINE MULTIPLEX ZIGZAG PNEUMATIC CLASSIFIER

The majority of these data on pneumatic classification was obtained using an Alpine Multiplex Zigzag Pneumatic Classifier (Figs. 4-1 and 4-2) consisting of a feeder, a zigzag column, a cyclone, fine and coarse product receivers, and a vacuum source. A positive displacement vacuum pump with a bag and a sintered metal filter for removing dust carried over from the cyclone was used for the experiments. In addition to the vibratory feeder used in a majority of the experiments, a rotary valve feeder was tested (Fig. 4-3). Section 4.5 compares the performance of these feeders.

A typical run followed these steps: ~1.5 kgm of feed was loaded into the feed hopper with an adjustment of the air flow to the desired value. A few hundred grams of particles were then fed and removed from the product receivers to fill the vibrating channel to the normal run depth. Next the feeder control was adjusted and the unit turned on. After a measured length of time (usually 1-2 min) the feeder was stopped and the particles in the column were allowed to classify. After all of the particles had either been elutriated or gravity discharged from the column, the operator shut off the air flow and removed the product receivers. To obtain an accurate feed rate, the operator divided the total feed rate by the time run. After the fine and coarse products were weighed, a riffle split sample from each was sent out for size analysis. Using this method several runs could be made from one loading, provided ~1/2 kgm was left in the feeder (see Section 4.5).

The fine and coarse samples were sent to the Fuel Test Techniques Branch for a size distribution analysis using the coated particle analyzer

Fig. 4-1. Alpine pneumatic classifier

Fig. 4-2. Alpine Multiplex Zigzag Pneumatic Classifier

Fig. 4-3. Rotary feeder

which is described in Appendix D. Briefly, this unit counts and sizes ~20 particles per second using a collimated light beam, a photodetector, and computer logic. The resulting data give the number of particles in a particular size interval (e.g., 48 particles between 400 μ and 419 μ), which is then used by a computer program to calculate a number-percent size distribution. From this distribution and the density vs size relationship, the program calculates a weight-percent size distribution. With this weight distribution for the fine and coarse products and their weight ratio, the program then computes the feed and the weight fraction of the feed that becomes the coarse product. Appendix E reproduces the program and a typical output for FSV type fuel. A more detailed description of the data reduction and analysis is given in Section 7.

4.2. SIMULATED FEED

The majority of the experiments on classification utilized simulated feed consisting of rejected, depleted fissile particles and rejected fertile particles burned back to their SiC coating. This type of feed was used because rejected FSV fuel was not available until the more recent experiments. Thus, all the initial tests were made with simulated fuel although some of the tests were later duplicated with actual FSV fuel. Figure 4-4 gives the size distribution of simulated feed. By comparing this with the size distributions of FSV fuel given in Figs. 4-5 and 4-6, it can be seen that there is a rough approximation of simulated feed to a combination of the four components of FSV fuel: Fissile A, Fissile B, Fertile A, and Fertile B.

4.2.1. Effect of Solids Feed Rate and Gas Flow Rate on Separation Efficiency

The major thrust of this study was to determine the efficiency of separation with respect to gas flow rate and solids feed rate. To establish this relationship, runs were made with the feed rate ranging from

Fig. 4-4. Particle size distribution of TRISO/TRISO fuel particles

Fig. 4-5. Particle size distribution of FSV fuel particles, Fissile A - Fertile B

Fig. 4-6. Particle size distribution of FSV fuel particles, Fissile B - Fertile A

50 to 1000 gm/min holding the air velocity constant at 3.15 m/sec. These tests were repeated for air velocities of 3.70, 4.25, and 4.80 m/sec. By analyzing the size distributions of the fine and coarse products and their weight ratios, the efficiency of separation, ϕ , was calculated for each 20 μ increment from 300 to 900 μ in the distribution. Tables 4-1 through 4-4 give the ϕ ratio versus particle size and solids feed rate at 3.15, 3.70, 4.25, and 4.80 m/sec. These were plotted as ϕ versus feed rate with constant diameter lines (Figs. 4-7 through 4-10). Each graph representing a particular air velocity shows that separability depends upon feed rate. In fact, as feed rate increases, the 50% cut point shifts downward and the sharpness of separation falls (the constant diameter lines come closer together). On obtaining the smooth curves represented in these figures, it was decided to curve fit least squares curves to the data. For this, ϕ was found to be a function of the feed rate of the form

$$\phi = \frac{\text{FEED RATE}}{A + B \cdot \text{FEED RATE}} \quad (4-1)$$

where A and B are constants that depend upon particle diameter and air velocity. Table 4-5 gives the values for the constants A and B as a function of diameter and air velocity.

The next step was to find the relationship between separation efficiency and air velocity. To achieve this, efficiency was plotted against air velocity with constant diameter lines for a constant feed rate. (See Figs. 4-11 through 4-13.) Examining these graphs begins to reveal the relationship between efficiency and air velocity: as the gas flow rate increases, the 50% cut point increases. Further, the spread between the constant diameter lines reaches a maximum at $\phi = 50\%$.

Several unsuccessful attempts were made to curve fit these data. Alternatives to this method would be (1) to find the relationship of A and

TABLE 4-1
SEPARATION EFFICIENCY VERSUS FEED RATE AND DIAMETER AT CONSTANT
AIR VELOCITY RATE OF 3.15 M/SEC

Diameter (Microns)	Feed Rate							
	78.9	89.1	139.5	177.1	337.5	387.4	452.5	484.4
300	0.20	0	0.14	0	0.63	0.04	0.14	0.12
320	0.10	0.09	0.19	0.16	0.48	0.45	0.41	0.49
340	0.17	0.31	0.32	0.33	0.62	0.68	0.54	0.73
360	0.27	0.47	0.43	0.44	0.70	0.75	0.67	0.77
380	0.23	0.38	0.34	0.30	0.60	0.68	0.65	0.74
400	0.17	0.33	0.22	0.25	0.52	0.68	0.66	0.77
420	0.22	0.45	0.38	0.36	0.60	0.71	0.69	0.81
440	0.27	0.47	0.43	0.45	0.67	0.73	0.74	0.85
460	0.43	0.60	0.60	0.55	0.73	0.78	0.80	0.89
480	0.83	0.93	0.89	0.90	0.92	0.97	0.97	0.98
500	0.89	0.97	0.95	0.92	0.96	0.97	0.98	0.99
520	0.92	0.98	0.95	0.96	0.97	0.99	0.99	0.99
540	0.95	0.99	0.97	0.98	0.98	0.99	0.99	1.00
560	0.96	1.00	0.98	1.00	0.99	1.00	1.00	1.00
580	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
600	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 4-2
SEPARATION EFFICIENCY VERSUS FEED RATE AND DIAMETER AT CONSTANT
AIR VELOCITY RATE OF 3.70 M/SEC

Diameter (Microns)	Feed Rate									
	63	75.3	91.9	129.3	136	168.1	178.2	239	321.5	369
300								0.03	0.04	0.16
320						0.01		0.01	0.09	0.12
340						0.04		0.05	0.18	0.27
360						0.07		0.10	0.32	0.35
380						0.06		0.08	0.27	0.34
400			0.03			0.02	0.05	0.04	0.09	0.20
420			0.01			0.04	0.03	0.08	0.18	0.27
440		0.01	0.01		0.02	0.06	0.04	0.08	0.27	0.35
460	0.15	0.11	0.13	0.11	0.14	0.23	0.23	0.34	0.42	0.53
480	0.36	0.44	0.55	0.36	0.50	0.71	0.70	0.80	0.80	0.88
500	0.47	0.52	0.64	0.49	0.55	0.79	0.80	0.84	0.90	0.89
520	0.64	0.69	0.75	0.63	0.68	0.89	0.87	0.91	0.92	0.94
540	0.78	0.78	0.83	0.77	0.82	0.93	0.92	0.94	0.96	0.95
560	0.76	0.86	0.91	0.83	0.88	0.96	0.95	0.97	0.96	0.97
580	0.84	0.89	0.94	0.90	0.90	1.00	0.98	0.98	0.98	0.98
600	0.90	0.89	0.97	0.90	0.95	1.00	0.99	1.00	0.99	1.00
620	0.95	0.94	1.00	0.95	1.00	1.00	1.00	1.00	1.00	1.00
640	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
660	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 4-3
SEPARATION EFFICIENCY VERSUS FEED RATE AND DIAMETER AT CONSTANT
AIR VELOCITY RATE OF 4.25 M/SEC

Diameter (Microns)	Feed Rate							
	81.1	104.8	199.7	292.7	381.6	448.2	514.6	708.2
300								
320								
340							0.01	0.01
360						0.01	0.02	0.02
380						0.01	0.01	0.02
400						0	0	0.01
420						0	0	0.02
440		0.01		0.01	0.01	0.01	0.01	0.01
460	0.01	0.02	0.08	0.05	0.07	0.15	0.10	0.10
480	0.02	0.04	0.30	0.25	0.34	0.43	0.45	0.44
500	0.07	0.11	0.42	0.34	0.47	0.59	0.51	0.51
520	0.16	0.20	0.63	0.45	0.57	0.70	0.63	0.67
540	0.28	0.38	0.75	0.61	0.72	0.81	0.71	0.78
560	0.47	0.53	0.87	0.73	0.78	0.84	0.83	0.84
580	0.58	0.68	0.92	0.81	0.86	0.92	0.87	0.89
600	0.68	0.75	0.93	0.87	0.93	0.94	0.88	0.91
620	0.74	0.77	0.97	0.92	0.97	0.97	0.90	0.95
640	0.80	0.89	1.00	0.96	1.00	1.00	0.95	1.00
660	0.87	0.95	1.00	1.00	1.00	1.00	1.00	1.00
680	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 4-4
SEPARATION EFFICIENCY VERSUS FEED RATE AND DIAMETER AT CONSTANT
AIR VELOCITY RATE OF 4.80 M/SEC

Diameter (Microns)	Feed Rate						
	38.9	116.1	288.0	334.4	512.7	782.8	1002.2
300							
320							0.03
340						0.01	0.09
360						0.02	0.14
380						0.02	0.11
400						0.01	0.06
420						0.01	0.08
440						0.02	0.09
460				0.01	0.02	0.11	0.20
480			0.01	0.02	0.08	0.34	0.45
500			0.02	0.05	0.16	0.43	0.55
520		0.01	0.06	0.15	0.29	0.55	0.60
540		0.02	0.12	0.26	0.46	0.65	0.70
560	0.01	0.08	0.25	0.39	0.60	0.74	0.80
580	0.02	0.18	0.38	0.50	0.69	0.83	0.83
600	0.04	0.29	0.48	0.62	0.77	0.83	0.85
620	0.08	0.44	0.68	0.75	0.85	0.88	0.93
640	0.15	0.61	0.79	0.78	0.89	0.94	0.97
660	0.32	0.65	0.82	0.83	0.94	0.97	1.00
680	0.36	0.80	0.90	0.92	0.97	1.00	1.00
700	0.65	0.88	0.95	0.96	1.00	1.00	1.00
720	0.80	0.93	1.00	1.00	1.00	1.00	1.00
740	0.89	0.97	1.00	1.00	1.00	1.00	1.00
760		1.00	1.00	1.00	1.00	1.00	1.00

Fig. 4-7. Separation efficiency versus feed rate and diameter at constant air velocity of 3.15 m/sec

Fig. 4-8. Separation efficiency versus feed rate and diameter at constant air velocity of 3.70 m/sec

Fig. 4-9. Separation efficiency versus feed rate and diameter at constant air velocity of 4.25 m/sec

Fig. 4-10. Separation efficiency versus feed rate and diameter at constant air velocity of 4.80 m/sec

TABLE 4-5
CONSTANTS A AND B OF EQUATION $\phi = \text{FEEDRATE}/A + B \cdot \text{FEEDRATE}$
VERSUS AIR VELOCITY AND DIAMETER

	Constant							
	A				B			
Air velocity, m/sec	3.15	3.70	4.25	4.80	3.5	3.70	4.25	4.80
Diameter, microns								
400	340.3	7,511	131,140	297,980	0.827	-9.34	-120.0	-280.7
420	226.0	9,701	64,800	312,880	0.904	-18.8	-58.3	-299.7
440	178.8	9,105	6,534	139,060	0.920	-18.7	-56.6	-127.6
460	88.6	493.9	7,479	49,715	1.024	1.054	-7.64	-48.7
480	12.50	103.0	3,891	36,811	1.010	0.920	-6.34	-45.2
500	6.57	70.5	1,080	17,139	1.010	0.925	-0.501	-20.6
520	4.83	35.0	444.3	13,429	1.004	0.974	0.555	-21.5
540	2.66	18.9	200.1	--	1.004	0.996	0.855	--
560	1.91	16.1	89.4	4,044	0.999	0.981	0.989	-8.38
580	--	10.56	53.5	1,991	--	0.982	0.995	-3.66
600	0	7.90	35.4	971.0	1	0.980	1.002	-1.13
620	0	3.74	29.5	465.1	1	0.988	0.981	0.445
640	0	0.86	19.35	227.9	1	0.998	0.968	0.545
660	0	0	11.32	85.3	1	1	0.974	0.906
680	0	0	3.92	72.0	1	1	1	0.969
700	0	0	0	21.94	1	1	1	0.969
720	0	0	0	10.53	1	1	1	0.979
740	0	0	0	5.18	1	1	1	0.989

Fig. 4-11. Separation efficiency versus air velocity and diameter at constant feed rate of 100 g/min

Fig. 4-12. Separation efficiency versus air velocity and diameter at constant feed rate of 300 g/min

Fig. 4-13. Separation efficiency versus air velocity and diameter at constant feed rate of 500 g/min

B with respect to a change in air velocity; (2) to find the relationship of A and B to diameter and then relate the change in air velocity as a shift of diameter; or (3) to keep the raw data in tabular form and use an interpolation method to obtain the correct value. The advantages of the first two alternatives are that they establish a direct relationship between the variables which could then be related to theory. The disadvantage would be the loss of accuracy when the data are curve fitted. The last alternative would be the most accurate method but would not give any relationship between the variables. Therefore, the approach taken was to relate the constants A and B to diameter and incorporate air velocity as a shift in diameter, resulting in the following equations:

$$K = \frac{\text{Feed}}{A + B \cdot \text{Feed}} \quad (4-2)$$

$$D = (26 - \text{Air}) \frac{205}{9} + d \quad (4-3)$$

$$A = \exp (28.52 - 0.03271 D) \quad (4-4)$$

$$B = 18 - \frac{4225}{D - 408} \quad \text{For } \begin{matrix} D < 410; B [=] -300 \\ D > 656.5; B [=] 1 \end{matrix} \quad (4-5)$$

4.2.2. Separation of SiC Hulls from Fertile Kernels

Another particulate system investigated using the Alpine classifier was the feed to the leachers. Reduction of the amount of insols (SiC hulls) going to the leacher simplifies the subsequent solid-liquid separation. Keeping in mind the principles of pneumatic classification, i.e., separation via differences in the hydraulic properties of either density or diameter or a combination of the two, the density and size distribution of the SiC hulls and the ThO_2 powder leaving the secondary burner were examined. While the particle density of the SiC hulls was one-third of that for the ThO_2 powder, the particle size distributions overlapped to such an extent that the two particle systems could not be separated.

The following experiment was run to determine whether the degree of separation might be adequate if the hulls were separated from the kernels as they left the crusher. First, fertile particles were weighed and then crushed in a double roll particle crusher. The crusher product was immediately classified and the two products were weighed. Samples were taken from the feed and from the fine and coarse products, burned, and then analyzed for weight percent thorium. Table 4-6 gives the results of the analysis and data reduction for two air velocities. At 0.75 m/sec air velocity, the separation resulted in the loss of less than 1/2% thorium to the fine stream containing the hulls and carbon, whereas in the thorium rich coarse stream, the product was stripped of 84 wt % of the SiC hulls and 89 wt % of the carbon coatings. This is a 6 to 1 and a 9 to 1 reduction in the SiC and carbon, respectively.

The product of the secondary burner continues to the dissolver/centrifuge, where the heavy metals and fission products are leached away from the SiC hulls and the hulls separated from the mother liquor in the centrifuge. This separation would allow the capacity of the centrifuge to be reduced by a factor of six and would give the option of handling 89% of the carbon coatings and the entrapped fission products as a solid waste.

An additional run to see if the SiC hulls could be separated from crushed kernels was attempted but was unsuccessful because the kernels could not be crushed in any of the available equipment. It is possible that the separation of hulls from crushed kernels may not be adequate due to the larger overlap of the size distributions.

4.2.3. Additional Findings

4.2.3.1. Density

To reduce the number percent size distribution data to weight percent, the relationship of density to size must be known. To determine this relationship, simulated feed was selectively cut at four diameters and analyzed for size distribution and then for density by air pycnometer.

TABLE 4-6
SEPARATION OF SiC HULLS AND CARBON COATINGS
FROM ThC₂ KERNELS

Run No.	Air Velocity (m/sec)	Feedrate (gm/min)	Fine Product				Coarse Product			
			ThC ₂ (wt %)	C (wt %)	SiC (wt %)	Total (wt %)	ThC ₂ (wt %)	C (wt %)	SiC (wt %)	Total (wt %)
1	0.75	46	0.26	16.77	15.17	32.20	62.76	2.05	2.98	67.79
2	0.4	22	0.28	15.08	11.34	26.70	48.00	12.74	12.56	73.30

Figure 4-14 illustrates the results of density versus mean size with a least squares straight line through the points. The equation of this line is:

$$\rho = 2.566 + 0.00246 d \quad (4-6)$$

where ρ = density in gm/cm

d = particle diameter in microns

The data point at 300 μ was ignored in the least squares calculation. If the density versus diameter relationship were described by two straight lines, one through the first two points and one through the last three, the change in the size analysis reduction would be less than 0.5%. Since the difference is small, this single expression was used in the data reduction. The theoretical relationship between a particle's density and its size will be discussed in Section 7, which deals with the runs using FSV type fuel.

4.2.3.2. Peak Height (Modal Effect)

Close inspection of Fig. 4-8 shows that constant diameter lines decrease as diameter decreases until 380 μ , at which point the next few lines increase and then decrease again. To make this clearer, Fig. 4-15 gives the variation of ϕ versus size at constant feed and air velocities. The maximum at approximately 360 μ corresponds to the minor mode whose peak is at 370 μ . The influence of additional modes and their relative height was first thought to be a peculiarity of this feed, but, as will be explained in Section 4.4.2, this effect is inherent in pneumatic classification.

4.2.4. Effect of the Addition of Graphite

All of the runs presented to this point used simulated feed consisting of fuel particles only. To study the effect of graphite on separation, several runs were made with a feed consisting of 5 and 10 wt % carbon at an air velocity of 3.7 m/sec. By superimposing the results of the size distribution analysis on Fig. 4-8, the effect of graphite on the separation

Fig. 4-14. Density versus particle size for simulated feed

4-27

Fig. 4-15. Separation efficiency versus diameter at constant feed rate of 300 g/min and air velocity of 3.70 m/sec

can be determined (Figs. 4-16 through 4-19). Table 4-7 summarizes the feed rates for the four runs. The percent increase of the effective feed rate of the second run over its total feed rate was inconsistent with the other three runs and was disregarded. The difference between the third and fourth runs can be explained by the fact that in the third run all graphite particles larger than 1000 μ were removed, whereas in the fourth run, all graphite particles smaller than 1000 μ were removed. Figure 4-20 gives the size distribution of the graphite particles used in those runs. The larger particles appear to have a much greater effect by weight than do the small particles. If these two runs are averaged to represent the effect of the entire graphite distribution, the following relation will describe the effect of graphite on the separation:

$$F_e = F_p + 2 F_g \quad (4-7)$$

where F_e = effective feed rate

F_p = particle feed rate

F_g = graphite feed rate

This expression was tested as reported in Section 4.4.

4.3. INITIAL TESTS WITH FSV FUEL

4.3.1. Description of FSV Fuel

FSV fuel consists of four mean particle sizes: Fissile A, Fissile B, Fertile A, and Fertile B (Figs. 4-5 and 4-6). The need for four particle sizes rather than two stems from the requirement for proper uranium and thorium loading in the various regions of the reactor. Since pneumatic classification relies on the size of the particles being separated, the two extreme combinations encountered - Fissile A/Fertile B (Fig. 4-5) and Fissile B/Fertile A (Fig. 4-6) — were two rod batches used in these

Fig. 4-16. Comparison of separation of simulated feed at 3.70 m/sec air velocity with additional 5 wt % graphite and with no graphite

Fig. 4-17. Comparison of separation of simulated feed at 3.70 m/sec air velocity with additional 10 wt % graphite and with no graphite

Fig. 4-18. Comparison of separation of simulated feed at 3.70 m/sec air velocity with additional 10 wt % graphite (lower portion of size distribution) and with no graphite

Fig. 4-19. Comparison of separation of simulated feed at 3.70 m/sec air velocity with additional 10 wt % graphite (upper portion of size distribution) and with no graphite

TABLE 4-7
EFFECT OF GRAPHITE ON SEPARATION
OF THE SIMULATED FEED

Run No.	Weight (% C)	Particle Feed Rate	Carbon Feed Rate	Total Feed Rate	Effective Feed Rate	Increase (%)
1	5	150	9.4	199.4	208	4.3
2	10	162	17	179	375	109.5
3	10(L) ^(a)	144	16	160	165	3.1
4	10(u) ^(b)	192	21	213	250	17.4

(a)_L - denotes lower portion of distribution.

(b)_u - denotes upper portion of distribution.

Fig. 4-20. Size distribution for tertiary crusher product

experiments. By testing these two extreme combinations, the limits of classification efficiency were found. These limits represent the extremes that can be expected from reprocessing the numerous combinations of fissile and fertile particles found in reactor fuel.

Appendix A gives the Quality Assurance data for these two rod batches plus a third containing Fissile A, Fertile A, and Fertile B particles. This rod batch was chosen for the Scrap Rod Program in lieu of the Fissile A/Fertile B batch for the reasons given in Section 4.3 and in Ref. 16. All three rod batches were rejected due to matrix nonuniformity caused by the failure of the pitch filler to penetrate one end of the rod completely. Aside from this flaw, the rods and the particles contained in them were within the limits set for reactor use.

4.3.2. Prediction of the Separation

The model derived from the experiments using simulated fuel was used to predict the separation of FSV fuel. The first prediction of the runs using Fissile B/Fertile A fuel gave totally unsatisfactory results. Errors as large as 43.2 wt % difference resulted. These errors result from differences between simulated feed and FSV type fuel. FSV fuel has a steeper slope for the density versus diameter curve and the modal intersection is shifted up by approximately 80μ . Using these two explanations as a basis, the model was adjusted to apply to FSV type fuel.

As mentioned briefly in Section 4.2.3.2 on Simulated Feed, the point of intersection of two size distribution modes affects the efficiency of separation. The effect is to increase the efficiency in the proximity of the intersection. By having the model equispace the constant diameter lines, a diameter correction was applied in order to spread the lines at the intersection of the modes. In this manner the model is kept general for all types of fuel providing the location and magnitude of the

correction shift is known. The intersection of the modes affects separation efficiency so that a diameter correction is needed to adjust the constant diameter lines of the equispace model.

The slope of the density curve also affects the spacing of the isodiameter lines. As the slope increases, the lines spread out indicating a better separation. This effect interacts with the effect of the modal intersection, and as a result they were hard to distinguish in this investigation. The effect of each could be studied if more time and the correct types of fuel were available. However, under the circumstances, a combined correction is required.

The uncorrected model (Fig. 4-21) was compared with the data taken in the runs. From this comparison, the shift of the constant diameter lines was determined and is given by the following equations:

$$\begin{array}{ll}
 d < 520 & D = 15.2 \times \left(\frac{d}{100}\right)^{2.15} \\
 520 < d < 560 & D = d \\
 d > 560 & D = 22.7 d^{0.507}
 \end{array}
 \left. \vphantom{\begin{array}{l} d < 520 \\ 520 < d < 560 \\ d > 560 \end{array}} \right\} (4-8)$$

where d = actual particle diameter
 D = particle diameter used in model

This corrected model (Fig. 4-22) agrees well with the spread distribution and with the close distribution at 200 gm/min. The error for other feed rates can be reduced by an amount ranging from $\pm 19\%$ to $\pm 4\%$ by using a constant feed rate of 150 gm/min. This implies that the effect of feed rate on separation is considerably reduced by the increased slope of the density curve. In Ref. 14, the rate of elutriation of fines from a fluidized bed increased for an increasing difference in the densities of the

Fig. 4-21. Uncorrected model for separation efficiency versus air velocity and diameter at constant feed rate of 200 g/min

Fig. 4-22. Model corrected for the effect of density; separation efficiency versus air velocity and diameter at constant feed rate of 200 g/min

particles: the larger the difference, the better the segregation and the less dependence upon solids concentration or feed rate.

4.3.3. Prediction of the Crossover

The ultimate use of the model is to predict the crossover between the fissile and fertile streams. The calculation of the separation is only one step in the final answer needed. With this in mind, the crossovers of two runs of FSV fuel were determined by wet chemical analysis. From these results, the particle size distributions of the fissile and the fertile particles in the feed were determined. Once these distributions were known, the ratio of fissile to feed for each size increment was calculated. When the fissile and fertile particles are assumed to be the same density for the same size, the crossover is given by:

$$X_v = \frac{\sum R_i^v W_i^c}{W_v} \quad (4-9)$$

$$X_\tau = \frac{\sum R_i^\tau W_i^f}{W_\tau} \quad (4-10)$$

$$R_i^v = 1 - R_i^\tau \quad (4-11)$$

where X = crossover

R = ratio of either fissile or fertile

W = weight

i = size increment

v = fissile

τ = fertile

c = coarse fraction

f = fines fraction

When this assumption is used, however, large errors result from density differences between fissile and fertile particles. That is, the

crossover predicted using the assumption is greater than that for the actual crossover. From this it is deduced that the fraction of fissile in a specific size increment in the feed is greater than the fraction of fissile in that increment in the coarse. The converse applies to the fertile fraction. In order to better predict the crossover based on this reasoning, the ratio of fissile in the coarse product per increment and the ratio of fertile in the fine product per increment was calculated using the weight percent crossover and the particle size distributions of the products. Using this ratio and the model, the predicted crossover of the other runs was within $\pm 14\%$ error. An additional test of the model for prediction of separation and crossover was provided by the Scrap Rod Program and is detailed in Section 4.4.

4.3.4. Density and Its Effect on Separation

The relationship of density to size in FSV fuel is very complex due to the manufacturing process. The fuel starts with ThC or UC/ThC kernels to which coatings of carbon and silicon carbide are applied. The kernels and each of the coatings have means ($\bar{X}$) and standard deviations (σ) associated with their diameter and thickness. The mean thickness for a particular coating is approximately equal for the four basic sizes of particles, leaving the difference of kernel diameters equal to the overall mean size difference. As a result, a fissile particle that has the same size as a fertile particle will have a larger than average coating thickness, while the fertile particles will have smaller than average coating thicknesses. This leaves the kernel of the fissile particle smaller than that of the fertile particle, and, since the kernel contributes the greatest fraction to particle mass, the fissile particle will also be less dense. From the data in Table 4-8, an average particle density was calculated for the Fissile B and Fertile A distributions at the following three particle sizes:

TABLE 4-8
QA FUEL SPECIFICATIONS

	Mean Diameter or Coating Thickness (Microns)	Standard Deviation (Microns)	Density (gm/cc)
Fissile B			
Kernel	240	20.0	9.5
Buffer	58	12.0	1.05
IPyC	32	5.7	1.90
SiC	25	3.3	3.19
Fertile A			
Kernel	370	33.0	9.5
Buffer	58	12.0	1.05
IPyC	32	5.7	1.90
SiC	25	3.3	3.19

$$\left. \begin{array}{l} \bar{X} - 2.25 \sigma \\ \bar{X} \\ \bar{X} + 2.25 \sigma \end{array} \right\} (4-12)$$

Figure 4-23 and Table 4-9 give these results of this calculation. Similar results would be expected for Fissile A and Fertile B fuel. Due to the statistics of combination, any particular size would have a range of densities. For this reason and because the combination of these curves to give density as a function of size for a blend would be very complicated, another approach was taken for establishing the density-size relation for the data reduction.

This alternate approach involved the linear approximation for density over the entire size range. FSV type fuel was selectively cut at four diameters and several density analyses were done by air pycnometer and mercury immersion. Figure 4-24 illustrates the results of the analyses with a least squares line drawn through the points. The equation for the lines is:

$$\rho = 0.8636 + 0.00488 d \quad (4-13)$$

where ρ = particle density in gm/cc

d = particle diameter in microns

Using this expression the number percent data may be reduced to an approximate weight percent relation. While this weight percent relation is an approximation, the deviation from the real value is within 0.5% as was the error mentioned in Section 4.2 on Simulated Feed. Any error that occurred as a result of this density approximation was corrected by the model through the various corrections used (see Section 4.4 for further details on the model).

Fig. 4-23. Theoretical density versus cumulative weight percent of particles

TABLE 4-9
THEORETICAL PARTICLE DENSITY VS PARTICLE DIAMETER

	Particle Diameter (Microns)	Particle Density (gm/cc)
Fissile B	326	3.64
	470	3.03
	614	2.77
Fertile A	426	4.48
	600	3.73
	774	3.39

Fig. 4-24. Weight percent mean diameter versus density at SiC coating for FSV type fuel

4.4. SCRAP ROD PROGRAM

The purpose of the Scrap Rod Program was to provide the first reliable data on particle breakage and fissile/fertile crossover produced by head-end reprocessing. To acquire these data, two one-half fuel blocks loaded with reject FSV type fuel were individually crushed, burned, and separated into a fissile rich stream and a fertile rich stream.

This section deals with the classification of the primary burner product produced in the program and, specifically, with the way in which this program served as a final test of both the Alpine pneumatic classifier and the model. Detailed analysis of each operation in the program is covered by Refs. 4, 5, 17, 18, and 19. This section is not meant to duplicate the documentation of the classification portion of the program, but to provide a link between this report and the work done previously (Ref. 4).

4.4.1. The Feed

Two batches of fuel rods were carefully chosen (Ref. 16) to represent the two extreme combinations of particle sizes and to provide traceability. Unfortunately, there were not enough Fissile A/Fertile B rods in storage to fill a half-length fuel block. Therefore, the closest combination to these was used: Fissile A/Fertile A/Fertile B. Figure 4-25 gives the size distribution. The other fuel rod batch that was used has the largest overlap of the fissile and fertile size distributions for any combination. Figure 4-6 gives the size distribution for the Fissile B/Fertile A batch.

These two rod batches were loaded into separate half-length fuel blocks and processed individually. The feed to the pneumatic classifier (the product of the primary burner) was drawn off continuously from a segregated bed, giving a varying fuel particle size distribution as well as

4-47

Fig. 4-25. Particle size distribution for Scrap Rod Run No. 1; Fissile A - Fertile A - Fertile B

a varying carbon content. The five sequential batches comprising each of the two runs were classified individually to assist in distinguishing any intra-run trends that might occur. The particle size distribution of the products produced from this separation is given in Appendix B.

Table 4-10 gives the weight percent carbon in the feed to and products from the pneumatic classifier. As can be seen, the diversity of feeds to the classifier in this program helped to distinguish many trends in the separation of TRISO/TRISO fuel. The identification of these trends and their effect on classification aided in the testing and optimization of the model.

4.4.2. Estimation of the Products

The model derived from the results of separating simulated feed was modified to predict the tests using FSV type fuel and the results of the Scrap Rod Runs. The results were not in accord with the predictions because the feed to the classifier in this program contained varying amounts of graphite, whereas in the preliminary tests it did not. Another contributing factor to this deviation was the varying particle size distribution between batches of a particular run. These two factors necessitated a further modification of the program to allow for carbon and varying fuel particle size distribution. The final result is a model that will predict the products of the separation of FSV type TRISO/TRISO fuel.

In the previous section on FSV type feed, the dependence upon feed rate exhibited by simulated fuel became negligible for feed rates less than 350 gm/min. For the model, a constant was used in place of the feed rate. By using this constant (150) in the model to predict the Scrap Rod Runs, large errors resulted (see Tables C-1 through C-10 in Appendix C). By increasing this constant from 150 to 325, the errors were reduced in all but two of the batches. This increase in the constant from 150 to 325

TABLE 4-10
FEED AND PRODUCT COMPOSITION

Batch No.	Feed Composition		Product Composition			
			Fines		Coarse	
	Carbon (wt %)	Particles (wt %)	Carbon (wt %)	Particles (wt %)	Carbon (wt %)	Particles (wt %)
Run No. 1						
1	39.0	61.0	46.6	53.4	23.9	76.1
2	29.7	70.3	34.9	65.1	22.9	77.1
3	23.5	76.5	29.5	70.5	14.8	85.2
4	21.8	78.2	28.3	71.7	13.8	86.2
5	6.2	93.8	9.9	90.1	4.4	95.6
Total	25.1	74.9	32.9	67.1	15.3	84.7
Run No. 2						
1	44.2	55.8	52.7	47.3	17.4	82.6
2	25.5	74.5	39.4	60.6	10.6	89.4
3	24.4	75.6	40.1	39.9	7.3	92.7
4	20.2	79.8	35.0	65.0	5.5	94.5
5	6.4	93.6	14.1	85.9	3.8	96.2
Total	24.5	75.5	40.4	59.6	7.7	92.3

represents the effect of graphite on the separation. In Section 4.1 this effect was examined and additional graphite was shown to affect separation the same way increasing feed rate does. A relationship between the effective feed rate and the actual feed rate of the particles and graphite was given. The addition of graphite to FSV type fuel had the same effect. However, in this case the effect of an increasing percentage of graphite replaced the effect of an increased feed rate. Through this change the model is now capable of predicting the separation of FSV type fuel for feed rates ranging from 0 to 350 gm/min and for concentrations of graphite ranging from 0 to 45%.

The deviation of the crossover predictions for batches 1 and 5 of Run 2 from the actual crossovers arises from the different size distributions of the feeds. This correlation can be seen by comparing Tables C-11 through C-15 in Appendix C with Figs. B-8 through B-12 in Appendix B and is illustrated by Fig. 4-26. For a given air velocity, solids feed rate, and concentration of graphite, the separation efficiency versus particle size resembles curve A of Fig. 4-26a for a balanced distribution of Fissile B and Fertile A particles (Fig. 4-26b). If a greater percentage of the feed were Fissile B (Fig. 4-26c), then the ϕ versus d curve would be represented by curve B. Conversely, if the Fertile A particles comprised the majority of the feed (Fig. 4-26d), then the ϕ versus d curve would be represented by curve C. As one mode of the distribution becomes more prominent, the separation efficiency relation is shifted in relation to particle size. This phenomenon results from the movement of the particles. If a majority of the particles are rising, then a greater percentage of the ones that would fall are entrained in the rising stream and, therefore, also rise. The same principle holds true for the situation where a majority of particles are falling. This effect is diminished when the modes of the distribution are further apart as in the case of the first Scrap Rod Run.

This modal effect was added to the model as a shift in diameter of the separation efficiency which varied linearly with the ratio of the percent

Fig. 4-26. Effect of relative size of modes upon separation efficiency

of Fissile B with the percent of Fertile A. Because of the interdependence of the effect of graphite and the effect of the size and proximity of the modes, the model was rechecked against the runs of FSV fuel without graphite. To compensate for the modal shift the graphite relation was reworked to provide a better prediction. With this final adjustment the model becomes:

Modal Shift

$$S_m = -27.4 - 160 (R_{V\beta} - R_{T\alpha}) \quad (4-14)$$

For $R_{V\beta} = 0$ or $R_{T\alpha} = 0$, $S_m [=] 0$

Graphite Influence

$$G = 100 + 9.25 R_g \quad (4-15)$$

Air Velocity Rate Shift

$$S_a = 592.2 - 123.4 V \quad (4-16)$$

Density Influence

$$\left. \begin{array}{ll} d < 520 & D = 15.2 \left(\frac{d}{100} \right)^{2.15} \\ 520 < d < 560 & D = d \\ d > 560 & D = 22.7 d^{0.507} \end{array} \right\} \quad (4-17)$$

Separation Efficiency

$$\alpha = S_m + S_a + D \quad (4-18)$$

$$\beta = e^{(25.9032 - 0.03271 \alpha)} \quad (4-19)$$

$$\gamma = 18 - \frac{4225}{(\alpha - 328)} \quad \left\{ \begin{array}{l} \text{For } \alpha < 330, \gamma [=] -300 \\ \text{For } \alpha > 576.5, \gamma [=] 1 \end{array} \right\} \quad (4-20)$$

$$\phi = \frac{G}{\beta + \gamma G} \quad \left\{ \begin{array}{l} \text{For } \phi < 0, \text{ then } \phi [=] 0 \\ \text{For } \phi > 1, \text{ then } \phi [=] 1 \end{array} \right\} \quad (4-21)$$

where [=] means set equal to,

variable d = diameter (microns),

D = density influence,

G = graphite influence,

R = weight fraction,

P = percent of feed,

S = diameter shift,

V = air velocity (m/sec),

α = intermediate value,

β = intermediate value,

γ = intermediate value,

ϕ = separation efficiency.

Subscript m denotes modal,

a denotes air velocity,

$v\beta$ denotes Fissile B,

$\tau\alpha$ denotes Fertile A.

A final run of the model gave predicted results within the range of +0.8 to -3.5 wt % of the actual or +3.3 to -6.4% error. With the ability to make accurate predictions of the separation over a variety of conditions, the prediction of the accompanying crossover was investigated.

4.4.3. Prediction of Crossover

As mentioned in Section 4.3 on FSV type fuel, the ratio of the weight of fissile particles to the total weight of particles of any size increment (denoted as the fissile ratio) increased from the coarse to the fine portion of the feed. This arose because of the density difference between fissile and fertile particles of the same size. By comparing the size distributions of the feed and the products to the resulting crossover, the relationship between the fissile ratio and size was found. Upon comparison of the three functions, the only difference found between them was the

position of the curves with respect to size. That is, the fissile ratio in the fines equalled the ratio for the feed in the next higher size increment (20μ), whereas the ratio for the coarse was the same as that for the feed but in the next lower increment. Therefore, when the ratio for the feed is known, the ratios for the fine and coarse product may be found by shifting the size up for the fine fraction and down for the coarse. When this method was applied to the runs, the crossover was predicted within +3 to -1.5 wt % or $\pm 14\%$ error.

4.4.4. Evaluation

The model was developed to simulate the pneumatic classification of simulated feed. For this simulation, the separation efficiency, ϕ , is a function of three parameters: feed rate, air velocity, and diameter. When this model was corrected to simulate FSV fuel, several changes resulted. First, since the efficiency of separation for FSV type fuel does not depend upon feed rates below 350 gm/min and the effect of an increasing percentage of graphite is the same as an increasing feed rate, the weight percent graphite was substituted for the solids feed rate. Second, the increased slope of the mean density relation resulted in the repositioning of the constant diameter lines. Third, the effect of dominate size distribution modes on the separation resulted in a variable diameter shift. Finally, the crossover prediction compensating for the density difference between equal sizes of fissile and fertile particles was added to the model.

The resulting model predicts separation and the accompanying crossover within ± 4 and ± 2 wt % of the actual values, respectively. This accuracy is sufficient for predicting the separation and crossover of FSV type fuel for design, process, and economic decisions concerning a fuel reprocessing plant.

4.5. FEEDING PERFORMANCE

In the earlier testing of the Alpine pneumatic classifier using simulated feed, the effect of feed rate on separation efficiency was pronounced (Figs. 4-7 through 4-10). For this reason two feeders were evaluated as to their suitability for metering simulated feed to the Alpine classifier.

4.5.1. Vibratory Feeder

The vibratory feeder (Fig. 4-27) supplied with the Alpine classifier had several deficiencies that were corrected. First, to eliminate fuel leakage caused by the loose fit of the bed level control gate on the feeding channel (which allowed fuel to flow around the sides and over the top), a rubber gasket was fitted to the gate providing a powder tight seal on the sides and top. Second, to lessen feed rate dependency upon the amount of material in the hopper, a funnel was fitted into the hopper with the outlet approximately 1 in. above the vibrating channel.

With these two modifications, testing proceeded to determine the feed rate accuracy and correlation with the potentiometer setting. With the hopper filled, the feed rate was measured at short time intervals (~ 2 min) over a period of 75 min. (Figure 4-28 gives the results.) The feed rate varied from 80 gm/min to 180 gm/min.

Close examination of the system revealed two factors which contributed to the feed rate inaccuracy. First, the feed rate was found to depend upon the hopper inventory. Five average feed rates were tested ranging from 145 to 206 gm/min. For each average, feed rate fluctuation was ratioed to maximum value, giving a normalized value. From Fig. 4-29, which gives the results for this normalized feed rate versus the amount in the hopper, the origin of the long term drift became obvious. As a result, feeding was discontinued before the hopper inventory dropped below 500 gm, the point at which the feed rate declines rapidly.

Fig. 4-27. Vibratory feeder

Fig. 4-28. Instantaneous feed rate of vibratory feeder

Fig. 4-29. Relationship of feed rate of vibratory feeder to material in hopper

During these tests, another dependence was discovered. The feed rate was found to depend upon the vacuum in the system, which varies as a function of air velocity. Figure 4-30 illustrates the approximate linear dependence of feed rate upon air velocity. As the vacuum increases (air velocity increases), the feeding channel is pulled down toward the feed inlet port by the flexible connector between the feeder and the classifier. This action produces a change in the vibrating frequency of the system and increases the incline of the channel. Both result in an increased feed rate.

In summary, the feed rate of the vibratory feeder depends upon the following parameters:

1. Bed level gate opening.
2. Potentiometer setting.
3. Air velocity (vacuum).
4. Incline of the feeding channel.
5. Solids level in the hopper.
6. Structural support.

No correlation between feed rate and the potentiometer setting was found due to the effects of the other variables.

4.5.2. Rotary Feeder

Because the feed rate of the vibratory feeder was affected by a large number of parameters resulting in large errors, another method of feeding was investigated: the rotary feeder (see Fig. 4-3). This is the same feeder used on the 10-cm primary burner in the product removal system (Ref. 20).

The accuracy and reproducibility of the rotary feeder were within ± 1 wt %, the relationship between feed rate and rpm was linear from 100 to 300

Fig. 4-30. Relationship between feed rate of vibratory feeder and air velocity rate (vacuum)

gm/min (see Fig. 4-31), and the feed rate was unaffected by air velocity (vacuum), solids level in the hopper, or the structural support. The only parameters found to affect the rotary feeder's feed rate were turning speed and powder bulk density.

To compare the performance on the classifier of the rotary feeder with the vibratory one, the separation efficiency of the rotary was overlaid onto Figs. 4-11 and 4-12 (which describe the vibratory feeder), giving Figs. 4-32 and 4-33. From examination of these figures, the effect on separability can be determined. If the overlay produces a vertical line, then the feeders are the same. If, however, the overlay has a negative slope, the rotary feeder gives a better separation, and a positive slope indicates a poorer separation.

At 100 gm/min (Fig. 4-32), the run at 3.15 m/sec showed a slight improvement in separation; at 3.70 m/sec no improvement occurred. The effective air velocity (at $\phi = 50\%$) increased for the 3.15 m/sec run to 3.25 m/sec; for the 3.70 m/sec run it decreased to 3.40 m/sec. This apparent decrease in sensitivity to air velocity change becomes even more apparent in Fig. 4-33, where the runs at 3.15 and 3.70 m/sec at 300 gm/min feed rate converge to 3.32 m/sec. These runs also exhibit a slight decrease in separability. Because of this insensitivity to changes in air velocity, the vibratory type of feeder was chosen over the rotary. To improve the accuracy of the vibratory feeder, a solids feed rate sensor is recommended in a closed control loop (Ref. 21).

Fig. 4-31. Relationship between feed rate of rotary feeder and its rpm

Fig. 4-32. Comparison of rotary feeder performance and vibratory feeder performance at 100 g/min

Fig. 4-33. Comparison of rotary feeder performance and vibratory feeder performance at 300 g/min

5. MODULAR PNEUMATIC CLASSIFIER

The entire work establishing the relationship between the operating parameters of pneumatic classification and crossover used the Alpine Multiplex Zigzag Classifier (Fig. 4-1). To increase the understanding of pneumatic classification and to verify the design of the Alpine, a modular classifier was constructed. Figures F-1 through F-6 in Appendix F detail the individual components of the unit, with Figs. 5-1 and 5-2 giving an assembled view. Where possible, the design and the dimensions of the modular unit were taken from the Alpine except that the zigzag column was sectioned and a baffle was installed in the coarse product take-off cone. By making the column in sections, the total height and the position of feed could be varied, permitting extensive parametric studies in the area of pneumatic classification of HTGR fuel.

The studies centered around finding the optimum height and feed point for HTGR fuel. Of the numerous combinations of height and position of the feed zone, only a few were explored. Figure 5-3 shows the six different configurations studied. For each conformation, one air velocity (3.70 m/sec) and four feed rates (100, 300, 500, and 700 gm/min) were used. From these 24 tests, the optimum design was deduced for TRISO/TRISO fuel.

5.1. FEED

In the 24 parametric tests on the modular pneumatic classifier, a common feed was utilized. With the availability of both simulated and FSV type fuel, the choice was based on previous testing. Simulated fuel was picked for the following reasons:

Fig. 5-1. Modular pneumatic classifier

Fig. 5-2. Schematic of modular pneumatic classifier

Fig. 5-3. Height and feed position configurations of modular classifier investigated

1. It was more sensitive to changes in the operating parameters of the Alpine classifier.
2. Its operating characteristics were best known.

The characteristics of this feed are covered in Section 4.2, Simulated Feed.

5.2. RESULTS

5.2.1. Effect of Height

To determine the effect of height on the efficiency of separation, four configurations were used (Figs. 5-3a, 5-3b, 5-3c, and 5-3e). In all of these arrangements, the feed position remained in the center. An equal number of sections was added above and below it to increase the height from the size of the Alpine classifier to over twice as high.

For evaluating the test, the separation efficiency data were overlaid on Figs. 4-11, 4-12, and 4-13. For the overlay, the feed rate and the separation efficiency for each size increment were used to locate the curve. This curve represents an equivalent air velocity at $\phi = 0.50$, and as this line deviates from the vertical, the separability of the modular classifier deviates from that of the Alpine. A negatively sloped line indicates an improved separation, while a positive slope indicates a poorer separation. Figures 5-4 through 5-6 illustrate the results of the overlaying for three feed rates, 100, 300, and 500 gm/min. From the comparison of these figures, the effect of the height of the column was found to depend upon the feed rate. At 100 gm/min (Fig. 5-4), there was no difference in the slopes of the curves for the four different heights. However, at 300 gm/min (Fig. 5-5) the efficiency began to improve for the coarse region ($\phi < 0.50$), and at 500 gm/min (Fig. 5-6) there was improvement over the entire range. This indicates the increased height is only needed for increased feed rates. Reference 22 states that increased height above five diameters has little effect upon separation. However, those tests

Fig. 5-4. Comparison with respect to height of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 100 g/min

Fig. 5-5. Comparison with respect to height of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 300 g/min

Fig. 5-6. Comparison with respect to height of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 500 g/min

were on a much larger scale with more tolerance allowed in the separation efficiency. For the classification of HTGR fuel a higher column will allow higher feed rates and therefore greater capacity.

5.2.2. Effect of Feed Position

The same method used to determine the effect of height was used to determine the effect of the feed position. The data which resulted from the tests of configurations 5-3d, 5-3e, and 5-3f were overlaid on Figs. 4-11, 4-12, and 4-13 and represented in Figs. 5-7, 5-8, and 5-9. Again, when the figures and curves are compared, the effect of feed position is negligible at a feed rate of 100 gm/min (Fig. 5-7), but as the feed rates increase, the effect of the feed position becomes clear. In Fig. 5-8, the effect of raising the feed zone can be evaluated. As would be expected, the separation efficiency for the coarse region ($\phi > 0.50$) improved while that for the fine region ($\phi < 0.50$) worsened. In Fig. 5-9, the effect of lowering the feed zone was found to give the opposite effect of raising the zone. Again, the effect of the changes in the design of the classifier was not seen until the higher feed rates were tested.

5.3. GENERAL

Having thus established the effects of the column height and the position of the feed zone, it can be seen that the one common point in all figures is that in every case the modular classifier gave better separation in the coarse region than the Alpine classifier. This has been attributed to the addition of the baffle to the coarse product takeoff cone. (See Figs. 5-4 through 5-9.)

Fig. 5-7. Comparison with respect to feed position of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 100 g/min

Fig. 5-8. Comparison with respect to feed position of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 300 g/min

Fig. 5-9. Comparison with respect to feed position of separation efficiency of modular classifier configurations with that of Alpine classifier at a constant solids feed rate of 500 g/min

6. SIEVING

The preceding sections have dealt with the pneumatic classification of HTGR fuel particles. For comparison, sieving was investigated. This investigation involved establishing the blinding rate of the screen, the throughput of the particles, the efficiency of separation, and comparison of these with their counterparts in pneumatic classification.

For the test three fuel compositions were used: simulated feed, Fissile A/Fertile B, and Fissile B/Fertile A. The first was used for comparison with the majority of pneumatic classification tests. The second and third types represent the two extreme combinations of distributions (minimum and maximum overlapping) encountered. The characteristics of these feeds have been discussed in Sections 4.1, 4.2, and 4.3.

6.1. DESCRIPTION OF EXPERIMENTAL PROCEDURE

All of the experiments were carried out on a Rotap sieve shaker using a 500 μ , 8 in. Tyler sieve to separate the fissile and fertile streams. A typical run entailed loading 200 gm of particles onto the screen and shaking it for a set time interval which varied from 5 min upward in multiples of five. When shaking was completed, the undersize and oversize fractions were weighed along with the amount accumulated on the screen. Without cleaning the screen, the fines were replaced on the screen and the shaking continued for a prescribed length of time. When the change in weight of the products was greater than 1 wt %/5 min, this procedure was repeated. When the weight change was less than 1%, the two fractions were removed and an additional 200 gm of particles loaded onto the screen without cleaning it.

This procedure was followed until the percent passing through the screen plotted against time yielded identical results for the last two

charges. Similar runs were made for 400 and 800 gm charges, and the series was repeated for the various fuel compositions.

In this manner a relationship between the type of feed, solids loading, blinding rate, throughput, and separation efficiency was found. Once this was established, a comparison between pneumatic classification and sieving was drawn.

6.2. BLINDING RATE

Basically, blinding rate describes how fast the screen openings plug with feed material. For irregularly shaped particles this rate is low, while for spherical particles like HTGR fuel particles the rate is high. This rate can be described either as the percent of the screen that is filled or as the weight percent of the feed passing through the screen, and these in turn can be described as functions either of the sieving time or of the cumulative weight of the feed passing through the screen. In this report, the percent of screen filled versus the cumulative weight of undersize feed will be used as the blinding rate.

Figures 6-1 through 6-3 give the blinding rates for the various types of feed. Simulated feed and Fissile B/Fertile A feed have similarly shaped curves; both approach the limiting value of 98 to 99% filled after only 225 to 325 gm of undersize feed have been collected. On the other hand, Fissile A/Fertile B feed has a much slower blinding rate, and the end result of 99% plugged will be achieved only after approximately 1700 gm of undersize feed have been collected.

6.3. THROUGHPUT

Throughput for a screen is defined as mass per unit screen area per unit time; this mass may be either the total feed weight or the feed weight

Fig. 6-1. Blinding rate of simulated feed

Fig. 6-2. Blinding rate of Fissile B - Fertile A FSV fuel

Fig. 6-3. Blinding rate of Fissile A - Fertile B FSV fuel

passing through the screen. The throughput of a screen is proportional to the load on the screen, the blinding rate of the screen, and the amplitude and frequency of the shaker vibration. Basically, the throughput of a screen parallels the blinding rate. This becomes apparent by comparing Figs. 6-4 through 6-9 with Figs. 6-1 through 6-3. Table 6-1 gives the throughput for the various runs.

From these figures two distinct rates can be seen. The first rate is controlled by the probability of a particle smaller than the opening coming in contact with the opening (Ref. 23). During this first rate the mean size of the particles passing through is greater than that specified for the screen; however, as the screen becomes filled, the mean size reduces to the value specified for the screen. At this point the second rate becomes controlling.

Whereas the first rate constant depends upon the number of particles per unit time that are close in size to the aperture, the second rate constant depends upon the frequency and amplitude of the shaker, and the mass of particles on the screen. The second rate results from an equilibrium in which the rate at which holes become plugged is equal to the rate at which they become unplugged. The second rate decreases with time as more and more holes become permanently plugged until the amount passing through the screen approaches zero.

6.4. EFFICIENCY OF SEPARATION

As defined earlier, the efficiency of separation, ϕ , is the ratio of the coarse product to the feed for a specified size interval. Figures 6-10 through 6-15 give the efficiency curves for the first and last charges for each run. A comparison of the curves for the first and last charges shows that the cut point ($\phi = 50$) decreases to a value equal to the screen size as the screen blinds with particles. In addition to the cut point

Fig. 6-4. Throughput of simulated feed, 200 gm charge

Fig. 6-5. Throughput of simulated feed, 400 gm charge

Fig. 6-6. Throughput of simulated feed, 800 gm charge

6-10

Fig. 6-7. Throughput of Fissile B - Fertile A FSV fuel, 200 gm charge

Fig. 6-8. Throughput of Fissile B - Fertile A FSV fuel, 400 gm charge

Fig. 6-9. Throughput of Fissile A - Fertile B FSV fuel, 800 g charge

TABLE 6-1
THROUGHPUT OF VARIOUS FEEDS

Type of Feed	Charge Size (gm)	1st Rate (gm/min-in. ²)	2nd Rate (gm/min-in. ²)	3rd Rate (gm/min-in. ²)
Simulated	200	0.41	0.047	--
	400	1.03	0.075	--
	800	1.68	0.067	--
Fissile B-Fertile A	200	1.33	0.024	0.019
	400	1.33	0.040	--
Fissile A-Fertile B	800	1.61	--	--

Fig. 6-10. Separation efficiency of simulated feed with 200 gm charge

Fig. 6-11. Separation efficiency of simulated feed with 400 gm charge

Fig. 6-12. Separation efficiency of simulated feed with 800 gm charge

Fig. 6-13. Separation efficiency of Fissile B - Fertile A FSV fuel with 400 gm charge

Fig. 6-14. Separation efficiency of Fissile B - Fertile A FSV fuel with 200 gm charge

Fig. 6-15. Separation efficiency of Fissile A - Fertile B FSV fuel with 800 gm charge

decreasing, the slope of the curve also decreases, indicating a poorer quality separation. In one case, Fissile B/Fertile A with a 200 gm charge, the final separation was extremely poor. Finally, Fig. 6-16 gives the size distribution of the particles that were trapped in the screen.

6.5. COMPARISON OF SIEVING WITH PNEUMATIC CLASSIFICATION

Sieving and pneumatic classification each have certain advantages and disadvantages which governed the final selection of which separation method to use. Sieving during the first and second rate periods has a better separation efficiency than pneumatic classification. Unfortunately, when permanent blinding occurs, as in Fig. 6-14, the efficiency of screening becomes worse than that of pneumatic classification. Further, as the screen becomes more and more blind, the 50% cut point shifts downward in diameter. This causes a varying quality and accuracy of separation over the life of the screen, which in effect is less desirable than poorer separation efficiency. Pneumatic classification has been chosen over sieving because:

1. The pneumatic classifier's cut point only changes when the air velocity changes or the particle size distribution changes.
2. The cut point of the classifier can be controlled by the air flow rate and thereby changed as needed, whereas the screen has only one cut point.
3. As the screen becomes permanently plugged, it must be removed from service.

Fig. 6-16. Size distribution of particles plugging a 500 micron sieve

7. DATA REDUCTION AND ANALYSIS

7.1. PARTICLE SIZE DISTRIBUTION

The conclusions drawn in this report derive mainly from the analysis and reduction of particle size distributions for the fine and coarse products. The analysis of these products was accomplished using a coated particle analyzer which operates on the assumption that the particles are spherical. The reduction of the data relied on the density versus size relationship, which was assumed to be linear. Thus, the accuracy and validity of the test results depend on the correspondence of these two assumptions with reality.

The coated particle analyzer sizes a particle by dropping it through a collimated light beam which causes the particle's image to pass across a $100 \pm 0.1 \mu$ wide slit. The light passing through the slit is measured by a photodetector. A logic circuit takes the maximum light blockage for the particle and transmits a corresponding pulse to a PDP 8 computer. The computer relates the pulse to a diameter (assuming a spherical shape), and adds one to a counting register for the corresponding size. The registers cover a size range from 300 to 1500 μ in 2 μ increments. Due to the speed of the instrument (approximately 20 particles per second), a statistically representative sample of 5000 particles (Ref. 24) can be analyzed in a short period of time. The results of this analysis are in the form of number of particles per size increment (e.g., 48 particles within the range of 420 to 439 μ). A detailed description of the coated particle analyzer and a sample of its output are given in Appendix D.

To reduce all these data to a usable form, a computer program (Appendix E) was written to accept the data as they came from the analyzer. The program first calculates the number percent size distribution and then converts the number percent size distribution to a volume percent size

distribution using a volume ratio.* Finally, this is converted to a weight percent size distribution using a density ratio.** The weight percent size distribution is needed for a comparison of the feed with the fine and coarse products, which are related by weight fraction. The comparison is made by proportioning the fine and coarse products, adding their weight distributions to obtain the distribution for the feed, and dividing the coarse product weight percent size distribution by the feed weight percent size distribution to obtain the fraction of the feed that becomes the coarse product for each size increment. This value, ϕ , describes the separation obtainable for a given feed under certain conditions.

For a discussion of the possible errors, see Section 4.2. Appendix E gives a typical printout for the program.

7.2. CROSSOVER ANALYSIS

The percent crossover of the fissile and fertile streams was calculated by two methods. The first method used a wet chemical determination of thorium and uranium in the fine and coarse products to establish the net crossover of these streams. The second method compared the size distributions of the feed and the products. Of the two methods, the former is the more accurate because it depends only upon the accuracy of the sampling, and the analysis and the auxiliary data needed, whereas, in addition to the above sources of error, the latter method depends upon the accuracy of the density relation.

7.2.1. Wet Chemical Method

After analyzing the samples for uranium and thorium content, the heavy metal from the fissile and the fertile particles in the products was calculated as follows:

* Volume Ratio - the average diameter of a size increment cubed divided by the sum of all of the elements' diameters cubed.

** Density Ratio - the increment's average density divided by the sum of all of the elements' average density.

Sample contains $\begin{cases} A\% \text{ U} \\ B\% \text{ Th} \end{cases}$

$$r = \frac{\% \text{ Th}}{\% \text{ U}} \text{ in fissile (App. A)}$$

Then, for every 100 gm

$$\text{Fissile heavy metal} = A\% + A\% \cdot r$$

and

$$\text{Fertile heavy metal} = B\% - A\% \cdot r$$

From this analysis, the heavy metal weight of the fissile particles in the fine and coarse product is obtained, and therefore the weight percent of fissile heavy metal lost to the coarse stream is known. This logic also applies to the fertile stream.

The error of this analysis depends upon the sum of the errors for each step. The error of riffle splitting has been shown to be as much as ± 5.35 wt % (Refs. 25 and 26), while the accuracy of the thorium and uranium determinations was within $\pm 0.1\%$ (Ref. 27). The final source of error is in the ratio of the uranium to thorium as given in the Quality Assurance data. When this ratio was used there was no error, but in the calculations for the Scrap Rod Run (Ref. 4), several of the ratios in the first runs were greater than the value given. The maximum deviation from the Quality Assurance data was $+2.0\%$. Since lack of the proper amount of thorium is the only direction in which error can be detected, the negative error cannot be checked. However, if the value in the Quality Assurance data given is assumed to be an average, then the $+2.0\%$ deviation should have a -2.0% counterpart. The possibility of attributing this error to sampling does not exist since the uranium and thorium are intimately mixed in the kernel. The sum of these errors gives a total error of $\pm 7.45\%$. Applied to a 10.00 wt % crossover, this error yields a range of 9.25 to 10.75.

7.2.2. Particle Size Analysis Method

This method defines crossover as the loss of either fissile or fertile particles to the other stream. The crossover obtained from particle size analysis has the sources of error previously mentioned. These arise because the prediction of the crossover from size distribution analysis involves knowing the weight ratios of the fissile and fertile particles to the total feed for each size increment. The sum of the fissile and fertile ratios is unity. These ratios were found by a trial and error method utilizing wet chemistry data in conjunction with size distribution data. Once the ratios were established, the correlation between them and the resulting crossover was determined.

The initial prediction for the fissile ratio resulted from fitting the overlap of the smooth curves of Fig. B-7 in Appendix B to the fissile and the fertile modes. Using this ratio, the crossover for FSV fuel and the Scrap Rod Run was estimated from Eqs. 4-9, 4-10, and 4-11. The different densities for the fissile and fertile particles caused large errors (+60.6% for the fissile loss and +9.4% for the fertile loss). By shifting the fissile ratio up by 20 μ and the fertile ratio down by 20 μ , the error was reduced to +12% for the fissile loss and -14% for the fertile loss. Then minor adjustments in the fissile and fertile ratios to give a smooth transition led to a final error of +14%. This final adjustment yielded the particle size distributions for Fissile B and Fertile A fuel (Fig. 4-6).

8. SUMMARY

In most solid-solid separation processes, the accuracy of the separation is not as critical as it is in the separation of the fissile and fertile fuel particles used in HTGRs. The existing theory on separation was not adequate for the prediction of this separation because of both the tight separation limits imposed by the fuel cycle economics (Ref. 1) and the closeness of the particle size distributions. For these two reasons, the efficiency of separation of fissile from fertile fuel particles was determined experimentally and an empirical matrix model found that would be able to predict the behavior of this separation. The basic equations governing the model were established from experimental data on a simulated fuel distribution because of the unavailability of FSV fuel.

The relationship that was established was between the separation efficiency (ϕ) and the solids feed rate (F) for each size increment and for several air velocities or

$$\phi = \frac{F}{A + BF} \quad (8-1)$$

The relationship between separation efficiency and feed rate which occurs with simulated fuel and is described by this equation is as follows. Due to the increased concentration of particles in the classifier with increased feed rate, the separation efficiency worsens and the cut point shifts downward in size.

The constants A and B were then related to diameter (d) at one air velocity (V). Then the change in air velocity was incorporated as a diameter shift (D) giving the following relationships:

$$D = 592.2 - 123.4 V + d \quad (8-2)$$

$$A = e^{(28.52 - 0.03271 D)} \quad (8-3)$$

$$B = 18 - \frac{4225}{(D - 408)} \quad \text{For } \begin{matrix} D < 410, B [=] - 300 \\ D > 656.5, B [=] 1 \end{matrix} \quad (8-4)$$

These four equations were the starting point for the model. Once these equations were formulated, the effect of graphite and the effect of the relative size of the distribution modes were incorporated. After a few tests, which indicated the presence of graphite gave similar results to tests without graphite only at higher feed rates, were run, FSV fuel became available.

With FSV type fuel available for testing, the experiments shifted to the study of this feed material to determine if there were any differences in the separation. The first difference noted was the shift and the spacing of the constant diameter lines. This shift was explained by the shift in the intersection of the size distributions and by the increased slope of the relationship between density and particle size. After making this correction, the lack of dependence upon feed rate, which also stems from the increased slope of the density relation, was noticed (Ref. 14) and the feed rate term in Eq. 8-1 was replaced by a constant.

The next step in refining the model occurred in predicting the results of the Scrap Rod Program. The ten feed batches used contained varying particle size distributions and varying amounts of carbon. When the runs which had similar distribution to the earlier FSV fuel were used, the prediction of the separation was good only when the constant that replaced the variable feed rate was increased. This increase was related to the addition of graphite in the feed. When using simulated feed earlier, similar results had occurred. The constant that replaced the feed rate in the simulated feed model correctly described the effect of graphite on the separation of FSV fuel, and a linear relationship between this constant and the percent graphite was added to the model.

Once the influence of graphite was established, the effect stemming from the relative breadth of the size distribution modes could be investigated. This investigation showed that the separation efficiency versus particle size shifted toward the smaller mode in an amount that is proportional to the net difference in the weight of the Fissile B and Fertile A particles in the feed. This result agrees with the observations made earlier in connection with the runs using simulated feed. With this last adjustment the model can now predict the separation within the range of +3.3 to -6.4% error. The model has as inputs the air velocity, percent carbon, and percent Fissile A, Fissile B, Fertile A, and Fertile B.

The final addition to the model converts separation parameters to percent crossover of the fissile and fertile streams. For this, the percent fissile in a particular size increment in the fine and coarse products must be related to the ratio in the feed. Fortunately, the relationship was straightforward. First, the fissile ratio of the fine product for any size increment is equal to the ratio for a 20 μ larger size in the feed. The reverse is the case for the coarse. That is, the fissile ratio is equal to the ratio for a 20 μ smaller size in the feed. With this added to the model, the percent crossover calculated was within $\pm 14\%$ error (e.g., if predicted crossover is 10 wt %, actual crossover will be between 8.6 and 11.4 wt %). The necessity for this shift supports the contention that on the average a fissile particle of the same size as a fertile particle is less dense.

The use of this model is its application to the reprocessing of FSV fuel. By knowing the particle size distribution of any batch, the optimum air velocity to give the least crossover can be determined. This crossover can then be related directly to the cost penalty. In the Scrap Rod Program, the two extreme size distributions encountered, Fissile A - Fertile A - Fertile B and Fissile B - Fertile A, were processed through the classification step of the head-end flowsheet. The fissile and fertile crossover which resulted from misclassification of whole particles was 2.8 and 0.3 wt % for the spread distribution, and 14.6 and 9.1 wt % for the overlapping distribution. An additional source of crossover is that due to the dust of

broken particles, a majority of which was classified with the fissile stream, giving a total fissile crossover of 3.4 and 8.6 wt % for the first case and 14.8 and 13.4 wt % for the second case. Cost penalties of 0.05 mils/kWhr and 0.09 mils/kWhr, respectively, can be attributed to the above total crossovers. (These figures are taken from the upper curves of Figs. 2-1 and 2-2.) In this manner, the economics of reprocessing can be estimated with greater accuracy, and optimum separation of the fuel can be assured. The only information required is the percent carbon in the feed and the amount of Fissile A, Fissile B, Fertile A, and Fertile B fuel in the feed. The former has been imposed by the design criteria for the secondary burner on the primary burner, and the latter may be obtained from Quality Assurance data on FSV fuel (Ref. 28).

With the separation process characterized for a set height and feed point, tests were conducted to determine the effect of height and feed point. First it was found that the increased height of the column gave no improvement of feed rates of around 100 gm/min. However, as the rate increased toward 500 gm/min, a marked improvement was noted. As the feed point was moved up, the efficiency of separation improved for both coarse and fine fractions. The reverse occurred when the feed point was lowered.

Up to this point the discussion has been concerned with the separation of the fissile from the fertile fuel after the fuel leaves the primary burner and before it enters the roll crushers. One other particulate system was investigated: crushed fertile particles. By classifying the fuel as it leaves the roll crushers, 84 wt % of the SiC hulls and 89 wt % of the carbon coatings can be removed from the kernels while only losing 0.5 wt % heavy metal. This has four advantages:

1. The load on the centrifuge would be reduced by a factor of six.
2. The carbon coatings, which are laden with fission products, could be diverted for disposal as a solid waste.
3. The burning load on the secondary burner would be reduced.

4. The liquid waste from the aqueous separation would be reduced.

However, this would require the separation of the heavy metal dust resulting from broken particles before the roll crusher. The dust would then be routed to the secondary burner. The weight percent broken particles, as given in Ref. 4, is

Fissile A	- 3.7 wt %
Fissile B	- 3.2 wt %
Fertile A	- 7.5 wt %
Fertile A & B	- 17.1 wt %

with an average of 0.7 wt % broken in the classifier.

Extensive testing showed that although sieving leads to a better instantaneous separation efficiency, the overall separation efficiency of sieving is poorer than separation by pneumatic classification because the cut point decreases with time as the screen becomes plugged. Sieving also has the disadvantage of permanent plugging of the screen openings so that after a period of time the screen must be replaced. Further, the cut point of the screen cannot be changed except by replacement, and a 64 in. screen is required to give a 200 gm/min throughput. Finally, the screener is harder to maintain because of the larger number of moving parts. Sieving was therefore eliminated as an alternative and pneumatic classification was adopted as the method of choice.

9. RECOMMENDATIONS

For the separation of HTGR fissile and fertile TRISO/TRISO fuel it is recommended that:

1. The method be pneumatic classification using the zigzag configuration.
2. The height and feed point of the classifier be of the configuration of Fig. 5-4e.
3. The cross sectional dimensions of the prototype classifier be increased to 1.5 in. x 3.0 in. from 1.5 in. x 1.5 in. with the 3.0 in. dimension corresponding to that of the feed opening.
4. A baffle be installed in the coarse product take-off cone to improve the separation efficiency for the coarse fraction.
5. A vibratory feeder be used with a solids flow rate sensor coupled in a closed control loop.

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APPENDIX A

ROD PROPERTIES

ROD PROPERTIES

<u>Batch No.</u>	<u>CR-14-N60126-3</u>		<u>CR-14-K30152-6</u>		<u>CR-14-K14228-13</u>		
Fissile A-Batch No. CU6A-	--		3198C	6196C	1274C		
Weight (gm/rod)	--		2.82	2.38	3.22		
Fissile B-Batch No. CU6B-	6049C	6050C	--		--		
Weight (gm/rod)	1.95	1.94	--		--		
Fertile A-Batch No. CT6A-	6056C	6064C	3087C		--		
Weight (gm/rod)	5.39	0.94	2.37		--		
Fertile B-Batch No. CT6B-	--		3016C		1020C	1030C	1032C
Weight (gm/rod)	--		2.45		2.05	2.89	2.96
Estimated Cross-Over (Wt.%)	9		2		<1		
Uranium to Thorium Ratio in the Fissile	0.2346		0.2359		0.2408		
Packing Fraction	61.0		61.5		61.6		
Electrical Resistivity (% < 0.5)	100.0		100.0		100.0		
Matrix Uniformity Min.	23		21		26		
Max.	24		32		34		
Volume % Macro.	39		24		35		
Diameter	0.488		0.488		0.489		
Length	1.940		1.940		1.950		
End Cap	0.07		0.13		0.13		
Fuel Homogeneity Mean	1.040		1.060		1.000		
Std. Deviation	0.020		0.060		0.050		
Uranium Weight Mean	0.2169		0.1786		0.1298		
(gm/rod) Std. Deviation	0.003		0.007		0.003		
Thorium Weight Mean	3.377		3.154		4.621		
(gm/rod) Std. Deviation	0.06		0.07		0.10		
Carbon Weight (gm/rod)	6.86		6.71		6.50		
Silicon Weight (gm/rod)	1.25		1.46		1.35		

<u>Batch No.</u>	<u>CR-14-N60126-3</u>	<u>CR-14-K30152-6</u>	<u>CR-14-K14228-13</u>
Surface Contamination			
Fission Gas Release (R/B)	9×10^{-6}	3.3×10^{-5}	8.5×10^{-6}
Thorium (gm/gm)	3.9×10^{-5}	2.4×10^{-4}	1.2×10^{-4}
Broken SiC			
Uranium (gm/gm)	5.5×10^{-4}	0	0
Thorium (gm/gm)	6.2×10^{-3}	0	0
Impurities (ppm)			
Boron Equivalent	2	2	2
Iron	40	40	40
Sulfur	520	100	1140
Titanium	40	40	40
Vanadium	40	40	40
Hydrogen	30	1	460
Ash	1600	2300	1470
Water	1	1	2
Production Status	3	3	AA

APPENDIX B

PARTICLE SIZE DISTRIBUTIONS OF PRODUCTS FROM
SCRAP ROD PROGRAM

Fig. B-1. Particle size distribution for Scrap Rod Run No. 1, batch combination

B-4

Fig. B-2. Particle size distribution, Scrap Rod Run No. 1, Batch No. 1

B-5

Fig. B-3. Particle size distribution, Scrap Rod Run No. 1, Batch No. 2

B-6

Fig. B-4. Particle size distribution, Scrap Rod Run No. 1, Batch No. 3

B-7

Fig. B-5. Particle Size distribution, Scrap Rod Run No. 1, Batch No. 4

B-8

Fig. B-6. Particle size distribution, Scrap Rod Run No. 1, Batch No. 5

Fig. B-7. Particle size distribution, Scrap Rod Run No. 2, batch combination

B-10

Fig. B-8. Particle size distribution, Scrap Rod Run No. 2, Batch No. 1

Fig. B-9. Particle size distribution, Scrap Rod Run No. 2, Batch No. 2

B-12

Fig. B-10. Particle size distribution, Scrap Rod Run No. 2, Batch No. 3

B-13

Fig. B-11. Particle size distribution, Scrap Rod Run No. 2, Batch No. 4

B-14

Fig. B-12. Particle size distribution, Scrap Rod Run No. 2, Batch No. 5

APPENDIX C

PREDICTIONS OF SEPARATIONS FOR SCRAP ROD RUNS

TABLE C-1
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 1, BATCH NO. 1
(Constant = 150.0, Air Velocity = 2.97 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.97	1.0	1.0	0.0	0.0	0.0	-0.0
320	3.38	3.4	3.4	0.0	0.0	0.0	-0.0
340	9.06	9.0	9.0	0.0	0.0	0.0	-0.0
360	16.08	16.0	16.0	-0.0	0.0	0.1	0.0
380	13.98	13.9	13.8	-0.0	0.1	0.1	0.0
400	8.68	8.5	8.4	-0.1	0.2	0.2	0.1
420	3.99	3.8	3.7	-0.1	0.2	0.3	0.1
440	1.51	1.3	1.2	-0.1	0.2	0.3	0.1
460	1.13	0.7	0.6	-0.1	0.4	0.5	0.1
480	1.83	1.1	0.5	-0.6	0.8	1.4	0.6
500	1.60	0.0	0.1	0.1	1.6	1.5	-0.1
520	2.22	0.0	0.1	0.1	2.2	2.2	-0.1
540	2.93	0.0	0.0	0.0	2.9	2.9	-0.0
560	3.60	0.0	0.0	0.0	3.6	3.6	-0.0
580	3.83	0.0	0.0	0.0	3.8	3.8	-0.0
600	4.24	0.0	0.0	0.0	4.2	4.2	-0.0
620	4.48	0.0	0.0	0.0	4.5	4.5	-0.0
640	4.29	0.0	0.0	0.0	4.3	4.3	-0.0
660	3.86	0.0	0.0	0.0	3.9	3.9	-0.0
680	3.06	0.0	0.0	0.0	3.1	3.1	-0.0
700	2.09	0.0	0.0	0.0	2.1	2.1	-0.0
720	1.41	0.0	0.0	0.0	1.4	1.4	-0.0
740	0.87	0.0	0.0	0.0	0.9	0.9	-0.0
760	0.34	0.0	0.0	0.0	0.3	0.3	-0.0
780	0.57	0.0	0.0	0.0	0.6	0.6	-0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	58.6	58.0	-0.6	41.4	42.0	0.6

TABLE C-2
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 1, BATCH NO. 2
(Constant = 150.0, Air Velocity = 2.97 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	1.56	1.6	1.6	-0.0	0.0	0.0	0.0
320	4.64	4.6	4.6	0.0	0.0	0.0	-0.0
340	10.00	10.0	10.0	0.0	0.0	0.0	-0.0
360	15.12	15.0	15.1	0.1	0.1	0.1	-0.1
380	11.51	11.3	11.4	0.1	0.2	0.1	-0.1
400	7.02	6.6	6.8	0.2	0.4	0.2	-0.2
420	2.73	2.5	2.5	0.0	0.3	0.2	-0.0
440	0.92	0.6	0.7	0.1	0.3	0.2	-0.1
460	1.32	0.8	0.7	-0.1	0.5	0.6	0.1
480	1.05	0.0	0.3	0.3	1.1	0.8	-0.3
500	1.59	0.0	0.1	0.1	1.6	1.5	-0.1
520	2.39	0.0	0.1	0.1	2.4	2.3	-0.1
540	3.15	0.0	0.0	0.0	3.2	3.1	-0.0
560	3.92	0.0	0.0	0.0	3.9	3.9	-0.0
580	4.28	0.0	0.0	0.0	4.3	4.3	-0.0
600	4.54	0.0	0.0	0.0	4.5	4.5	-0.0
620	5.07	0.0	0.0	0.0	5.1	5.1	-0.0
640	5.14	0.0	0.0	0.0	5.1	5.1	-0.0
660	4.70	0.0	0.0	0.0	4.7	4.7	-0.0
680	3.33	0.0	0.0	0.0	3.3	3.3	-0.0
700	2.33	0.0	0.0	0.0	2.3	2.3	-0.0
720	1.42	0.0	0.0	0.0	1.4	1.4	-0.0
740	0.80	0.0	0.0	0.0	0.8	0.8	-0.0
760	0.60	0.0	0.0	0.0	0.6	0.6	-0.0
780	0.87	0.0	0.0	0.0	0.9	0.9	-0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	53.0	54.1	1.1	47.0	45.9	-1.1

TABLE C-3
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 1, BATCH NO. 3
(Constant = 150.0, Air Velocity = 2.97 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	1.20	1.2	1.2	-0.0	0.0	0.0	0.0
320	3.67	3.7	3.7	-0.0	0.0	0.0	0.0
340	9.43	9.4	9.4	-0.0	0.0	0.0	0.0
360	15.68	15.7	15.6	-0.1	0.0	0.1	0.1
380	12.70	12.6	12.6	-0.0	0.1	0.1	0.0
400	6.89	6.8	6.7	-0.1	0.1	0.2	0.1
420	2.59	2.5	2.4	-0.2	0.0	0.2	0.2
440	1.02	0.9	0.8	-0.1	0.1	0.2	0.1
460	0.86	0.5	0.5	0.0	0.4	0.4	-0.0
480	1.59	0.7	0.4	-0.3	0.9	1.2	0.3
500	2.66	1.2	0.2	-1.0	1.5	2.4	1.0
520	2.41	0.0	0.1	0.1	2.4	2.3	-0.1
540	3.03	0.0	0.0	0.0	3.0	3.0	-0.0
560	3.60	0.0	0.0	0.0	3.6	3.6	-0.0
580	4.04	0.0	0.0	0.0	4.0	4.0	-0.0
600	4.78	0.0	0.0	0.0	4.8	4.8	-0.0
620	5.05	0.0	0.0	0.0	5.1	5.0	-0.0
640	4.91	0.0	0.0	0.0	4.9	4.9	-0.0
660	4.50	0.0	0.0	0.0	4.5	4.5	-0.0
680	3.72	0.0	0.0	0.0	3.7	3.7	-0.0
700	2.27	0.0	0.0	0.0	2.3	2.3	-0.0
720	1.62	0.0	0.0	0.0	1.6	1.6	-0.0
740	0.75	0.0	0.0	0.0	0.7	0.7	-0.0
760	1.04	0.0	0.0	0.0	1.0	1.0	-0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	55.2	53.7	-1.5	44.8	46.3	1.5

TABLE C-4
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 1, BATCH NO. 4
(Constant = 150.0, Air Velocity = 2.97 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	1.27	1.3	1.3	-0.0	0.0	0.0	0.0
320	3.66	3.7	3.7	-0.0	0.0	0.0	0.0
340	8.78	8.8	8.8	0.0	0.0	0.0	-0.0
360	14.41	14.4	14.4	-0.0	0.0	0.1	0.0
380	11.44	11.3	11.3	0.0	0.1	0.1	-0.0
400	6.92	6.7	6.7	0.1	0.3	0.2	-0.1
420	3.15	2.9	2.9	0.0	0.3	0.2	-0.0
440	1.17	1.0	0.9	-0.0	0.2	0.2	0.0
460	0.83	0.4	0.5	0.0	0.4	0.4	-0.0
480	1.51	0.6	0.4	-0.2	0.9	1.1	0.2
500	1.53	0.0	0.1	0.1	1.5	1.4	-0.1
520	2.45	0.0	0.1	0.1	2.4	2.4	-0.1
540	2.98	0.0	0.0	0.0	3.0	2.9	-0.0
560	3.78	0.0	0.0	0.0	3.8	3.8	-0.0
580	4.33	0.0	0.0	0.0	4.3	4.3	-0.0
600	4.93	0.0	0.0	0.0	4.9	4.9	-0.0
620	5.67	0.0	0.0	0.0	5.7	5.7	-0.0
640	5.65	0.0	0.0	0.0	5.6	5.6	-0.0
660	4.69	0.0	0.0	0.0	4.7	4.7	-0.0
680	4.04	0.0	0.0	0.0	4.0	4.0	-0.0
700	2.68	0.0	0.0	0.0	2.7	2.7	-0.0
720	1.75	0.0	0.0	0.0	1.7	1.7	-0.0
740	0.92	0.0	0.0	0.0	0.9	0.9	-0.0
760	0.69	0.0	0.0	0.0	0.7	0.7	-0.0
780	0.79	0.0	0.0	0.0	0.8	0.8	-0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	50.9	51.1	0.3	49.1	48.9	-0.3

TABLE C-5
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 1, BATCH NO. 5
(Constant = 150.0, Air Velocity = 2.97 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.47	0.5	0.5	0.0	0.0	0.0	-0.0
320	1.58	1.6	1.6	0.0	0.0	0.0	-0.0
340	4.56	4.6	4.6	0.0	0.0	0.0	-0.0
360	8.94	8.9	8.9	-0.0	0.0	0.0	0.0
380	7.57	7.5	7.5	0.0	0.1	0.1	-0.0
400	5.17	5.0	5.0	0.0	0.2	0.1	-0.0
420	2.26	2.1	2.1	0.0	0.2	0.2	-0.0
440	1.05	0.9	0.8	-0.0	0.2	0.2	0.0
460	0.76	0.4	0.4	0.0	0.4	0.3	-0.0
480	1.25	0.4	0.3	-0.1	0.8	0.9	0.1
500	1.60	0.0	0.1	0.1	1.6	1.5	-0.1
520	2.59	0.0	0.1	0.1	2.6	2.5	-0.1
540	3.65	0.0	0.1	0.1	3.7	3.6	-0.1
560	4.57	0.0	0.0	0.0	4.6	4.5	-0.0
580	5.68	0.0	0.0	0.0	5.7	5.6	-0.0
600	6.32	0.0	0.0	0.0	6.3	6.3	-0.0
620	7.97	0.0	0.0	0.0	8.0	7.9	-0.0
640	8.04	0.0	0.0	0.0	8.0	8.0	-0.0
660	7.71	0.0	0.0	0.0	7.7	7.7	-0.0
680	6.04	0.0	0.0	0.0	6.0	6.0	-0.0
700	4.33	0.0	0.0	0.0	4.3	4.3	-0.0
720	3.14	0.0	0.0	0.0	3.1	3.1	-0.0
740	1.70	0.0	0.0	0.0	1.7	1.7	-0.0
760	1.10	0.0	0.0	0.0	1.1	1.1	-0.0
780	0.70	0.0	0.0	0.0	0.7	0.7	-0.0
800	1.23	0.0	0.0	0.0	1.2	1.2	-0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	31.8	32.1	0.4	68.3	67.9	-0.4

TABLE C-6
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 1
(Constant = 150.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.04	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.16	0.2	0.2	-0.0	0.0	0.0	0.0
340	0.29	0.3	0.3	-0.0	0.0	0.0	0.0
360	0.38	0.4	0.4	-0.0	0.0	0.0	0.0
380	0.49	0.5	0.5	-0.0	0.0	0.0	0.0
400	1.31	1.3	1.3	-0.0	0.0	0.0	0.0
420	6.28	6.2	6.3	0.0	0.0	0.0	-0.0
440	13.33	13.3	13.1	-0.1	0.0	0.2	0.1
460	13.36	13.2	12.8	-0.4	0.2	0.6	0.4
480	9.54	9.0	8.3	-0.7	0.5	1.2	0.7
500	5.81	4.6	3.7	-0.8	1.2	2.1	0.8
520	4.96	2.9	1.8	-1.1	2.1	3.2	1.1
540	6.31	2.9	1.4	-1.5	3.4	4.9	1.5
560	7.31	2.7	1.0	-1.7	4.6	6.4	1.7
580	7.97	2.4	0.7	-1.7	5.5	7.2	1.7
600	7.71	1.9	0.5	-1.4	5.8	7.2	1.4
620	5.90	1.1	0.3	-0.8	4.8	5.6	0.9
640	3.65	0.5	0.1	-0.3	3.2	3.5	0.3
660	2.95	1.0	0.1	-0.9	1.9	2.9	0.9
680	1.03	0.0	0.0	0.0	1.0	1.0	-0.0
700	0.51	0.0	0.0	0.0	0.5	0.5	-0.0
720	0.73	0.0	0.0	0.0	0.7	0.7	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	64.3	52.9	-11.4	35.7	47.1	11.4

TABLE C-7
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 2
(Constant = 150.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.03	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.08	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.18	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.25	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.38	0.3	0.4	0.0	0.0	0.0	-0.0
400	1.21	1.2	1.2	0.0	0.0	0.0	-0.0
420	5.62	5.5	5.6	0.1	0.2	0.0	-0.1
440	11.89	11.1	11.7	0.6	0.8	0.2	-0.6
460	11.44	9.4	10.9	1.5	2.0	0.5	-1.5
480	7.87	5.3	6.9	1.6	2.6	1.0	-1.6
500	5.35	2.3	3.5	1.1	3.0	1.9	-1.1
520	5.19	1.5	1.9	0.4	3.7	3.3	-0.4
540	6.59	1.2	1.5	0.3	5.4	5.1	-0.3
560	7.75	1.0	1.0	0.0	6.8	6.7	-0.0
580	8.46	0.5	0.8	0.3	7.9	7.7	-0.3
600	8.57	0.7	0.6	-0.1	7.8	8.0	0.1
620	7.99	0.7	0.4	-0.3	7.3	7.6	0.3
640	5.07	0.0	0.2	0.2	5.1	4.9	-0.2
660	2.98	0.0	0.1	0.1	3.0	2.9	-0.1
680	1.47	0.0	0.0	0.0	1.5	1.4	-0.0
700	0.64	0.0	0.0	0.0	0.6	0.6	-0.0
720	1.01	0.0	0.0	0.0	1.0	1.0	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	41.4	47.2	5.8	58.6	52.8	-5.8

TABLE C-8
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 3
(Constant = 150.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.02	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.07	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.17	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.23	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.25	0.2	0.2	-0.0	0.0	0.0	0.0
400	1.25	1.2	1.2	0.0	0.0	0.0	-0.0
420	5.52	5.4	5.5	0.1	0.1	0.0	-0.1
440	11.15	10.7	11.0	0.3	0.4	0.1	-0.3
460	11.94	10.6	11.4	0.8	1.3	0.5	-0.8
480	8.93	6.4	7.8	1.4	2.5	1.1	-1.4
500	5.53	2.4	3.6	1.2	3.1	2.0	-1.2
520	5.49	1.3	2.0	0.7	4.2	3.5	-0.7
540	6.71	0.8	1.5	0.7	5.9	5.2	-0.7
560	8.23	0.6	1.1	0.5	7.6	7.2	-0.5
580	8.63	0.5	0.8	0.3	8.2	7.8	-0.3
600	8.65	0.8	0.6	-0.2	7.9	8.0	0.2
620	6.98	0.0	0.4	0.4	7.0	6.6	-0.4
640	4.45	0.0	0.2	0.2	4.4	4.3	-0.2
660	3.17	0.0	0.1	0.1	3.2	3.1	-0.1
680	1.49	0.0	0.0	0.0	1.5	1.5	-0.0
700	0.59	0.0	0.0	0.0	0.6	0.6	-0.0
720	0.58	0.0	0.0	0.0	0.6	0.6	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	41.4	47.8	6.4	58.6	52.2	-6.4

TABLE C-9
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 4
(Constant = 150.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.03	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.07	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.15	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.21	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.34	0.3	0.3	-0.0	0.0	0.0	0.0
400	1.18	1.1	1.2	0.0	0.0	0.0	-0.0
420	5.30	5.2	5.3	0.0	0.1	0.0	-0.0
440	11.20	10.9	11.1	0.2	0.3	0.1	-0.2
460	11.48	10.4	11.0	0.6	1.1	0.5	-0.6
480	8.21	6.0	7.2	1.1	2.2	1.0	-1.1
500	5.42	2.6	3.5	0.9	2.8	1.9	-0.9
520	5.11	1.2	1.8	0.6	3.9	3.3	-0.6
540	6.44	0.6	1.4	0.8	5.8	5.0	-0.8
560	8.19	0.5	1.1	0.6	7.7	7.1	-0.6
580	9.07	0.5	0.8	0.4	8.6	8.2	-0.4
600	9.22	0.6	0.6	0.1	8.6	8.6	-0.1
620	7.21	0.0	0.4	0.4	7.2	6.8	-0.4
640	5.23	0.0	0.2	0.2	5.2	5.0	-0.2
660	2.94	0.0	0.1	0.1	2.9	2.9	-0.1
680	1.42	0.0	0.0	0.0	1.4	1.4	-0.0
700	0.63	0.0	0.0	0.0	0.6	0.6	-0.0
720	0.95	0.0	0.0	0.0	1.0	0.9	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	40.4	46.5	6.0	59.6	53.5	-6.0

TABLE C-10
PREDICTION OF THE SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 5
(Constant = 150.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.01	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.02	0.0	0.0	-0.0	0.0	0.0	0.0
340	0.09	0.1	0.1	-0.0	0.0	0.0	0.0
360	0.14	0.1	0.1	-0.0	0.0	0.0	0.0
380	0.16	0.2	0.2	-0.0	0.0	0.0	0.0
400	0.82	0.8	0.8	0.0	0.0	0.0	-0.0
420	3.52	3.4	3.5	0.1	0.2	0.0	-0.1
440	8.13	7.0	8.0	1.0	1.2	0.1	-1.0
460	8.82	6.1	8.4	2.4	2.7	0.4	-2.4
480	6.73	3.2	5.9	2.7	3.6	0.9	-2.7
500	4.85	1.1	3.1	2.0	3.7	1.7	-2.0
520	4.89	0.5	1.7	1.2	4.4	3.1	-1.2
540	6.63	0.3	1.5	1.2	6.3	5.1	-1.2
560	8.14	0.2	1.1	0.8	7.9	7.1	-0.8
580	10.38	0.5	1.0	0.5	9.9	9.4	-0.5
600	10.88	0.0	0.8	0.8	10.9	10.1	-0.8
620	9.09	0.0	0.5	0.5	9.1	8.6	-0.5
640	6.83	0.0	0.3	0.3	6.8	6.6	-0.3
660	4.11	0.0	0.1	0.1	4.1	4.0	-0.1
680	2.65	0.0	0.1	0.1	2.7	2.6	-0.1
700	0.81	0.0	0.0	0.0	0.8	0.8	-0.0
720	0.78	0.0	0.0	0.0	0.8	0.8	-0.0
740	1.51	0.0	0.0	0.0	1.5	1.5	-0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	23.4	37.2	13.7	76.6	62.8	-13.7

TABLE C-11
PREDICTION OF SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 1
(Constant = 325.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.04	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.16	0.2	0.2	-0.0	0.0	0.0	0.0
340	0.29	0.3	0.3	-0.0	0.0	0.0	0.0
360	0.38	0.4	0.4	-0.0	0.0	0.0	0.0
380	0.49	0.5	0.5	-0.0	0.0	0.0	0.0
400	1.31	1.3	1.3	-0.0	0.0	0.0	0.0
420	6.28	6.2	6.2	-0.0	0.0	0.1	0.0
440	13.33	13.3	12.9	-0.4	0.0	0.4	0.4
460	13.36	13.2	11.9	-1.2	0.2	1.4	1.2
480	9.54	9.0	7.3	-1.7	0.5	2.3	1.7
500	5.81	4.6	2.6	-1.9	1.2	3.2	1.9
520	4.96	2.9	1.0	-1.8	2.1	3.9	1.8
540	6.31	2.9	0.7	-2.1	3.4	5.6	2.1
560	7.31	2.7	0.5	-2.2	4.6	6.8	2.2
580	7.97	2.4	0.4	-2.1	5.5	7.6	2.1
600	7.71	1.9	0.3	-1.7	5.8	7.5	1.7
620	5.90	1.1	0.1	-1.0	4.8	5.8	1.0
640	3.65	0.5	0.1	-0.4	3.2	3.6	0.4
660	2.95	1.0	0.0	-1.0	1.9	2.9	1.0
680	1.03	0.0	0.0	0.0	1.0	1.0	-0.0
700	0.51	0.0	0.0	0.0	0.5	0.5	-0.0
720	0.73	0.0	0.0	0.0	0.7	0.7	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	64.3	46.8	-17.5	35.7	53.2	17.5

TABLE C-12
PREDICTION OF SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 2
(Constant = 325.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.03	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.08	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.18	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.25	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.38	0.3	0.4	0.0	0.0	0.0	-0.0
400	1.21	1.2	1.2	0.0	0.0	0.0	-0.0
420	5.62	5.5	5.6	0.1	0.2	0.1	-0.1
440	11.89	11.1	11.5	0.4	0.8	0.4	-0.4
460	11.44	9.4	10.2	0.8	2.0	1.2	-0.8
480	7.87	5.3	6.0	0.7	2.6	1.9	-0.7
500	5.35	2.3	2.4	0.1	3.0	2.9	-0.1
520	5.19	1.5	1.1	-0.4	3.7	4.1	0.4
540	6.59	1.2	0.8	-0.4	5.4	5.8	0.4
560	7.75	1.0	0.5	-0.5	6.8	7.2	0.5
580	8.46	0.5	0.4	-0.2	7.9	8.1	0.2
600	8.57	0.7	0.3	-0.4	7.8	8.3	0.4
620	7.99	0.7	0.2	-0.5	7.3	7.8	0.5
640	5.07	0.0	0.1	0.1	5.1	5.0	-0.1
660	2.98	0.0	0.0	0.0	3.0	2.9	-0.0
680	1.47	0.0	0.0	0.0	1.5	1.5	-0.0
700	0.64	0.0	0.0	0.0	0.6	0.6	-0.0
720	1.01	0.0	0.0	0.0	1.0	1.0	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	41.4	41.2	-0.2	58.6	58.8	0.2

TABLE C-13
PREDICTION OF SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 3
(Constant = 325.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.02	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.07	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.17	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.23	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.25	0.2	0.2	-0.0	0.0	0.0	0.0
400	1.25	1.2	1.2	0.0	0.0	0.0	-0.0
420	5.52	5.4	5.5	0.0	0.1	0.1	-0.0
440	11.15	10.7	10.8	0.0	0.4	0.4	-0.0
460	11.94	10.6	10.7	0.1	1.3	1.3	-0.1
480	8.93	6.4	6.8	0.4	2.5	2.1	-0.4
500	5.53	2.4	2.5	0.1	3.1	3.0	-0.1
520	5.49	1.3	1.1	-0.2	4.2	4.4	0.2
540	6.71	0.8	0.8	0.0	5.9	5.9	-0.0
560	8.23	0.6	0.5	-0.1	7.6	7.7	0.1
580	8.63	0.5	0.4	-0.1	8.2	8.2	0.1
600	8.65	0.8	0.3	-0.5	7.9	8.4	0.5
620	6.98	0.0	0.2	0.2	7.0	6.8	-0.2
640	4.45	0.0	0.1	0.1	4.4	4.4	-0.1
660	3.17	0.0	0.0	0.0	3.2	3.1	-0.0
680	1.49	0.0	0.0	0.0	1.5	1.5	-0.0
700	0.59	0.0	0.0	0.0	0.6	0.6	-0.0
720	0.58	0.0	0.0	0.0	0.6	0.6	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	41.4	41.6	0.2	58.6	58.4	-0.2

TABLE C-14
PREDICTION OF SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 4
(Constant = 325.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.03	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.07	0.1	0.1	-0.0	0.0	0.0	0.0
340	0.15	0.2	0.2	-0.0	0.0	0.0	0.0
360	0.21	0.2	0.2	-0.0	0.0	0.0	0.0
380	0.34	0.3	0.3	-0.0	0.0	0.0	0.0
400	1.18	1.1	1.2	0.0	0.0	0.0	-0.0
420	5.30	5.2	5.2	0.0	0.1	0.0	-0.0
440	11.20	10.9	10.8	-0.0	0.3	0.4	0.0
460	11.48	10.4	10.3	-0.1	1.1	1.2	0.1
480	8.21	6.0	6.2	0.2	2.2	2.0	-0.2
500	5.42	2.6	2.5	-0.1	2.8	2.9	0.1
520	5.11	1.2	1.0	-0.2	3.9	4.1	0.2
540	6.44	0.6	0.8	0.1	5.8	5.7	-0.1
560	8.19	0.5	0.5	0.0	7.7	7.7	-0.0
580	9.07	0.5	0.4	-0.1	8.6	8.7	0.1
600	9.22	0.6	0.3	-0.3	8.6	8.9	0.3
620	7.21	0.0	0.2	0.2	7.2	7.0	-0.2
640	5.23	0.0	0.1	0.1	5.2	5.1	-0.1
660	2.94	0.0	0.0	0.0	2.9	2.9	-0.0
680	1.42	0.0	0.0	0.0	1.4	1.4	-0.0
700	0.63	0.0	0.0	0.0	0.6	0.6	-0.0
720	0.95	0.0	0.0	0.0	1.0	0.9	-0.0
740	0.00	0.0	0.0	0.0	0.0	0.0	0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	40.4	40.4	-0.0	59.6	59.6	0.0

TABLE C-15
PREDICTION OF SEPARATION FOR SCRAP ROD RUN NO. 2, BATCH NO. 5
(Constant = 325.0, Air Velocity = 3.70 m/sec)

Diameter	Feed	Actual	Fines Predicted	Error	Actual	Coarse Predicted	Error
300	0.01	0.0	0.0	-0.0	0.0	0.0	0.0
320	0.02	0.0	0.0	-0.0	0.0	0.0	0.0
340	0.09	0.1	0.1	-0.0	0.0	0.0	0.0
360	0.14	0.1	0.1	-0.0	0.0	0.0	0.0
380	0.16	0.2	0.2	-0.0	0.0	0.0	0.0
400	0.82	0.8	0.8	0.0	0.0	0.0	-0.0
420	3.52	3.4	3.5	0.1	0.2	0.0	-0.1
440	8.13	7.0	7.9	0.9	1.2	0.3	-0.9
460	8.82	6.1	7.9	1.8	2.7	0.9	-1.8
480	6.73	3.2	5.1	2.0	3.6	1.6	-2.0
500	4.85	1.1	2.2	1.1	3.7	2.6	-1.1
520	4.89	0.5	1.0	0.5	4.4	3.9	-0.5
540	6.63	0.3	0.8	0.5	6.3	5.8	-0.5
560	8.14	0.2	0.5	0.3	7.9	7.6	-0.3
580	10.38	0.5	0.5	0.0	9.9	9.9	-0.0
600	10.88	0.0	0.4	0.4	10.9	10.5	-0.4
620	9.09	0.0	0.2	0.2	9.1	8.9	-0.2
640	6.83	0.0	0.1	0.1	6.8	6.7	-0.1
660	4.11	0.0	0.1	0.1	4.1	4.1	-0.1
680	2.65	0.0	0.0	0.0	2.7	2.6	-0.0
700	0.81	0.0	0.0	0.0	0.8	0.8	-0.0
720	0.78	0.0	0.0	0.0	0.8	0.8	-0.0
740	1.51	0.0	0.0	0.0	1.5	1.5	-0.0
760	0.00	0.0	0.0	0.0	0.0	0.0	0.0
780	0.00	0.0	0.0	0.0	0.0	0.0	0.0
800	0.00	0.0	0.0	0.0	0.0	0.0	0.0
820	0.00	0.0	0.0	0.0	0.0	0.0	0.0
840	0.00	0.0	0.0	0.0	0.0	0.0	0.0
860	0.00	0.0	0.0	0.0	0.0	0.0	0.0
880	0.00	0.0	0.0	0.0	0.0	0.0	0.0
900	0.00	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL =	100.00	23.4	31.4	8.0	76.6	68.6	-8.0

APPENDIX D

DESCRIPTION AND OPERATION OF THE
COATED PARTICLE ANALYSER

AUTOMATIC SIZE ANALYSIS OF COATED FUEL PARTICLES

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ABSTRACT

An optical system for the fast determination of diameters, coating thicknesses and densities of coated fuel particles is described. The results of four measurements are compared with the results obtained by other methods and demonstrate the high accuracy and the reproducibility of the technique used.

1. INTRODUCTION

A number of different methods are used for determining particle diameter coating thickness and density of coated fuel particles. The major disadvantage of all these techniques is the relatively long time required for measuring a certain number of particles and the necessity to use different methods for the determination of density.

An alternative method described in this paper avoids these disadvantages by utilizing a fast optical data collecting system of high accuracy. This system allows the determination of the diameter of particles in the range 300 μm - 1500 μm with an error of better than $\pm 2 \mu\text{m}$ and with a rate of 20 - 100 particles per second. An on-line computer stores the measured data and calculates all parameters required.

By weighing the particles before and after the measurement and taking into account the number and the mean volume of the particles measured the mean particle density can be determined

$$\rho = \frac{G}{\bar{V} \cdot n}$$

G ... weight of measured particles

$\bar{V}$... mean volume of particles

n ... number of measured particles

By measuring before and after a coating step the mean coating thickness and the mean coating density ρ_i can be determined.

$$\rho_i = \frac{\frac{G_i}{n_i} - \frac{G_{i-1}}{n_{i-1}}}{\bar{V}_i - \bar{V}_{i-1}}$$

2. PRINCIPLE OF MEASUREMENT

A parallel light beam illustrates a narrow parallel slit. The beam is partially interrupted by the measured particle. The reduction of the light current which is measured by a photo-sensitive diode is proportional to the particle diameter (perpendicular to the direction of motion). The peak-value is detected, digitalized and passed on into a PDP-8/E computer via CAMAC and stored. Preceding the measurement the system is calibrated with high precision steel balls.

3. EQUIPMENT FOR PARTICLE SIZE ANALYSIS (PSA)

3.1. The opto-mechanical part (Fig. 1) includes the particle feed system, the optical system, a pre-amplifier and the necessary control devices. The particles to be measured are poured into the feed system where they are picked up and carried along by a pneumatic system. After passing the optical measuring device they are collected in a container. For checking the correct function of the optical as well as the detection system a testing device is built into the equipment.

3.2. Figure 2 shows the processing of the pulse delivered by the photo diode which is carried out by a special CAMAC unit (KDM-1). The plug-in panel of this unit includes a baseline stabilized amplifier, the peak detector, control logic, an analog to digital converter, and the brightness control for the lamp used in the optical system. The digital values of particle diameters are stored in a PDP-8/E computer with the following sub-units: 12 k memory, mass storage (tape or disc), VR 14 display, Calcomp Plotter Model 565.

3.3. After stating the measuring conditions and after calibrating the system, the programme classifies the particle diameters and stores them in a software multichannel. The channels cover the diameter range from 300 μm

- 1500 μm . Each channel is calibrated in microns and has a width of 2 μm . The maximum storage capacity of one channel is 4095 particles. The content of the storage is visible on the display during the measurement and evaluation. The computer evaluates the data after the measurement is completed and the limits for the evaluation range are defined by the operator. The software includes the following calculations (output on teletype): Number of particles measured, mean particle diameter, standard deviation, variation factor, limiting values, total volume of particles measured, mean particle volume.

4. RESULTS

In Figs. 3 to 10 the print-out and the plotting of four different measurements are demonstrated.

Figures 3 and 4 show the results of the measurement of steel balls with the diameter of $1000 \mu\text{m} \pm 1 \mu\text{m}$ (specified by the supplier), which are used for the calibration of the equipment. Results obtained from fuel particles are shown in Figs. 5 and 6 (kernels) and in Figs. 7 and 8 (coated particles).

Provided that the difference of diameter is large enough, mixed samples can be measured as well. Figures 9 and 10 demonstrate the simultaneous measurement of kernels (same as Figs. 5 and 6) and of coated particles (same as Figs. 7 and 8).

A comparison of results for the overall diameter, particle density, mean coating thickness, and coating density measured with conventional methods and with the Particle Size Analyser for two coating steps is given in Table 1. Taking into account the limits of error of the different methods the values are in good agreement.

5. CONCLUSION

The Particle Size Analyser described allows the fast determination of particle size as well as layer thickness and the density of coatings. The examples shown demonstrate the high accuracy and reproducibility of the results. Since a skilled operator needs only a few minutes for performing the measurements and the evaluation of the results, this equipment is especially suited for the on-line control of the coating process in production units.

Fig. 1. Particle size analyser

Fig. 2. Block diagram of the electronic data processing

PSA

DATE:73.05.20
SAMPLE:000.001

EVALUATION RANGE
FROM: 990
TO : 1010

NUMBER OF PARTICLES: 563

MEAN DIAMETER [MY]: 1000

STANDARD DEVIATION: 1.5

VARIATION FACTOR [%]: 0.1

DIAMETER LIMITING VALUES:

95% LIMITS [MY]: 997 1003

99% LIMITS [MY]: 996 1004

COMMON VOLUME [CMM]: 0.295676E+003

MEAN VOLUME [CMM]: 0.525180E+000

←←←←

Fig. 3. Dimensions and distribution of calibration balls

Fig. 4. Size distribution of calibration balls

PSA

DATE:73.05.20
SAMPLE:000.003

EVALUATION RANGE
FROM: 350
TO : 450

NUMBER OF PARTICLES: 3271

MEAN DIAMETER [MY]: 399

STANDARD DEVIATION: 12.3

VARIATION FACTOR [%]: 3.1

DIAMETER LIMITING VALUES:

95% LIMITS [MY]: 374 423

99% LIMITS [MY]: 366 432

COMMON VOLUME [CMM]: 0.108768E+003

MEAN VOLUME [CMM]: 0.332521E-001

←←←←

Fig. 5. Dimensions and distribution of kernels

Fig. 6. Size distribution of kernels

PSA

DATE:73.05.50
SAMPLE:000.002

EVALUATION RANGE
FROM: 650
TO: 950

NUMBER OF PARTICLES: 3267

MEAN DIAMETER [MY]: 772

STANDARD DEVIATION: 36.4

VARIATION FACTOR [%]: 4.7

DIAMETER LIMITING VALUES:

95% LIMITS [MY]: 699 845

99% LIMITS [MY]: 674 870

COMMON VOLUME [CMM]: 0.795497E+003

MEAN VOLUME [CMM]: 0.243494E+000

←←←←

Fig. 7. Dimensions and distribution of coated particles

Fig. 8. Size distribution of coated particles

PSA

DATE:73.05.20
SAMPLE:000.000

EVALUATION RANGE
FROM: 650
TO: 950

NUMBER OF PARTICLES: 3614

MEAN DIAMETER [MY]: 772

STANDARD DEVIATION: 36.2

VARIATION FACTOR [%]: 4.7

DIAMETER LIMITING VALUES:

95% LIMITS [MY]: 700 845

99% LIMITS [MY]: 675 870

COMMON VOLUME [CMM]: 0.881160E+003

MEAN VOLUME [CMM]: 0.243818E+000

←←←←

PSA

DATE:73.05.20
SAMPLE:000.000

EVALUATION RANGE
FROM: 350
TO : 450

NUMBER OF PARTICLES: 1024

MEAN DIAMETER [MY]: 399

STANDARD DEVIATION: 11.8

VARIATION FACTOR [%]: 3.0

DIAMETER LIMITING VALUES:

95% LIMITS [MY]: 375 423

99% LIMITS [MY]: 367 431

COMMON VOLUME [CMM]: 0.341191E+002

MEAN VOLUME [CMM]: 0.333194E-001

←←←←

Fig. 9. Dimensions and distribution of a mixed sample

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Fig. 10. Size distribution of a mixed sample

TABLE 1
COMPARISON OF RESULTS FOR DIAMETER, COATING THICKNESS
AND DENSITY MEASURED BY DRAGON AND SGAE

	DRAGON	SGAE-PSA
SiC coated particles without outer PyC		
Overall diameter (μm)	1043	1043
Particle density (g/cm^3)	5.02	5.00
Thickness of SiC layer (μm)	34 (x-ray) 32 (Hg)	31
SiC density (g/cm^3)	3.21 (Flotation) 3.14 (Batch weight)	3.21
Particles with outer PyC		
Overall diameter (μm)	1156	1161
Particle density (g/cm^3)	4.14	4.11
Thickness of outer PyC layer (μm)	57 (x-ray) 56 (Hg)	59
PyC density (g/cm^3)	1.77 (Flotation) 1.74 (Batch weight)	1.72

APPENDIX E

COMPUTER PROGRAMS USED FOR DATA REDUCTION

DIAMETER	AC 30 WEIGHT %	AC 31 WEIGHT %	TOTAL WEIGHT %	COARSE TOTAL
300	.12	.00	.12	.00
320	.93	.01	1.00	.01
340	2.82	.11	2.93	.04
360	3.95	.25	4.23	.07
380	1.75	.11	1.86	.06
400	2.97	.06	3.04	.02
420	6.54	.22	6.82	.04
440	6.60	.39	6.99	.06
460	2.06	.60	2.66	.23
480	1.12	2.63	3.90	.71
500	1.27	4.73	6.04	.73
520	.72	5.66	6.33	.99
540	.53	7.24	8.43	.73
560	.92	8.43	9.40	.90
580	.00	7.67	7.67	1.00
600	.00	6.92	6.92	1.00
620	.00	4.37	4.37	1.00
640	.00	4.30	4.30	1.00
660	.00	5.03	5.03	1.00
680	.00	4.09	4.09	1.00
700	.00	1.89	1.89	1.00
720	.00	.43	.43	1.00
740	.00	.60	.60	1.00
760	.00	.00	.00	.00
780	.00	.00	.00	.00
800	.00	.00	.00	.00
820	.00	.00	.00	.00
840	.00	.00	.00	.00
860	.00	.00	.00	.00
880	.00	.00	.00	.00
900	.00	.00	.00	.00

AC 30

DIAMETER	NUMBER PER CENT	WEIGHT PER CENT	WEIGHTED WEIGHT PER CENT
300	.92	.36	.12
320	6.35	3.03	.98
340	15.06	8.70	2.62
360	17.52	12.12	3.95
380	6.57	5.40	1.75
400	9.47	9.12	2.97
420	17.22	20.20	6.54
440	15.46	20.36	6.60
460	4.19	6.37	2.06
480	1.92	3.46	1.12
500	1.96	3.91	1.27
520	.92	2.22	.72
540	.70	1.20	.52
560	.92	2.23	.92
580	.00	.00	.00
600	.00	.00	.00
620	.00	.00	.00
640	.00	.00	.00
660	.00	.00	.00
680	.00	.00	.00
700	.00	.00	.00
720	.00	.00	.00
740	.00	.00	.00
760	.00	.00	.00
780	.00	.00	.00
800	.00	.00	.00
820	.00	.00	.00
840	.00	.00	.00
860	.00	.00	.00
880	.00	.00	.00
900	.00	.00	.00

AC 31

DIAMETER	NUMBER PER CENT	WEIGHT PER CENT	WEIGHTED WEIGHT PER CENT
300	.00	.00	.00
320	.13	.02	.01
340	.30	.16	.11
360	1.30	.42	.23
380	.60	.17	.11
400	.23	.09	.06
420	1.06	.41	.23
440	1.23	.57	.39
460	1.72	.39	.60
480	6.63	3.36	2.63
500	10.45	7.07	4.73
520	10.30	3.33	5.66
540	13.34	11.60	7.34
560	12.30	12.55	3.43
580	10.31	11.35	7.67
600	8.31	10.23	6.92
620	5.25	7.21	4.87
640	4.65	7.10	4.80
660	4.40	7.44	5.03
680	3.24	6.06	4.09
700	1.36	2.30	1.39
720	.23	.63	.43
740	.36	.89	.60
760	.00	.00	.00
780	.00	.00	.00
800	.00	.00	.00
820	.00	.00	.00
840	.00	.00	.00
860	.00	.00	.00
880	.00	.00	.00
900	.00	.00	.00

LIST OF PROGRAM SYMBOLS USED

A - Number of particles per size increment
B - Volume percent
C - Summing register
D(I,1) - Diameter
D(I,2) - Number percent
D(I,3) - Weight percent
D(I,4) - Weighted weight percent or total weight percent
D(I,5) - Weighted weight percent or separation efficiency
F(1) - Fines weight fraction of feed
F(2) - Coarse weight fraction of feed
I - Counter
J - Counter
K - Counter
L - Counter
M - Data file
N - Number of runs
S - Output format
Z - Label

APPENDIX F

DRAWINGS FOR MODULAR CLASSIFIER

Fig. F-1. Feed section of the pneumatic classifier used for fissile/fertile particle separation
(Sheet 1 of 2)

Fig. F-2. Schematic of cyclone for fines particle separator component of pneumatic classifier
(Sheet 1 of 3)

Fig. F-2. Schematic of cyclone for fines particle separator component of pneumatic classifier
(Sheet 2 of 3)

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Fig. F-2. Schematic of cyclone for fines particle separator component of pneumatic classifier
(Sheet 3 of 3)

Fig. F-3. Schematic of pneumatic classifier feed adaptors

Fig. F-4. Schematic of top take-off and cyclone-to-fines adaptor components of pneumatic classifier

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SECTION B-B

Fig. F-5. Zigzag chamber component of pneumatic classifier

Fig. F-6. Coarse particle take-off cone assembly component of pneumatic classifier

APPENDIX G

ABBREVIATIONS FOR SECTION 3

ABBREVIATIONS FOR SECTION 3

C	Diagonal Matrix Describing a Separation Process
d	Diameter of a Particle
f	Column Matrix Describing the Size Distribution of the Feed
ff	Friction Factor
$\bar{F}$	Force
g	Gravitational Constant
o	Column Matrix Describing the Size Distribution of the Oversize Product
P	Pressure
Re	Reynolds Number
t	Time
u	Column Matrix Describing the Size Distribution of the Undersize Product
V	Velocity
Y	Element of a Matrix
μ	Viscosity
ρ	Density
ϕ	Separation Efficiency

Subscripts f denotes fluid

p denotes particle

t denotes terminal

i denotes matrix element number