DEVELOPMENT OF A GAS CLASSIFICATION METHOD FOR
SEPARATING FT. ST. VRAIN TRISO-TRISO FUEL PARTICLES

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ABSTRACT

A method for separating Ft. St. Vrain TRISO-TRISO fuel particles in a vertical gas classifier has been defined. Step-by-step development of the classifier from bench-scale to a pilot-plant system is discussed. Separation of the fissile and fertile fuel particles to 99% pure fissile particles and 96% pure fertile particles was demonstrated in the pilot plant.

SUMMARY

A gas classification method for separating Ft. St. Vrain TRISO-TRISO fuel particles has been developed at the Idaho Chemical Processing Plant (ICPP). The method consists of a vertical column in which the smaller fissile particles are elutriated by an upward stream of gas; the larger fertile particles settle through the gas stream and are collected at the bottom.

The feasibility of the process was demonstrated through bench-scale comparative testing of the vertical model with a distinctly different horizontal-displacement gas classification model. Although both methods were determined to be feasible, the vertical method appears much more promising because of the simplicity of its design; a pilot-plant model was constructed and separation of the fuel particles was successfully demonstrated. A parametric study of operating variables in the pilot-plant system showed that maximum separation of the particle types could be achieved at about 11.7 ft/sec fluidizing velocity. Product purities of > 99% pure fissile particles and > 96% pure fertile particles were obtained at this fluidizing velocity.

Particle breakage was an early problem in the pilot-plant system but a modification of the distributor plate design essentially eliminated any further breakage. Continuous, steady-state feeding was difficult to achieve with all of three methods tested: gravity flow, mechanical rotary (star) valve, and forced-air. Of the three, the forced-air system appears most promising, but requires additional testing.

Additional refinement of the air classifier design is necessary and is in progress. Comparative testing with a "zigzag" column is underway to determine if effective separation can be achieved with a lower L/D ratio. Scale-up of the pilot-plant system to a size large enough for the HTGR Fuel Reprocessing Project scheduled for operation in FY 1980 should not be a significant problem because the pilot-plant system is sized to accept a feed rate equivalent to that expected in the demonstration plant.

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I. INTRODUCTION

Irradiated nuclear fuel from the Ft. St. Vrain reactor, the first High Temperature Gas-Cooled Reactor (HTGR), will be processed at ICPP to demonstrate the technology for recovering uranium and thorium from these graphite-matrix fuels. The demonstration, now scheduled for FY-1980, will involve processing over 2000 Ft. St. Vrain fuel elements (blocks) at a rate of 12 blocks/day.

The Ft. St. Vrain reactor is fueled by two types of thorium and uranium carbide kernels; the kernels are spherical ($\sim 250 \mu\text{m}$ diameter) and are covered with successive coatings of a buffer carbon, pyrolytic carbon, SiC, and another pyrolytic carbon coating. One of these TRISO-TRISO fuel-particle types is called a fertile particle; the other is a fissile particle. These particles are randomly dispersed in a cylindrical graphite matrix called a fuel compact, and the compacts are positioned in fuel channels bored through large blocks of graphite. These large blocks are hexagonal in cross-section, 14-inches across the flats, and 31-inches long.

Before irradiation, the kernels of the fertile particles consist only of thorium carbide; the kernel of the fissile particles consist of a four-to-one mixture of thorium carbide and 93-percent-enriched uranium carbide. Once irradiated, the fertile particles will contain thorium and U-233, a breeder product of thorium. The fissile particles, however, will contain residual thorium, U-233, U-235, U-238, and the capture daughter of U-235, U-236. Principally because of the U-236, a nuclear poison in the fissile particles, the fissile particles will be processed separately from the fertile particles during reprocessing of the Ft. St. Vrain fuel. HTGR fuel recycle economics generated at the Oak Ridge National Laboratory suggest that the two particle types be separated so that the fissile-particle fraction contain no more than 5-wt% fertile particles while the fertile-particle fraction contain less than 15-wt% fissile particles^[1]. Table I summarizes the physical and chemical make-up of the two particle types. From this table, a separation point of 35 mesh (500 μm) was selected to yield maximum separation. The results of all tests were evaluated, on the basis of a screen analyses of

TABLE I

PHYSICAL ANALYSIS OF HTGR FISSILE AND FERTILE PARTICLE MIXTURE

Sieve Analysis			Analytical Chemistry Analysis			
U.S. Standard Mesh, Screen Size	Equivalent Particle Diameter, μm	Amount Retained on Screen, Wt%	Particle Density,g/cc	Thorium content Wt%	Uranium content Wt%	
Fertile Parti- cles	30	590	32.88	3.77	56.57	0.02
	35	500	26.00	3.81	56.67	0.01
	40	420	3.70	(a)	49.86	1.08
Fissile Parti- cles	45	350	22.51	2.74	26.88	6.05
	50	300	12.79	2.56	19.90	4.99
	60	250	<u>2.12</u>	(a)	34.69	2.18
		100.00				

(a) Insufficient quantity in sample to determine density.

process samples. A 90-percent pure fertile fraction means, for example, that 90 weight percent of the sample was retained on a 35-mesh screen.

Before the particles can be separated, however, they must be recovered from the large fuel blocks. This requires several complex steps-- the first of which is bulk crushing. In this step, the blocks are dropped into a large jaw crusher which reduces them to 6-inch pieces; a second, smaller, jaw crusher then reduces the 6-inch pieces to 2-inch pieces. Finally, a roll crusher decreases the fuel to about 3/16-inch pieces.

The fuel pieces will be continuously fed to a fluidized-bed burner in which the bulk graphite matrix and the outer PyC coating on the particles will be burned away leaving the silicon-carbide fuel particles; the particles will then be classified into fertile and fissile fractions using a gas classifier. Once separated, the fertile particles will be crushed to break the silicon-carbide coating to expose the inner carbon coatings and the carbide kernel. (The fissile fraction will be stored and may be intermittently processed identically to the fertile fraction.) A second fluidized-bed burning step, operating on a batch basis, will then burn the inner carbon and carbide coatings of the crushed particles to oxidize the carbide kernels to their oxides. These oxides will then be leached from the secondary burner product by thorex acid solution^(a), and a continuous centrifuge will separate the leachate from the remaining silicon carbide particle hulls. The leachate will be complexed, adjusted, then fed to a solvent extraction system for separation of the thorium and uranium from fission products and also for partitioning of the thorium from the uranium. The purified uranium nitrate liquid product from the solvent extraction will be denitrated in a final fluidized-bed denitrator, and the granular product from the denitrator will be returned to the fuel fabricator for recycle to future HTGR fuel elements.

Considerable effort is ongoing at Oak Ridge National Laboratory, General Atomics, and ICPP to develop the individual process steps which make up the HTGR reprocessing headend. This report, however, covers only the gas classification of the fissile and fertile particles.

(a) 13 M HNO₃, 0.05 M HF, 0.1 M Al(NO₃)₃.

In the early stages of development, the concept for separating HTGR fuel particles was a vibratory screen, designed to yield three products: (1) fertile particles ($> 500 \mu\text{m}$ in diameter); (2) fissile particles ($500 \mu\text{m} - 250 \mu\text{m}$);, and (3) unburned carbon ($< \mu\text{m} 250$)^(a). This separation would be accomplished simply by equipping the screener with appropriate screen sizes. There are, however, two basic problems with this concept: 1) vibratory screens have moving parts which wear and require lubrication. Maintenance of such a system in a highly radioactive environment would be difficult. Screen faces also blind easily with spherical particles, and any mechanism for prevention or minimization of screen-face blinding would increase screen wear, cause screen deformation and contribute to particle breakage, 2) unburned carbon typically is present in pieces ranging in size from 1/8" nominal diameter down to fine dust less than $100 \mu\text{m}$ in diameter. Complete separation of this unburned carbon from the fissile and fertile particles is impossible by screening.

With the apparent unsuitability of vibratory screens, various types of air (gas) classifiers were considered. Centrifugal classifiers (cyclone type) require high air velocities which cause particle breakage; centrifugal/mechanical classifiers (whizzer type) also cause particle breakage and have the disadvantage of mechanical parts. Both centrifugal types commercially available (especially the whizzers) are not sized for particles as large as the HTGR's.

Development effort at ICPP has concentrated on two distinctly-different gas classification concepts, one based on vertical gas flow and the other on horizontal gas flow. Since the classification studies began at ICPP, classification systems employing both the horizontal- and the vertical-displacement concepts became commercially available. The commercial horizontal-displacement model was found to be much too large for even a plant-scale application for HTGR particles^[2], but the commercial-displacement classifier, an Alpine Multiplex Zigzag Air Classifier, was purchased for comparative testing with the model developed

(a) The amount of unburned carbon found in primary-burner product from pilot-plant data has been as much as 10-wt% but averages about 5-wt%.

at ICPP. To date, only brief scoping tests have been made with the zigzag model, but these preliminary runs indicate that specified plant-scale separations can also be achieved with this design. Future testing will compare efficiency of separation based on gas usage, cross-sectional column area, L/D, etc., to determine a plant design.

II. BENCH-SCALE FEASIBILITY STUDIES

Before a large commitment to a gas-classification development effort was begun, it was first desirable to demonstrate the feasibility of the two concepts (vertical- and horizontal-displacement gas classification) on a limited bench-scale. Each concept will be discussed separately.

A. VERTICAL DISPLACEMENT GAS CLASSIFICATION

1. Principle

A down-flowing stream of mixed fissile and fertile particles is contacted in a vertical vessel by an upflowing gas stream. Adjustment of the gas flow to a velocity greater than the terminal (or settling) velocity of the smaller, less dense fissile particles but less than the terminal velocity of the fertile particles causes particle separation by elutriation of the fissile particles from the top of the vessel. The fertile particles are collected at the bottom of the vessel.

2. Theoretical Consideration

Based on the measured particle size and density distribution from Table I, the theoretical settling velocities for a range of fissile and fertile particles can be determined [3]. These velocities are a function of the Reynolds Number,

$$N_{RE} = \frac{D\rho v_t}{\mu}$$

Where: D = particle diameter
 ρ = density of fluid (air)
 v_t = terminal velocity of particle
 μ = viscosity of fluid (air)

For $0.4 < N_{RE} < 500$ (the nominal range expected for these particles),

$$v_t = \left[\frac{4}{225} \times \frac{(\rho_s - \rho)^2 g^2}{\rho \mu} \right]^{1/3} D$$

Where: ρ_s = density of particle

g = acceleration of gravity

This equation is the basis of the theoretical terminal velocities shown in Table II.

TABLE II

THEORETICAL TERMINAL VELOCITIES OF
SINGLE FISSILE AND FERTILE PARTICLES

Fissile Particles		Fertile Particles		Calculated
Density ^(a) , g/cc	Diameter ^(a) , cm	Density ^(a) , g/cc	Diameter ^(a) , cm	Terminal Velocity, ft/sec
2.5	0.025	---	---	4
3.5	0.035	---	---	7
---	---	3.5	0.045	9
---	---	3.8	0.060	12.5

(a) An assumed range from analysis of data from Table I and other sources.

3. Description of Vertical Classifier

The apparatus used for the vertical-displacement classification studies (Figure 1) is a glass column 18-in high and 11/16-inches in diameter with a top 6-inch disengaging section 1-1/2 in. in diameter. Air enters the column at the bottom through a distributor and leaves at the top through a cyclone; the cyclone is needed to separate fissile particles from the fluidizing air. Particles were fed by gravity to the column at a point 12-inches above the air distributor.

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Figure 1. Vertical Displacement Classifier

In all preliminary tests, the desired air velocity was attained before the particles were fed to the column. Tests were made to determine separation efficiency as a function of air velocity and residence time^(b) in the column. Other tests were made to define separation efficiency at fixed residence times and with recycling of the unelutriated particles (bottom fraction). Following each test, the overhead and bottom fractions were weighed to determine the mass of particles elutriated, and screened through a 35-mesh screen to determine purity.

4. Experimental Testing and Results

The air velocity for the initial tests was set at the calculated separation velocity, 8 ft/sec, and several tests were made at various residence times in the column. However, at this air velocity, even at long residence times, less than a quarter of the feed particles were elutriated from the column. Obviously 8 ft/sec was insufficient to separate the particles in this apparatus. Subsequent tests were made using higher air velocities, and adequate separation was obtained above 9 ft/sec. The calculated separation velocity, 8 ft/sec, was based on a single particle; the variance between experimental results and theoretical calculations is attributed to the interaction of the mass of particles in an air stream.

The results of subsequent classification tests at various air velocities and residence times are summarized in Table III. Fissile and fertile particle purities as a function of residence time are shown in Figure 2. These results show that even at low residence times, a 95-percent-pure fissile fraction and an 85-percent-pure fertile fraction can easily be obtained. Other tests were run in an attempt to reduce residence time and air flow by recycling the bottom particle fraction after a fixed residence time. However, it soon became clear that recycling the bottom fraction had the same effect as increasing the residence time, so further recycling tests were discontinued.

(b) Residence time is defined as the length of time particles in the bed were in contact with the fluidizing air. (This included the time spent feeding particles to the column).

Figure 2. Purity of Particle Fractions as a Function of Residence Time and Air Velocity in the Vertical Classifier

TABLE III

RESULTS OF VERTICAL DISPLACEMENT CLASSIFICATION
FOR VARIOUS AIR VELOCITIES AND RESIDENCE TIMES

<u>Superficial Air velocity, ft/sec</u>	<u>Residence time of particles, sec</u>	<u>Particles elutriated, %</u>	<u>Purity of elutri- ated particles, %</u>	<u>Purity of unelutriated particles, %</u>
9.2	15	22.42	99.92	73.84
9.2	60	33.32	99.91	85.89
9.2	120	35.10	99.93	88.25
9.2	180	36.60	98.70	89.63
10.5	15	30.18	99.44	81.81
10.5	60	38.13	99.33	92.20
10.5	120	38.38	99.52	92.69
10.5	180	38.67	99.35	93.00
11.6	15	38.07	93.50	88.52
11.6	60	41.56	95.56	94.90
11.6	120	40.95	96.46	94.58
11.6	180	42.67	93.76	95.30
12.8	15	49.84	77.23	91.62
12.8	60	53.12	76.20	95.20
12.8	120	51.93	77.80	95.19
12.8	180	51.95	77.63	95.08

B. HORIZONTAL-DISPLACEMENT GAS CLASSIFICATION

1. Principle

A free-falling mixture of fertile and fissile particles is contacted by a horizontally-flowing air stream in which the smaller, less-dense fissile particles are displaced farther horizontally than the larger fertile particles. A partition, strategically placed in the trajectories of the particles, divides the particle stream into fissile and fertile particle fractions.

2. Description of Horizontal Classifier

The apparatus used in feasibility testing of the horizontal-displacement classifier is shown in Figure 3. The glass classifier was 4 inches in diameter and 8-inches high; a partition divided the vessel into two chambers of equal size. Particles were fed by gravity through a slot 1-inch long by 3/16-inches wide; air flowed through a perforated plate in a 1-inch diameter tube. The fraction of particles separated in each test were collected in graduated cylinders.

3. Experimental Testing and Results

Initial tests were made to evaluate the efficiency of particle separation as a function of air flow. Particles were fed to the classifier at their maximum rate (about 130 grams/minute). The data obtained during these initial tests are presented in Figure 4 which shows the resulting fissile-and fertile-particle fraction purities as a function of air flow rate. Acceptable purities for both fissile and fertile particles were not simultaneously achieved at any air flow rate studied by this method; low air flow and recycling of the fertile-particle fraction appeared necessary to obtain acceptable purities.

Several tests were then made in which the fertile-particle fraction was recycled as many as four times using various air flow rates. During the first few tests, one air flow rate was used for each of four recycle stages; the air flow rate was then increased and another four-stage cycle completed. In a final test, the air flow rate was reduced for each successive stage in a four-stage recycle test. These tests were the bases for the parametric curves showing fissile-and fertile-particle purities as a function of

Figure 3. Horizontal Displacement Classifier

Figure 4. Purity of Particle Fractions as a Function of Air Flow Rate in the Horizontal Classifier

number of recycle stages and air flow rate (Figures 5 and 6, respectively). Separation which resulted in both fissile and fertile particles simultaneously within acceptable purity limits was only achieved in one test--the one with decreasing air flow in each successive stage (and only after four stages).

C. CONCLUSIONS FROM FEASIBILITY TESTS

Although acceptable product purities were obtained on a bench-scale in both the vertical and horizontal gas classifiers, the results with the vertical model were much more promising. Because of these results, a decision was made to pursue the development of the vertical-displacement concept and discontinue work with the horizontal-displacement model. The principal factor in this decision was that particle purities much greater than minimum were easily obtainable in one stage of the vertical classifier, whereas barely minimum acceptable purities were only achieved after four stages with the horizontal classifier.

Equipment design consideration also favored pursuing the vertical concept instead of the horizontal. For the vertical-displacement method, column L/D and the height (or location on the column) of the particle feed point above the gas distributor appeared to be the only critical equipment design factors. However, for the horizontal-displacement methods, many more design factors must be considered ^(a), including: the air inlet dimension, the particle-feed inlet dimension, the location of the stream splitting divider (partition)--including horizontal distance from feed inlet, vertical distance below air inlet, and pitch--, the number of stages, and the particle recycle method (or a design to incorporate multiple stages without recycle -- such as a cascade). From the apparent complexity-of-development standpoint, the vertical-displacement method appeared more promising.

(a) Several other bench-scale horizontal models were tested in which particle-and air-inlet dimensions, partition location, and overall vessel configuration were varied. Separation efficiency was not seemingly improved in all models tested.

Figure 5. Purity of Fissile-Particle Fraction as a Function of Number of Stages and Air Flow Rate in the Horizontal Classifier

Figure 6. Purity of Fertile-Particle Fraction as a Function of Number of Stages and Air Flow Rate in the Horizontal Classifier

III. PILOT-PLANT GAS CLASSIFIER DEVELOPMENT

Based on the results of the bench-scale feasibility studies, a 2-inch diameter gas classifier pilot plant (GCPP) was constructed to continue the testing and development of the vertical-displacement gas classification method. Although feasibility of this concept had been demonstrated, it remained to demonstrate the concept on a pilot-plant scale where continuous particle feeding, continuous product withdrawal, and various fluidizing gas velocities could be studied. It was desirable also to study particle breakage and to generally observe the ease of operation of the classifier and its sensitivity to operating variables.

A. EXPERIMENTAL EQUIPMENT AND OPERATING PROCEDURES

The GCPP was designed based on scale-up of the bench-scale vertical displacement model. A flow diagram of the GCPP is shown in Figure 7. The classification column is a 2-in diameter Sch.40 stainless steel pipe 20 inches long with a 3-in diameter expanded top section 10-in long. Feed particles flow by gravity to the column from a 6" x 2" reducer feed pot through a ball valve in a 1/2-in diameter pipe. Gas enters the bottom of the classifier through a 1/4-in thick perforated steel plate distributor containing 75 holes 1/16-inch in diameter. Fluidizing gas and elutriated fissile particles leave the top of the classifier through a 1/2-in pipe and pass to a cyclone. The cyclone is 3 inches in diameter and 7 inches long having a conical bottom section 5 inches long. Elutriated particles are separated from the air in the cyclone and flow by gravity to a 6" x 2" reducer collection pot. Off-gas leaves the cyclone and enters a filter pot containing a sintered metal filter equipped for air blowback; a collection pot below the filter housing collects the fines. The off-gas from the filter is piped to the top of the enclosed module for release through HEPA filters.

Fertile particles are continuously withdrawn from the classifier through a 1/4" diameter pipe located on a 45° slope immediately above the distributor plate. Another 6" x 2" reducer is used to collect the bottom product. Air was used as the fluidizing gas in all runs.

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Figure 7. Gas Classifier Pilot Plant

The operating procedure was, 1) set the air velocity to the classifier column at the specified rate, 2) charge a known weight of feed to the feed pot, and 3) start flow of feed to the classifier by opening the feed control valve. No attempt was made to maintain a fluidized bed in the classifier; i.e., bottom product was continually withdrawn by gravity as rapidly as the fertile particles reached the distributor plate. Similarly, overhead product was continuously withdrawn, separated in the cyclone, and collected.

Following each run (a run consisted of separating approximately 2500 grams of particles), the contents of each collection pot were weighed, reduced to 100-g samples in a sample splitter, and screened through a 35-mesh screen in a sonic sifter. The "purities" of each fraction were determined by weighting the quantity of solids left on the screen and comparing that value to the quantity which passed through the screen.

At the completion of each run and analysis, the separated particle fractions were recombined, mixed, sampled, and the sample re-screened to determine if any particle breakage had occurred. During one run, the samples of the feed mixture and each product fraction were leached in a thorex acid solution to verify the amount of particle breakage.

The column is operated in a particle feed rate range of 80-250 grams/min and uses about 15 scfm of air. Based on processing 12 blocks/day of Ft. St. Vrain fuel, it is estimated that 250 kg/day of mixed fissile and fertile particles will be processed^[5]. This rate corresponds to a particle feed rate to the classifier of 175 grams/min. Therefore, the GCPP is approximately a "plant-scale" unit.

B. RESULTS OF EXPERIMENTAL TESTING

Twelve runs were made using four different feed rates and three different fluidizing velocities to define the effect of these variables on the separation efficiency^(a) of the classifier. These runs were

-
- (a) Separation efficiency is a measure of the purities of both the overhead (wt% fissile particles in fraction) and bottom (wt% fertile particles in fraction) fractions resulting from each GCPP run.

followed by six more where three different particle feed methods were studied. In all eighteen runs, particle breakage was evaluated by simple screen analysis and in one run, breakage was determined by chemical leaching of all particle samples.

1. Separation Efficiency

The results of the twelve runs at specified particle feed rates and fluidizing velocities are summarized in Table IV and plotted in Figure 8. A feed rate range of 80 to 250 grams per minute and fluidizing velocities in the range 10 to 11.7 ft/sec were used.

All classification runs were made using actual product from the four-inch diameter pilot-plant burner also being developed at ICPP. This product contained an average of five weight percent unburned graphite ranging from fine dust to 1/8" pieces. By far the largest amount of unburned graphite was smaller than 1/16". All but the few largest pieces of graphite (usually amounting to less than a dozen in a 2500 g run) were elutriated with the overhead (fissile particle) fraction in all runs. These large pieces would remain fluidized in the column throughout the run and would fall into the fertile particle collection pot only at the end of each run when the fluidizing air was shut off.

2. Particle Breakage

Particle breakage in the GCPP must be kept to a minimum to reduce the cross-mixing of heavy metals in both fissile and fertile particles. The extent of particle breakage in the GCPP was determined by screening the feed and product mixtures before and after each run and by microscopic examination of samples of each mixture. For one run, the samples were also subjected to a hot thorex acid leach to confirm the particle breakage results obtained by screening. (Leaching should give high values for particle breakage because particles which are only cracked or chipped will be counted as broken by the leaching analysis yet these particles will properly classify).

TABLE IV

SUMMARY OF GCPP RUNS DEMONSTRATING FT. ST. VRAIN PARTICLE
PURITIES AS A FUNCTION OF FEED AND AIR RATES

<u>Run Number</u>	<u>Superficial Fluidizing Air Velocity, ft/sec</u>	<u>Particle Feed Rate, g/min</u>	<u>Purity of Fissile Particles, wt%</u>	<u>Purity of Fertile Particles, wt%</u>
GCPP - 1	10	95	99.4	69.2
GCPP - 2	10	150	99.4	70.6
GCPP - 3	10	210	99.4	66.8
GCPP - 4	11.2	80	99.5	89.3
GCPP - 5	11.2	125	99.4	85.1
GCPP - 6	11.2	200	98.9	82.2
GCPP - 7	11.5	90	98.9	91.6
GCPP - 8	11.5	135	98.8	90.5
GCPP - 9	11.5	220	97.5	92.0
GCPP - 10	11.7	100	99.0	95.9
GCPP - 11	11.7	125	96.0	97.0
GCPP - 12	11.7	170	94.9	89.5

Figure 8. GCPP Product Purities as a Function of Feed Rate and Fluidizing Velocity

Particle breakage was high during initial scoping tests in the GCPP as a result of jet-grinding, caused by an improperly designed distributor plate. The original distributor plate had only 45 holes, 1/32-in diameter. Most of the holes were easily plugged by feed particles which resulted in high gas velocities through the remaining unplugged holes; a jet grinding action was thus imparted to the particles in the column. Particle breakage was as high as 20 percent using this initial plate. Increasing the number and diameter of the holes to 75 and 1/16-in, respectively, reduced particle breakage to less than 0.5 percent as determined by screen analysis. The leaching analysis indicated that the feed sample had 5.5% broken particles (by uranium analysis of the leachate), and the products from the classifier were found to have 5.4% breakage (the variance can be attributed to the difficulty in obtaining a representative sample). A thorium analysis of the leachate from the same sample showed 10.9% broken particles in the classifier feed and 13.4% broken particles in the classifier product. The variance in the analytical results between the uranium and thorium analyses will be discussed in a later section.

3. Particle Feeding

Three methods of feeding the classifier were studied: gravity flow, mechanical feeding and forced-air feeding. The feed particles (product from the primary burner) are free flowing even with up to 10 wt% unburned carbon, but steady-state gravity feed was difficult to maintain through the feed system. Frequently, pieces of unburned carbon lodged in the partially-opened feed control valve and restricted flow; however, the restriction could always be cleared by further opening the valve. A mechanical rotary (star) valve was found to feed continuously, but resulted in abrasion of the valve surfaces and excessive particle breakage. A commercial forced-air feeding device periodically plugged with graphite pieces in the feed. Preliminary tests using a similar but larger forced-air device did not result in frequent plugging.

C. DISCUSSION OF RESULTS

Separation of Ft. St. Vrain fissile and fertile particles by gas classification at near plant-scale rates has been demonstrated. Specified purities of both particle fractions were obtained with negligible particle breakage and with negligible interference from unburned carbon in the feed. Continuous, steady-state feeding was difficult to maintain with all three methods tried but the air jet method appears promising.

1. Separation Efficiency

The results of the parametric studies in the GCPP indicate that acceptable separation efficiencies can readily be achieved. The purity of the fissile-particle fraction appears slightly more sensitive to feed rate than does the purity of the fertile-particle fraction. The fertile-fraction purity, however, is considerably more sensitive to fluidizing air velocity than is the purity of the fissile fraction in the range studied.

As much as 5-percent unburned graphite in the feed to the classifier seems to have no adverse effect on the separation efficiency. Nearly all graphite is elutriated with the fissile fraction; the few large pieces which inevitably fall into the fertile fraction may pose a problem downstream of the classifier because they will have to be processed with the fertile particle in the particle crusher. The settling velocity of these large pieces is so close to that of the fertile particles that separation by gas classification is precluded. The large pieces are several times larger than the largest fertile particles, and could be separated from the particles by a grate located upstream of the particle crusher and recycled to the primary burner.

2. Particle Breakage

Particle breakage appears to be undetectable in a properly designed classifier. Particle breakage was significant in the initial classifier which had an improperly designed distributor plate; the modification which increased the size and number of holes

in the distributor plate essentially eliminated partial plugging of the holes and thus prevented jet grinding of the particles. Additional modifications to smooth the air flow path leaving the top of the classifier are expected to assure minimal particle breakage.

A leach analysis of product streams from the classifier gives high values of particle breakage because kernels of particles which are slightly cracked or chipped will be leached, indicating breakage, even though such particles will properly classify and not contribute to cross-mixing. The inconsistency between the uranium and thorium analyses can be attributed to at least two factors: 1) possible non-representative solids samples, and 2) the analytical technique for thorium is not well developed and involves a large number of steps. Thus, more confidence was placed in the results by the simpler uranium analysis. Nonetheless, the analyses showed that very little breakage is occurring in the classifier. The relatively high percentage of broken particles in the classifier feed is believed to have resulted during the fuel crushing and burning operations.

3. Particle Feeding

Gravity feeding was the most trouble-free of three particle feeding methods tested. However, steady-state gravity feeding was difficult to maintain because of the large pieces of unburned graphite which periodically plugged the feed control valve. The reliability of a gravity feed system for plant application is questionable. The reliability of a mechanical feeding device also appears questionable because of wear, lubrication requirements, etc., although the rotary valve tested did result in steady-state feeding. Forced air feeding systems appear most promising because they can potentially feed as steadily as a mechanical device while having the advantage of no moving parts. Additional testing of such a device is underway.

IV. CONCLUSIONS AND RECOMMENDATIONS

A method for separating unirradiated Ft. St. Vrain fissile and fertile particles by vertical-displacement gas classification has been successfully developed at ICPP. The vertical-displacement classification method was selected over several other classification concepts including vibratory screens, whizzers, cyclones, and a horizontal-displacement gas classifier. The feasibility of the vertical method was first determined using a bench-scale apparatus; this concept was then scaled-up to a two-inch pilot-plant system in which an acceptable range of operating variables was determined. The success of this development effort has proven the acceptability of gas classification in separating the two Ft. St. Vrain particle types. During the pilot-plant development studies, the following specific conclusions were derived.

1. The system has only been operated using unirradiated Ft. St. Vrain fuel particles. Therefore, care should be taken in extrapolating these results to irradiated fuel particles, especially from the particle breakage standpoint, because the effect of irradiation on the integrity of the SiC hull has not been thoroughly tested.
2. Greater than 95% pure fissile particles and 85% pure fertile particles can be obtained at a fluidizing velocity of 11.7 ft/sec. As great as 99% pure fissile particles and 96% pure fertile particles was obtained.
3. The fluidizing velocity should be kept between 10.5 and 12.5 to insure acceptable product purities.
4. From the bench-scale feasibility tests, increasing the residence time of particles in the column (i.e., maintaining a bed) did not appreciably increase product purities.
5. Large variances in particle feed rate (as much as 100 percent change) have a very small effect on the resulting purities of either fraction.

6. Steady-state feeding of the classifier was only achieved using a mechanical rotary feeder. However, severe abrasion of the feeder and significant particle breakage resulted. Gravity feeding was erratic because of the large variance in particle size. Forced-air feeding has not been thoroughly tested but offers promise as an acceptable method.

7. Particle breakage in the classifier can be virtually eliminated by a design which will insure a low pressure drop across the distributor plate and will prevent excessive particle contact with fixed surfaces such as in the overhead withdrawal piping.

8. All but the large pieces (1/16" - 1/8") of unburned graphite in the feed will be elutriated with the fissile-particle fraction.

9. Equipment scale-up should not be a significant problem, because the GCPP is already capable of processing Ft. St. Vrain particles at the estimated throughput rate for the HTGR Fuel Reprocessing Project.

Although the GCPP has been successfully demonstrated as an acceptable method for separating Ft. St. Vrain fuel particles, additional refinement of the design and definition of a workable feeding system are required. Specifically, it is recommended that:

1. The commercial Alpine Multiplex air classifier be comparatively tested with the GCPP to evaluate the merits of its unique "zig zag" design. Specifically, the manufacturer claims a much greater degree of separation for a fixed column height in the zigzag design than in the straight-column design of the GCPP.

2. Testing of the refined forced-air feeder and other feed mechanisms continue until an acceptable method for feeding primary burner product to the classifier can be defined.

3. The need for and a method of separating the unburned graphite from either classified fraction be evaluated.

4. The techniques for analyzing for uranium and thorium be refined. Ideally, a rapid "field" method is desirable for spot checking particle breakage.

5. Particulate flow metering devices be analyzed for potential application in detecting and counting particle flow in the classifier.

6. A series of tests be completed in the GCPP using CO₂ as the fluidizing gas in place of air. Projections are that use of air in the entire HTGR headend may be curtailed because of off-gas cleanup equipment requirements.

V. REFERENCES

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