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BREAKING SILICON CARBIDE COATED UNIRRADIATED
FT. ST. VRAIN FUEL PARTICLES BY JET GRINDING

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MASTER

DATE PUBLISHED—APRIL 1974

PREPARED FOR THE

U.S. ATOMIC ENERGY COMMISSION
IDAHO OPERATIONS OFFICE UNDER CONTRACT AT (10-1)-1375 S-72-1

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$4.00; Microfiche \$0.95

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ICP-1043

Chemical Separations Processes for
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Date Published -- April 1974

Prepared for the
U. S. Atomic Energy Commission
Idaho Operations Office
Under Contract AT(10-1)-1375 S-72-1

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ABSTRACT

The feasibility of using jet grinders to break unirradiated silicon carbide coatings from Ft. St. Vrain fuel particles was studied experimentally. The results show that jet grinding is an effective means of separating the silicon carbide coating from the uranium- and thorium-containing fuel kernel.

SUMMARY

During reprocessing of Ft. St. Vrain fuel, the silicon carbide coatings must be removed from the fuel particles during the particle crushing step to expose thorium and uranium carbides for burning and dissolution. Roll crushers, which have been considered for particle crushing, could require excessive maintenance. Jet grinding was studied as an alternative to roll crushing, because jet grinders are readily adaptable to remote operation and require little maintenance.

Jet grinding tests were made using a small jet inserted through the wall of an 11/16-inch I.D. glass column. The column contained a fluidized bed of unirradiated Ft. St. Vrain fertile particles. The particle breaking rate was determined as a function of jet size, jet orientation, and jet pressure. Graphite was also mixed with particles during some tests to determine its effect on the breaking rate.

The results show that the breaking rate is a strong function of jet size, jet orientation, and jet pressure, but is not appreciably affected by the presence of graphite particles. The jet grinder product is ideal for subsequent processing, because the unbroken kernel separates from the silicon carbide hulls. Few fines are generated; this reduces the potential for bridging and minimizes elutriation of unburned particles during secondary burning.

The difference between particle breaking rates of unirradiated and irradiated particles was not determined; the particle breakage rates and product size distribution may be significantly different for irradiated particles. No attempt was made to maximize particle breaking efficiency in this study; breaking efficiencies greater than reported herein are conceivable.

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I. INTRODUCTION

During head-end reprocessing of Ft. St. Vrain fuel, silicon carbide coated fissile and fertile particles (Figure 1) will be separated from the crushed graphite matrix by burning the bulk graphite in a primary fluidized-bed burner. The fissile particles (initially containing Th and U-235) and the fertile particles (initially containing only Th) will be separated in a gas classifier. The silicon carbide coating on particles from the classifier must then be broken to expose the inner carbon layers and the uranium and thorium carbide kernels for secondary burning.

During early pilot-plant development, the silicon carbide coatings were crushed by double-roll crushers at the desired throughput rates, but the roll tolerances and the gap settings required close monitoring. Wear, misalignment, or gap-setting changes in the order of three or four thousandths of an inch could result in unbroken particles or pulverized particles.

Close roll-crusher tolerances would be difficult to monitor and maintain in a "hot" cell. The roll crusher requires a motor, bearings, lubrication, and several moving parts, all of which could create serious problems for remote operation and maintenance. A jet grinder, on the other hand, has no moving parts, motors, bearings, or critical tolerances. The coatings on the particles are broken by particle impact on a plate or with other particles after being accelerated by a high-speed gas jet.

Fig 1. Silicon Carbide Coated Ft. St. Vrain Particle.

II. JET GRINDING PRINCIPLES

A jet grinder is an orifice through which gases normally flow at sonic velocity. This high-speed gas jet is used to accelerate solid particles to at least the minimum velocity (threshold velocity) required to fracture the particles upon impact with another object. There is a jet velocity above which the particles no longer enter or remain in the jet stream. In this case, the particles are deflected from the stream and are not fully accelerated.

The maximum gas velocity attainable through a jet orifice can be theoretically determined by combining the equations of mechanical energy and continuity, and assuming ideal gas behavior^[1,2]. The resulting equation is:

$$v_j^2 \max = C^2 = \frac{g_c \gamma P}{\rho} \quad C = \sqrt{\frac{g_c \gamma P}{\rho}} = \sqrt{\frac{g_c \gamma R T}{M}} \quad (1)$$

where

v_j	=	Jet velocity
C	=	Speed of sound
g_c	=	Gravitational conversion constant
γ	=	Ratio of heat capacities of the gas at constant pressure and constant volume: C_p/C_v
P	=	Absolute pressure
ρ	=	Gas density
R	=	Gas constant
T	=	Absolute temperature
M	=	Molecular weight of gas

Since the maximum velocity is reached only at the true throat of the nozzle, P , ρ and T are evaluated at the nozzle throat. If P_3 (Figure 2) is decreased while P_1 is held constant, the gas velocity will increase until P_2 reaches a critical value corresponding to sonic gas velocity. Lowering P_3 beyond this value will not decrease P_2 or increase the gas velocity further. The critical pressure is given by the equation:

$$P_{2c} = P_1 \left(\frac{2}{\gamma + 1} \right)^{\gamma/(\gamma-1)} \quad (2)$$

$$\frac{P_{2c}}{P_1} = 0.528 \quad \text{for diatomic gases} \quad (3)$$

This result implies that whenever the upstream pressure is twice the throat pressure, the gas velocity is sonic. Increasing P_1 will not increase the gas velocity, but will increase the mass flow rate because the gas density is increased.

Fig. 2. Flow of Gas Through the Jet Orifice.

III. EXPERIMENTAL JET GRINDER TESTING

A sketch of the equipment used for the jet grinding experiments is shown in Figure 3. The column and cyclone were constructed of glass, and the jet grinders were 1/8-inch O.D. stainless steel tubing, welded closed on one end with a single small hole drilled through the tube wall.

During the experimental testing, fluidizing air flowed through a rotameter, into the vessel plenum, through a porous glass distributor plate, and through the bed of fissile and fertile particles.

The jet air, after metering, flowed through the jet orifice and impinged on a stainless steel impact plate, except during four runs when the jet either impinged on another jet, the vessel wall, or was directed into the bed. The jet air accelerated the fluidized particles which fractured on impact with the plate or other particles. The kernels from the broken particles settled to the bottom of the bed, and the hulls and fines were elutriated by the combined jet and fluidizing air. The bulk of the fines and hulls were separated from the gas stream by a cyclone and collected in a graduated cylinder. The remainder of the fines was collected on a filter.

The fertile particles used for the starting bed were prepared by burning the graphite matrix from scrap fuel compacts. The particles were then screened into + 35 U.S. Mesh (fertile) and - 35 U.S. mesh (fissile) fractions.

With the exception of Run 14, all starting beds consisted of 10 grams of fertile particles; the duration of each run was one hour. The starting bed in Run 14 consisted of 22.2 g of fertile particles, and the duration of the run was 50 minutes.

Operating procedures were: set the jet and fluidizing air flowrates, charge the bed to the column, and shut off the jet and fluidizing air after operating for one hour. During each run, the overhead volume was recorded as a function of time. After the run, the bed and overhead fractions were weighed and screened to determine their size distributions.

Fig. 3. Flow Diagram of the Experimental Jet Grinding Equipment.

IV. OPERATING CONDITIONS AND RESULTS

Operating conditions and results of the jet grinding tests are summarized in Table 1. The first three runs were made to determine the effect of two jets in the bed on particle breaking rate. The effect of jet diameter on breaking rate was studied in Runs 4, 5, 6, 10, and 11. Runs 7 and 8 were made to study the effect of jet pressure on breaking rate. Runs 9 and 12 were used to determine the effect of the presence of graphite on breaking rate. Run 13 provided additional information on the effect of jet orientation on breaking rate, and Run 14 was made to provide a reliable material balance.

Four different jet sizes were tested. Table 2 gives the diameter and cross-sectional area for each jet used in the runs. Three jet pressures were tested: 20, 35 and 50 psig. To determine if graphite particles would interfere with jet grinding, one gram of -4 +25 mesh graphite was added to the bed during Run 9, and one gram of -18 +25 mesh graphite was added to the bed during Run 12. Three jet orientations were tested: (1) upward, (2) horizontal, and (3) vertically opposed. All jet orientation tests were made with 0.0135-in.-diameter jets.

Since the run length and the starting bed weight were constant for the first 13 runs, the final overhead volume was used in the data analysis as a measure of relative breaking efficiency. The relative breaking rates were determined by recording the volume of overhead product as a function of time for each of the runs. Since the jet air rate was constant during a given run, the jet air usage was determined by dividing the overhead product volume by the volume of jet air required to produce that product volume.

Several graphs were plotted using the data to show the effect of the operating variables on breaking rate, breaking efficiency, and air usage. The overhead volume collected in the graduated cylinder as a function of time is shown in Figure 4 to indicate the relative breaking rates for each of the first 13 runs.

These data are also plotted in Figures 5 through 7 to show the effect of jet cross-sectional area and jet air pressure on breaking rate and air usage. Table 3 compares the effects of jet orientation in the bed on air usage. The overhead product size distribution for eight runs is plotted in Figure 8.

Run 14 was made specifically to obtain material for chemical analysis of the jet grinder products. Three product samples were analyzed: the final bed, the overhead product collected during the first 15 minutes of the run (approximately 80% of the particles were broken in that time period), and the overhead product from the remaining 35 minutes of the run. The results of the chemical analyses are summarized in Figure 9.

TABLE I
SUMMARY OF JET OPERATING CONDITIONS AND RESULTS

Run No.	Orifice Diameter, inches	No. Jets	Jet Orientation	Jet Pressure, psig	Jet Air, scfm	Fluidizing Air, scfm	Graphite Added to Starting Bed	Final Overhead Volume, cc	cc Overhead/ scf Jet Air	Bed -35 Mesh, %
1.	0.0135	2	Up ^(a)	50	0.25	1.04	No	2.40	0.160	54.6
2.	0.0135	2	Opposed ^(b)	50	0.25	1.04	No	2.1	0.140	45.6
3.	0.0135	2	Plate ^(c)	50	0.25	1.04	No	1.77	0.118	39.5
4.	0.0135	1	Plate ^(d)	50	0.125	1.17	No	1.80	0.240	41.4
5.	0.0210	1	Plate	50	0.40	0.89	No	3.40	0.142	86.1
6.	0.0280	1	Plate	50	0.53	0.32	No	3.10	0.097	82.0
7.	0.0135	1	Plate	35	0.09	1.20	No	0.78	0.144	16.7
8.	0.0135	1	Plate	20	0.05	1.25	No	0.20	0.067	2.0
9.	0.0135	1	Plate	50	0.125	1.17	Yes	0.95	0.127	9.0
10.	0.0350	1	Plate	50	0.88	0.02	No	3.07	0.058	74.4
11.	0.0135	1	Plate	50	0.125	1.17	No	1.90	0.253	43.0
12.	0.0135	1	Plate	50	0.125	1.17	Yes	2.00	0.267	39.0
13.	0.0135	1	Up ^(e)	50	0.125	1.17	No	0.22	0.029	3.5
14.	0.0280	1	Vessel Wall ^(f)	50	0.53	0.90	No	9.00	0.340	99.5

(a) Jets located at midpoint of bed and near top of bed--both pointing upward 1 inch apart.

(b) Jets located at midpoint of bed and near top of bed--jets pointing at each other 1 inch apart.

(c) Jets located at midpoint of bed and near top of bed-- both pointing at impact plate 1/8 inch away.

(d) Jet located at midpoint of bed-- pointing at impact plate 1/8 inch away.

(e) Jet located at midpoint of bed-- pointing upward.

(f) Jet located at midpoint of bed--pointing at vessel wall 1/4 inch away.

TABLE 2
JET-SIZE DATA

<u>Jet Diameter, in.</u>	<u>Jet Area, in.²</u>
0.0350	0.000962
0.0280	0.000616
0.0210	0.000346
0.0135	0.000143

Fig. 4. Particle Breaking Curves for Thirteen Jet Grinding Tests.

Fig. 5. Effect of Jet Size on Particle Breaking.

Fig. 6. Effect of Jet Size on Air Usage.

Fig. 7. Effect of Jet Pressure on Particle Breaking and Air Usage.

V. DISCUSSION OF EXPERIMENTAL RESULTS

Three groups of particle breaking rate curves are shown in Figure 4: very rapid breaking, very slow breaking, and an intermediate group. Jets larger than 0.0135-in.-diameter resulted in the three very rapid breaking curves. The very slow breaking group resulted from: (1) two runs made at jet pressures lower than 50 psig, (2) a run in which graphite particles had been added to the bed and graphite particles lodged between the jet and impact plate, and (3) a run without an impact plate. The intermediate group resulted from: (1) the three runs with two jets, (2) one run made with graphite particles in the bed, and (3) two runs with an impact plate and 50 psig jet pressure. Run 1 resulted in an unusual curve because sufficient force was available from the two jets pointing upward to elutriate the entire bed, including whole particles. After the run, the overhead product was returned to the column and fluidized comparably to the other runs. The resulting overhead product volume of 2.4 cc rather than the initial value of 4.50 cc was used in the data analysis.

A peak rate occurs between 0.0002 in^2 and 0.0006 in^2 jet cross-sectional area, as shown in Figure 5. Although the three larger jets tested were almost twice as effective as the smallest jet on the basis of overhead volume collected, the larger jets used 3-to-7 times more air. Figure 6 is analogous to Figure 5, but the ordinate in Figure 5 was divided by the total jet air used during the one-hour run. It appears that air usage efficiency decreases rapidly with increasing jet size.

The results shown in Figure 7 indicate that regardless of whether air usage efficiency or breaking rate is considered, the highest pressure was the most effective.

The horizontal jet with an impact plate was the most effective orientation as shown in Table 3. Two jets used in conjunction with an impact plate were not as effective as a single jet; this result indicates that the 11/16-in. I.D. column was possibly not large enough for the two jets to be independent. The two opposing jets should be very effective, but it was difficult to insure that the two very small air streams impinged on one another. If they were misaligned slightly, they would probably be no more effective than two separate jets without impact plates.

The results of Run 9 appeared to show a decrease in breaking rate when graphite was added to the bed; actually, the larger graphite pieces were lodging between the jet tube and impact plate and preventing the fertile particles from entering the jet stream. When smaller graphite pieces were used in Run 12, the graphite did not lodge in front of the jet, and no decrease in the breaking rate was observed.

The average overhead product size, as shown in Figure 8, is 45 mesh (~ 0.014 in. diam). Data for some of the runs are not presented because the resulting overhead sample was either too small for an accurate screen analysis or graphite added to the bed drastically changed the size distribution.

The most surprising result of the experiments was the manner in which the fertile particles were broken. The jet grinder cracked the silicon carbide hull and buffer layers in half, and the whole, unbroken kernel separated from the hull. A photograph of a typical broken particle showing the cracked hull, buffer carbon, and whole kernel is shown in Figure 10.

Almost 100% of the particles were broken in half, and few fines were generated. Immediately upon cracking, the hulls were elutriated from the bed before further breakage could occur. The ThC_2 kernel, which is very tough, remained unbroken in the bed. Microscopic examination of the bed following each run failed to show any broken kernels. When the kernel is released from the hull, very little carbon is left on the kernel and little thorium remains with the carbon buffer layer. Chemical analysis of the jet grinding products shows that 99% of the thorium remains in the bed and only 1% is elutriated with the hulls and carbon. Nearly all of the silicon carbide and 90% of the carbon also leaves the bed to form the overhead product.

TABLE 3
EFFECT OF JET ORIENTATION ON AIR USAGE

<u>Orientation</u>	<u>No. of Jets</u>	<u>Overhead, cc/Jet Air, scf</u>
Upward	2	0.160
Opposed (vertical)	2	0.140
Impact Plate (horizontal)	2	0.118
Upward	1	0.029
Impact Plate (horizontal)	1	0.240, 0.253, 0.267

Fig. 8. Overhead Product Size Distribution.

* NOTE: OVERHEAD # 1 WAS THE OVERHEAD PRODUCT COLLECTED DURING THE FIRST 15 MINUTES OF THE RUN. APPROXIMATELY 80 % OF THE PARTICLES WERE BROKEN DURING THIS TIME PERIOD. OVERHEAD # 2 WAS COLLECTED DURING THE REMAINING 35 MINUTES OF THE RUN.

Fig. 9. Run 14 Product Analyses Showing Mass Balance of Thorium, Carbon, and Silicon Carbide.

Fig. 10. Fertile Particle Broken by Jet Grinding.

VI. CONCLUSIONS AND RECOMMENDATIONS

Jet grinding is a candidate for breaking Ft. St. Vrain fuel particles. Based on preliminary experimental studies using unirradiated Ft. St. Vrain fertile particles, (1) required maintenance is low, (2) equipment is simple and easy to operate, (3) crushing efficiency is essentially independent of wear relative to a roll crusher, and (4) the product particle size is relatively large with few fines (large particles decrease the fines bridging potential during solids transport and elutriation of fines during secondary burning). A plant-size jet grinder would require a considerable quantity of jet gas (~35 scfm based on maximum test rates) and hence generates considerable off-gas. If required, generation of excessive off-gas could be reduced by recycling the off-gas to the jets or to other process equipment.

Although the purpose of the preliminary tests was not to maximize breaking efficiency, the results identify those factors which significantly influence breaking efficiency. If the number of jets must be minimized, a jet with a cross-sectional area between 0.0002 and 0.0006 in² is the best choice. If gas consumption is to be minimized, a jet area of 0.00014 is superior. Based on gas consumption or the breaking effectiveness of one jet, the highest practical gas pressure to the jet is the most effective in breaking the particles. The most effective jet arrangement is horizontal orientation used in conjunction with an impact plate. The addition of one gram of graphite to 10 grams of bed does not affect breaking efficiency.

Since only 1% of the thorium elutriates with the hulls, the overhead product could possibly be discarded (assuming irradiated particles break similarly to the unirradiated particles) or burned and leached separately from the bed. Another possibility might be to install jet grinders in the secondary burner to allow simultaneous breaking and burning.

Further studies should evaluate: (1) the effect of jet-to-impact-plate distance on breaking efficiency, (2) the effect of gas pressures higher than 50 psig on breaking efficiency, (3) erosion rates of impact plates and jets, (4) the effectiveness of continuous operation, (5) the problems in recycling the jet grinder off-gas, and (6) the effectiveness of jet gases other than air on particle breaking.

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