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TITLE MAGNETIC SEPARATION AS A PLUTONIUM RESIDUE ENRICHMENT PROCESS

AUTHOR(S) LARRY R. AVENS, NMT-6
JAMES T. MCFARLAN, NMT-6
UBALDO F. GALLEGOS, NMT-2

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Magnetic Separation as A Plutonium Residue Enrichment Process

L.R. Avens, U.F. Gallegos, and J.T. McFarlan

Actinide Materials Chemistry Group
Los Alamos National Laboratory
P.O. Box 1663, MS F-510
Los Alamos, New Mexico 87545

ABSTRACT

We have subjected several plutonium contaminated residues to Open Gradient Magnetic Separation (OGMS) on an experimental scale. Separation of graphite, bomb reduction sand, and bomb reduction sand, slag, and crucible, resulted in a plutonium rich fraction and a plutonium lean fraction. The lean fraction varied between about 20% to 85% of the feed bulk. The plutonium content of the lean fraction can be reduced from about 2% in the feed to the 0.1% to 0.5% range dependent on the portion of the feed rejected to this lean fraction. These values are low enough in plutonium to meet economic discard limits and be considered for direct discard.

Magnetic separation of direct oxide reduction and electrorefining pyrochemical salts gave less favorable results. While a fraction very rich in plutonium could be obtained, the plutonium content of the lean fraction was to high for direct discard. This may still have chemical processing applications.

OGMS experiments at low magnetic field strength on incinerator ash did give two fractions but the plutonium content of each fraction was essentially identical. Thus, no chemical processing advantage was identified for magnetic separation of this residue.

The detailed results of these experiments and the implications for OGMS use in recycle plutonium processing are discussed.

INTRODUCTION

Magnetic separation is a method for the segregation of materials based on differences in magnetic susceptibility. One magnetic separation method called Open Gradient Magnetic Separation (OGMS) can be used on dry powders. When a powder encounters a strong magnetic field, particles with an overall positive susceptibility (paramagnetic) are attracted toward the highest field gradient while those with an overall negative susceptibility (diamagnetic) are repelled from the highest field gradient. This phenomenon serves as a basis for physical separation.

Our interest in the magnetic separation of plutonium residues began when we learned of Oak Ridge National Laboratory magnetic separation work on uranium (1,2). Some success was shown in the separation of uranium from magnesium fluoride. We chose to examine magnetic separation of plutonium residues since the magnetic susceptibility of plutonium and its compounds is similar to, or in some cases greater than, that of uranium (Figure 1).

Judging from Figure 1 we should be able to separate many common impurities from plutonium by OGMS. All compounds with a negative susceptibility should react in the opposite direction from plutonium compounds in a magnetic field. Also,

if the residue could be ground into a powder fine enough for all the particles present to be discrete compounds, then a perfect separation is possible. However in practice this is not practical. As the particles become very small (below about 50 micrometers) other physical forces such as electro-static attraction, become similar in magnitude to the force of gravity or the force created by the magnetic field. This is one reason a complete or perfect separation is difficult to achieve. Since we are forced to work with larger particles we can assume that many of the large particles are not dis-crete phases but mixtures. Thus, the deflection of a particle under the influence of a magnetic field is proportional to the weighted average of the volume magnetic susceptibilities of the particle components.

Given these facts we can see that complete separation should not be a goal of this separation method. A more real-istic goal would be to process residues in such a manner as to obtain a plutonium rich fraction and a plutonium lean fraction. The rich fraction would then be processed for plu-tonium recovery while the lean fraction could be discarded directly if its plutonium content met economic discard lim-its. If such a separation could be made numerous benefits would be realized, e.g. reduced feed bulk into a dissolver,

richer solution from dissolution into ion exchange or solvent extraction, and reduced salt load in subsequent evaporation steps.

Chemical (solution) methods of plutonium recovery processing generate large quantities of waste. A dry separation method, however, woulu not create any "new" waste and would allow direct discard of a portion of the residue. Such a method would certainly be beneficial to the DOE defense complex in light of recent waste minimization guidance. Hence, we have evaluated magnetic separation as a plutonium residue enrichment process for several contaminated residues and report the results here.

EXPERIMENTAL

The equipment used for this magnetic separation work is the Magnetic Barrier Laboratory Separator (Model LB-1) purchased from the S.G. Frantz Company Inc (3). The separator was installed in a glove box enclosure and slightly modified by removing all electronic controls and locating them outside the glovebox enclosure. Also, an alternative power supply (Model TCR-150-S4-1D-10T) was purchased from Electronic Instruments Inc. to allow operation at 2.0 Amps. At this power level the magnetic field is approximately 20,000 Gauss in the working area. The LB-1 separator has a magnetic force to

field gradient ratio approximately 3.5 times larger than the Model L-1 separator used in the ORNL work (1).

The LB-1 concentrates mixtures in three different modes diamagnetic, paramagnetic or ferromagnetic. The selected mode depends on the magnetic susceptibility of the species one wishes to isolate or concentrate. In general, the sample is fed onto a vibrating tray at a pre-determined rate. Flow rate along the tray is determined by a combination of slope (longitudinal angle) and vibration amplitude. The application of a magnetic field effects separation based on the magnetic susceptibility of the particles. The force exerted on the particles is in a direction perpendicular to the particle flow and field direction. (This separation aspect is unique to the Barrier Magnetic Separator.) Diamagnetic particles experience a force which urges them toward the operator (away from the magnet) while the converse is true of paramagnetic particles. At the lower end of the tray a divider at the center line separates the particles into two fractions (Figure 2).

Diamagnetic separation is effected by additional sloping of the feed tray in a direction perpendicular to the direction of flow and away from the operator (negative transverse angle). The sample is fed into the apparatus at the top of

the tray and toward the front (i.e. nearest the operator) .
In the absence of a magnetic field the particles move away
from the operator and to the rear of the chute. When the
field is applied, diamagnetic particles are repelled and pre-
vented from crossing the chute center line by the field gra-
dient while paramagnetic particles are drawn across the chute
center line by both gravity and the field. In operation, the
fraction collected nearest the operator is enriched in the
diamagnetic portion of the feed.

Conversly, paramagnetic separation requires the chute be
oriented with a positive transverse angle (i.e. toward the
operator). The feed material is introduced at the rear of
the tray (away from the operator). Now gravity draws the par-
ticles down the tray and towards the operator with paramag-
netic particles prevented from crossing the tray center line
by the magnetic field. We have used the paramagnetic separa-
tion mode more than the diamagnetic separation mode in this
work because we wished to concentrate the paramagnetic pluto-
nium compounds from the feed matrices which are largely dia-
magnetic. However, the diamagnetic mode has use if a frac-
tion very low in paramagnetic species is desired.

Ferromagnetic separations require the use of the "Low
Field Control" unit. This vendor supplied option allows

operation of the separator at low magnetic fields, thereby allowing separation of materials containing ferromagnetic particles.

Very sensitive separations can be made through: 1) adjustment of longitudinal and transverse tray angles, 2) control of the magnetic field strength, and 3) multiple sample passes under various conditions.

Sand, slag, and crucible (SS&C) residue, bomb reduction sand, contaminated graphite, electrorefining (ER) salt, direct oxide reduction (DOR) salt and incinerator ash were the test matrices evaluated by OGMS. In general the residues were crushed and sized through standard sieves to remove fine particles. Particular information concerning particle sizes is included in the discussion of each residue studied. Experimental runs used 30 to 200 grams of bulk residue. The longitudinal tray angle was held at 20 degrees throughout our experimental work.

Plutonium values were obtained by two methods; nondestructive neutron counting and certified destrucive radiochemical analysis by the analytical chemistry group (CLS-1) at Los Alamos National Laboratory. For some residues high levels of americium or light elements (fluoride, magnesium, carbon, etc.) introduced considerable uncertainty in

the neutron count results. However, since the neutron results were used as a comparison between rich and lean fractions, rather than absolute plutonium values, these uncertainties do not affect our conclusions.

Usually, a plutonium contaminated residue was run through the separator under a variety of operating conditions with neutron counting used to give an indication of separation performance. When a particular separation protocol was determined (based on the neutron counting) the samples were remixed and the separation repeated using the determined separation parameters. Samples were then collected for certified analysis. When the quantity of plutonium contaminated residue permitted, three samples were subjected to magnetic separation to increase statistical confidence in the result.

RESULTS AND DISCUSSION

A. Sand, Slag and Crucible

Sand, Slag and Crucible (SS&C) residue results from the chemical reduction of plutonium tetrafluoride to plutonium metal using calcium metal as the reductant (4). The byproduct is a calcium fluoride slag. The reduction occurs in a magnesium oxide crucible that cannot be reused. The crucible is insulated from the pressure vessel with magnesium oxide sand.

SS&C is a lean residue, generally containing only 1-5% plutonium. The plutonium recovery method at Los Alamos involves grinding and pulverization of the residue prior to nitric acid dissolution (4). The plutonium is recovered and purified by ion exchange from the nitric acid solution.

Economic discard levels vary from site to site and year to year and are highly dependent on the particular residue (4). In general, recent discard levels for SS&C have been between about 5 and 10 grams of plutonium per kilogram of bulk material. We hoped to acheive separation such that an appreciable quantity of the feed material would meet these economic discard limits.

For our magnetic separation experiments we intercepted a batch of SS&C residue after crushing and pulverization. We first wished to investigate the effect of particle size on separation. Thus, a portion of the SS&C was seived through two screens with openings of 250 and 90 micrometer. This gave three fractions with: 1) particle sizes larger than 250 micrometer, 2) smaller than 250 but larger than 90 micrometer, and 3) smaller than 90 micrometer. X-Ray diffraction showed that the fraction less than 90 micrometer in size was mostly calcium fluoride. Also, scanning electron microscopy (SEM) of various samples of SS&C found the chemical form of the pluto-

nium to be exclusively plutonium oxide. The plutonium present in the residue appeared as plutonium rich inclusions in magnesium oxide, calcium oxide or fluoride rather than discrete particles of plutonium oxide (Figure 3).

Paramagnetic separation test results and operating parameters for these samples are shown in Table 1. The parameters used for these experiments were arrived at through separate experiments where neutron counting was used as the diagnostic. In the initial experiments a small portion (about 0.5%) of ferromagnetic material was invariably found adheared to the magnet pole pieces. In any large scale operation removal of the ferromagnetic material prior to separation at high field would be required.

While there are a variety of ways to report the results, we chose to give the bulk split and the plutonium split. The bulk split is simply the percentage of the feed that reports to the diamagnetic and paramagnetic fractions. The plutonium split is the plutonium content of either the diamagnetic or paramagnetic fraction in grams of plutonium per kilogram of bulk in that fraction. For example, in Table 1 the sample with particles larger than 250 micrometer splits into a diamagnetic fraction that consist of 67.3% of the feed for the experiment. This fraction has a plutonium content of about

7.6 g Pu/kg of bulk.

Separation was most effective on the largest particle size fraction with over 67% of the material being rejected as diamagnetic in one pass with a plutonium content of 7.64 g Pu/kg of bulk. Separation was less effective on the intermediate sized fraction. Here, about 32% of the feed was rejected with a plutonium content of 6.00 g Pu/kg of bulk. Even at the relatively high transverse angle of 3u degrees, only 7.7% of the bulk of the fine fraction was rejected. Also, the plutonium content (this fraction was too high to be considered for direct disposal. Repeated pass experiments through the magnetic field were not performed on these samples.

The success with the seived material led us to examine the paramagnetic separation of SS&C as received. We quickly found that no set parameters would reliably give a lean fraction low enough in plutonium to be considered discardable.

Another group of experiments was conducted using repeated passes through the field in the paramagnetic mode. Here, three feed samples were passed through the magnetic field at a relatively high transverse tray angle, then only the lean fraction was recycled through the field at successively reduced transverse tray angles until the lean fractions had a

plutonium content below 10 g Pu/kg of bulk.

The results from these experiments are shown in Table 2. To acheive a discardable component from all the samples, four passes through the field were required. Also, the discardable fraction consist of only about 33% of the original feed.

Table 3 shows the results from a similar experiment where particles smaller than 45 micrometer were removed from the SS&C before magnetic separation. Here only three passes were required to acheive the discard level on all three samples. Also note that two of the three samples reached the discard level after only two passes. Another important point is that the discard fraction comprises about 66% of the feed bulk. This lean fraction contains only about 25% of the plutonium in the feed batch.

The question arises that if separation at 15 degrees transverse tray angle gives a discardable lean fraction, why not hold this parameter constant and attempt to acheive a one pass separation? Experiments to demonstrate this were unsuccessful. It appears that if one attempts to separate too large a fraction in one pass the separation efficiency suffers. Modest feed rates (about 10 g bulk/min), separating modest fractions of material appear to give "complete" separation under that set of conditions. For example, other

experiments showed that if SS&C was run at 35 degrees trans-
verse angle and the plutonium rich paramagnetic fraction was
run again under the same set of conditions, no separation
occured on the second pass.

The same samples were subjected to magnetic separation
in the diamagnetic mode. The results in Table 4 indicate that
20 to 30% of the feed can be rejected with the very low plu-
tonium content (about 1 to 2 g Pu/kg bulk).   This is quite
impressive since these results were obtained in only one
pass. The scatter in the results is likely due to incomplete
seiving of the sample with the high plutonium value. Similar
results were observed in the paramagnetic separation results
(Table 3).

One would expect that the rich fraction from the dia-
magnetic separation experiments could be reprocessed in the
paramagnetic mode to acheive higher overall separation per-
formance (more feed rejected with a low plutonium content).
However, attempts to demonstrate this separation protocol
were unsuccessful.

Magnetic separation of SS&C as received in the diamag-
netic separation mode gave a maximum of 20% of the bulk re-
jected into the lean fraction. However, the plutonium content
of this fraction was above 20 g Pu/kg of bulk. This again

demonstrates the detrimental effects of fine particles.

A few experiments were conducted to examine the effect of feed rate on separation performance. We found that separation suffers at rates above about 10 g/min. Similar results were obtained for most of the residues examined in this study.

B. Bomb Reduction Sand

A recent change at Los Alamos is the segregation of the bomb reduction sand from the slag and crucible to moe' fine particle limits for waste destined for the Waste Isolation Pilot Plant. The bomb reduction sand is fused electrical grade magnesium oxide. The sand is used to insulate the reduction crucible from its outer pressure containment vessel in the bomb reduction process. Several experiments were conducted to acheive magnetic separation of a plutonium rich fraction from this material. The L3-1 was operated exclusively in the paramagnetic mode for these separations.

Table 5 shows the results from two samples of sand. Again a trace of ferromagnetic material was observed. The sized sand was seived before it was introduced into the glovebox line for use in the bomb reduction process. (The

sand used was held on a screen with 90 micrometer openings.)
After the sand was used in the normal mode of operation in
the bomb reduction process it was passed through the mag-
netic field only once at a transverse tray angle of 15 de-
grees. As the results show, most of the plutonium was concen-
trated in only 15 percent of the bulk while the lean fraction
is well into the discard range. The separation performance
here is quite impressive. It has been pointed out that the
lean fraction could be recycled to the bomb reduction pro-
cess. Magnetic separation with recycle of the lean fraction
to bomb reduction would lead to a substan ial reduction in
the sand requiring chemical recovery. This reduction in bulk
to dissolution is significant as it has been estimated that
over 1000 l of solution waste is generated in the chemical
recovery of 1 kilogram of plutonium from this lean residue.

Magnetic separation of the sand as it was received from
the bomb reduction process was not as favorable. The result
reported is from the 15 degree magnetic separation pass. How-
ever, two passes at a transverse tray angle of 30 and 20 de-
grees were performed on this sample prior to the 15 degree
run. After the 30 and 20 degree runs the lean fraction still
held 14 g Pu/Kg of bulk. Also, it should be noted that the
rich fraction is twice as large here as in the sized sand re-

sult. Since we did not attempt a one pass 15 degree run on this sand sample we cannot say that a one pass separation is not possible. However, we feel that the advantages of sizing the sand prior to use in the bomb reduction process are readily apparent.

C. Graphite

Graphite is widely used as casting molds for actinides (4). Recovery methods generally center around either crushing the molds or grinding away the surface where the plutonium contamination resides. The resulting graphite powders are then leached in nitric acid to selectively dissolve the actinides. Economic discard levels for this residue are generally in the range of 5 g Pu/kg of bulk.

For our magnetic separation experiments a portion of a graphite mold was crushed in a mortar and seived through 60 mesh (250 micrometer opening) and 170 mesh (90 micrometer opening) screens. The material not passing the 170 mesh screen was subjected to magnetic separation in the paramagnetic mode. The results in Table 6 show that over 40% of the graphite can be rejected with a plutonium content of about six grams of plutonium per kilogram of graphite. Doubtless a fraction leaner in plutonium could have been obtained with

further passes at lower transverse tray angle. Experiments were discontinued due to the relatively high radiation field from the americium content of the sample.

D. Incinerator Ash

Incinerator ash results from the burning of plutonium contaminated materials. The particle size of the ash was quite small and no sizing of these residues was performed. The residue is relatively rich in plutonium (up to 30%) but is extremely difficult to chemically process for plutonium recovery. The processing difficulties arise from the variability of ash composition and recalcitrant nature of the plutonium oxide in the residue.

Essentially all DOE sites have used incineration as a volume reduction method. Due to the difficulty of processing the economic discard limits for this residue are relatively high at about 25 g Pu/kg of bulk. Current process technology involves a nitric acid leach with plutonium recovery from the acid solution.

Table 7 shows our magnetic separation results. Since the ash contains a large portion of ferromagnetic material, our separation experiments were conducted at low magnetic field strength and the results are reported for the more magnetic

and less magnetic fractions. For calcined ash we found that parameters could be adjusted such that a separation could be acheived. However, both the more magnetic fraction and the less magnetic fraction contained similar quantities of plutonium.

Since the paramagnetic susceptibility varies between various compounds of an element (Figure 1) we attempted magnetic separation of fluorinated ash. Here a lean fraction depleted in plutonium was obtained but the plutonium level was so high and the size of the fraction so small that little processing advantage would result from such a separation.

We also demonstrated magnetic separation of leached incinerator ash heel. Here a lean fraction consisting of 14 percent of the bulk was obtained. The plutonium content of this fraction was near the discard level but it is questionable that separation of such a small fraction would be useful.

It is possible that some incinerator ash matrices exist that would give more favorable results with OGMS. This was not pursued.

E. Pyrochemical Salts

1. Electrorefining Salt

Electrorefining (ER) is an electrochemical purification process for plutonium metal (4). In this process impure plutonium metal is oxidized to Pu III anodically and is transported through a sodium/potassium chloride molten salt phase to a cathode. The plutonium III is reduced to pure metal at the cathode and is collected. At the end of the purification process the salt contains a considerable amount of plutonium chloride and plutonium metal shot.

Various process technologies have been used to recover the plutonium present in this salt matrix (4). Dissolution of the salt in caustic followed by filtration gives a filtration cake low in chloride. This cake is then dissolved in nitric acid to give a chloride to nitrate conversion. Purification is then acheived in the nitric acid system. More recently Los Alamos, Rocky Flats Plant, and Pacific Northwest Laboratories have developed chloride solution ion exchange and solvent extraction processes for pyrochemical salt recovery (4).

The limited development of aqueous process technologies and the problems of handling corrosive chloride solutions in

stainless steel glovebox enclosures have led to economic discard limits which vary between about 5 to 25 grams of plutonium per kilogram of bulk residue.

Our magnetic separation results for this residue are reported in Table 8. The ER salt sample was received in the crushed and pulverized condition and was split into three smaller samples for the separation experiments. Sample A was subjected to separation in the paramagnetic mode. A small fraction (2%) very rich in plutonium was obtained but the lean fraction was much too high in plutonium to be considered discardable. Further test in the paramagnetic separation mode showed that if the transverse angle was reduced to the point that more material was transported into the rich fraction, selectivity suffered (i.e. the plutonium content of the separated fractions was very near their initial value). The remainder of the experiments were conducted in the diamagnetic separation mode.

Similar to the paramagnetic separation results, diamagnetic separation results from sample B show that a fraction rich in plutonium can be obtained. However, the lean fraction is still far above any reasonable discard limit.

Sample C was seived to remove particles smaller than 90 micrometer. While this appears to improve separation, the

lean fraction is still high in plutonium.

One reason as to why magnetic separation of ER residue fails to give a very lean fraction may be due to the chemical form of the plutonium in the salt. If a portion of the plutonium in the ER salt exist as a plutonium halide, then the plutonium is actually dissolved in the salt matrix rather than a mixture of hetrogeneous phases. Attempts to ver.fy this through SEM failed as difficulty was encountered prepai- ing the samples.

2. Direct Oxide Reduction Salt

Direct Oxide Reduction (DOR) is a pyrometallurgical pro- cess where plutonium oxide is reduced to plutonium metal by calcium (4). The reaction takes place in a molten calcium chloride salt flux. The salt flux is used to sorb the calcium oxide reaction product.

Economic discard limits and chen cal process technology for DOR salt are very similar to those for ER salt. We re- ceived our salt as a massive piece of calcium chloride /calcium oxide. The lower portion of the salt, which con- tained most of the plutonium in the salt cake, was cleaved from the bulk, crushed, and seived. This is an important de- parture from experiments on other residues studied in this

report. By isolating only the rich fraction of the salt, we
enriched the feed material prior to the magnetic separation
experiment.   The fraction larger than 170 mesh but smaller
than 60 mesh was used for magnetic separation experiments in
the paramagnetic mode.

The results from these experiments are shown in Table 9.
The salt was passed through the field first at 35 degrees
with only the lean fraction being recycled at 15 then 5 de-
grees transverse tray angles. The first and second passes
through the field gave a very small rich fraction that ap-
peared as a dark colored powder. This was probably plutonium
metal that had not coalesced into the product button in the
DOR process. On the third pass the transverse tray angle was
reduced to the point where depletion of the lean fraction was
more successful. This still left the lean fraction ot the
salt with a plutonium content of 11 g Pu/kg of bulk. However,
the bulk fraction of the salt not processed had a plutonium
content considerably lower than this value (about 2 g/kg).

An economic assessment of these results would show if
separation of a very small plutonium rich fraction from this
residue would be useful.

CONCLUSIONS

We have shown that OGMS can be used to enrich certain residues in plutonium. Hence, potential chemical processing applications exist in that some of the residues studied allowed the separation of a portion of the feed into a lean fraction low enough in plutonium content to be considered for direct discard. The residues amenable to OGMS enrichment includer SS&C residue, bomb reduction sand, and plutonium contaminated graphite. The benefit that results from this type of operation is the concentration of the plutonium in feed materials prior to plutonium recovery by conventional methods. Highgrading lean feeds increases the capacity of the dissolution equipment since reduced bulk is processed, increases the plutonium concentration in subsequent process solutions allowing more efficient ion exchange or solvent extraction operations, and decreases solution volume to evaporators or other contaminated solution handling processes.

For a few types of residues such as DOR salt and ER Salt, OGMS can be used to produce a rich fraction and a lean fraction where the latter might not meet economic discard levels. Potential processing applications still exist, however, where processing facilities have a "fast" processing

portion and a "slow" processing portion. The advantage here is that most of the plutonium can be processed more quickly and efficiently in the fast portion of the plant.

The incinerator ash samples we studied could not be processed by OGMS to give a plutonium rich and plutonium lean fraction. An improved DMS separator or selected ash pretreatment methods might improve the separation of this residue. Also, since the incinerator ash consist of rather small particles, High Gradient Magnetic Separation, a wet method, might be successfully applied.

Residues that were separated successfully by DMS consist of heterogeneous particles. In the residues of this type (SS&C, sand, and graphite) there exist a broad spectrum of plutonium content in the particles. The particles high in plutonium content are, of course, more highly paramagnetic and thus, are deflected more strongly in the magnetic field. We suggest that in ER salt that at least some of the plutonium is dissolved in the salt phase making physical separation methods inpractical. For incinerator ash it appeared that the plutonium is equally distributed between the more magnetic and less magnetic fractions.

Higher field or modified design of DMS equipment might give more sensitive or more complete separations.

Acknowledgment

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Compound/Element   Susceptibility, 10^{-6}

Paramagnetic

Compound/Element	Susceptibility
FeO	+ 7200
Fe_2O_3	+ 3586
Cr_2O_3	+ 1960
UO_2	+ 2370
PuF_4	+ 1760
Am	+ 1000
PuO_2	+ 730
Ni_2O_3	+ 660
Pu	+ 610
U	+ 409
PuF_6	+ 173
Th	+ 134
CrO_3	+ 40
Ca	+ 40
Al	+ 16

Diamagnetic

Compound/Element	Susceptibility
Si	- 4
Graphite	- 6
MgO	- 10
CaO	- 15
ThO_2	- 16
MgF_2	- 23
CaF_2	- 28
SiO_2	- 30
NaCl	- 30
Al_2O_3	- 37
K Cl	- 39
$CaCl_2$	- 54
CaI_2	-109

Figure 1. Magnetic susceptibility of selected elements and compounds.

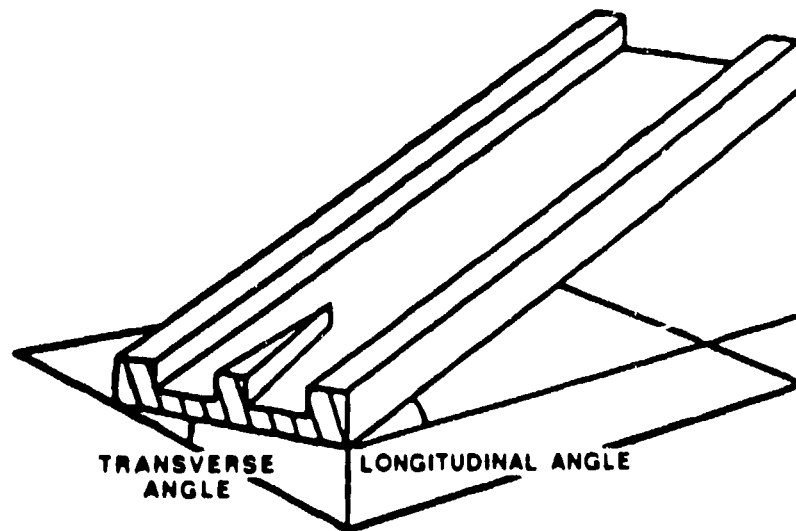Figure 2. A drawing of the LB-1 magnetic separator tray show-
ing the longitudinal and transverse angles. As shown, the
transverse tray angle is negative and the operator is located
to the right of the tray.
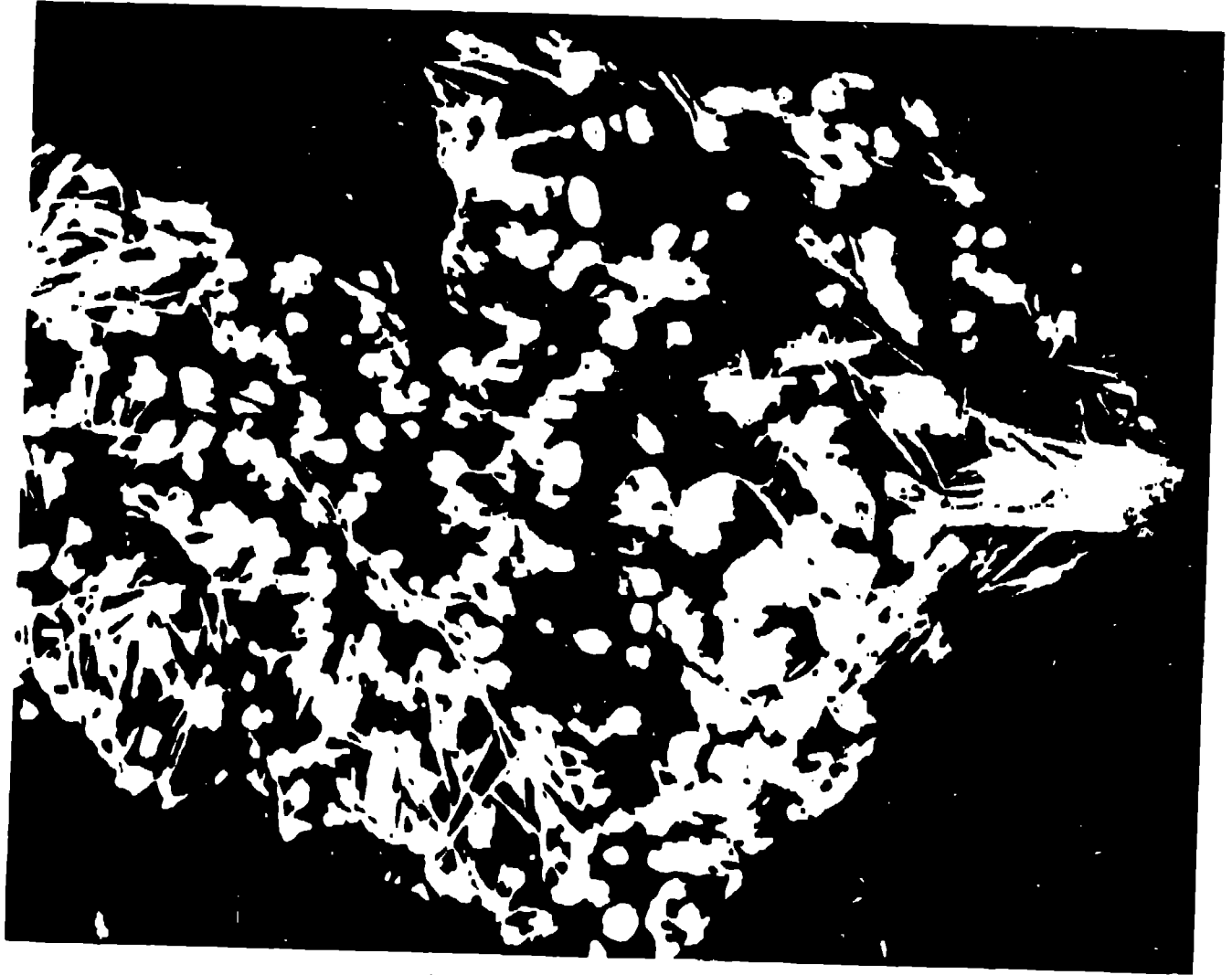
$|\leftarrow \rightarrow|$ =25 microns.

Figure 3. A backscatter electron image of a calcium fluoride particle with plutonium oxide on the surface at 400X. The plutonium appears as the white areas in the image.

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT	
		PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
> 250MM	15	67.3	32.7	7.64	32.1
< 250MM > 90MM	5	31.6	68.4	6.00	21.9
< 90MM	30	7.7	92.3	10.5	18.7

TABLE 1: MAGNETIC SEPARATION RESULTS ON SIZED SAND SLAG AND CRUCIBLE MATERIAL

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
		PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
13		80.0	20.0	17.6	32.9
13A	40	60.3	39.7	13.2	32.5
13B		68.2	31.8	15.0	29.9
13		77.2	22.8	17.4	49.9
13A	30	59.0	41.0	15.0	26.0
13B		64.5	35.5	11.3	30.2
13		45.8	54.2	8.9	30.9
13A	20	50.7	49.3	13.7	30.0
13B		58.0	42.0	12.6	28.4
13		32.9	67.1	9.3	34.0
13A	15	30.6	69.4	3.8	27.3
13B		35.1	64.9	7.2	26.7

(a) All plutonium values were obtained by neutron counting. While some scatter is observed in the values, we have observed that neutron counting of this residue is generally accurate ≈ 25% of the chemical analysis value.

Table 2: Magnetic separation results on sand slag and crucible residue as received

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
		PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
15		87.9	12.1	12.1	48.3
16	35	85.0	15.0	15.0	67.3
17		83.3	16.7	16.7	79.5
15		73.7	26.3	5.7	31.6
16	25	76.3	23.7	6.0	76.1
17		77.1	22.9	17.9	67.5
15		63.6	36.4	5.2 (6.3)	53.3 (45.8)
16	15	66.1	33.9	5.4 (7.1)	54.5 (30.5)
17		70.1	29.9	10.4 (8.0)	60.5 (46.7)

(a) Numbers in parentheses indicate chemical analysis values.
Other plutonium values are neutron count results.

Table 3: **Magnetic separation results on sand slag and crucible with particles smaller than 45 micrometer removed.**

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
		PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
15		18.9	81.1	0.90	30.0
16	- 2	24.4	75.6	6.5	26.5
17		19.3	80.7	0.87	33.1
15		28.3	71.7	1.8	38.2
16	0	29.3	70.7	5.1	31.6
17		23.0	77.0	1.5	27.4

(a)   Plutonium values were obtained by neutron counting.

Table 4:   Magnetic separation results on sized SS&C in the diamagnetic mode

SAMPLE	BULK FEED SPLIT		PLUTONIUM SPLIT	
	PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
Sized Sand	84.7	15.3	5.1	53.6 [a]
Sand as Received	68.7	31.3	8.6	31.3 [b]

(a)   Plutonium values were obtained by chemical analysis

(b)   Plutonium valves were obtained by neutron counting

Table 5:   Magnetic separation results for bomb reduction sand

TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
	PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
35	42.1	57.9	18.0	38.9
20	46.0	54.0	13.7 (6.1)	34.0 (26.6)

(a)   Plutonium values in parenthesis are chemical analysis values.   Other plutonium values are from neutron counting.   The neutron counts in this case were inflated by the presence of relatively large quantities of americum.

Table 6:   Magnetic separation results for plutonium contaminated graphite powder

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
		LESS MAGNETIC FRACTION (%)	MORE MAGNETIC FRACTION (%)	LESS MAGNETIC FRACTION (g Pu/kg bulk)	MORE MAGNETIC FRACTION (g Pu/kg bulk)
Calcined Ash	25	87.8	12.2	184	162
Calcined Ash	30	14.7	85.3	217	200
Fluorinated Ash	30	97.8	2.2	263	118
Leached Ash Heel	30	86.0	14.0	49.0	28.0

(a)   All Plutonium values are derived from neutron counting.

Table 7:   **Magnetic separation results for several incinerator ash sample**

SAMPLE	TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
		PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
A	15	98.0	2.0	63.2	341
B	0	45.8	54.2	31.5	101
B	-2	50.0	50.0	72.5	148
C	-2	88.1	11.9	39.9	263

(a) Plutonium results for samples A and C are from neutron counting. Results for sample B are from chemical analysis.

Table 8: Magnetic separation results for electorefining salt

TRANSVERSE TRAY ANGLE (DEGREES)	BULK FEED SPLIT		PLUTONIUM SPLIT (a)	
	PLUTONIUM LEAN DIAMAGNETIC FRACTION (%)	PLUTONIUM RICH PARAMAGNETIC FRACTION (%)	PLUTONIUM LEAN DIAMAGNETIC FRACTION (g Pu/kg bulk)	PLUTONIUM RICH PARAMAGNETIC FRACTION (g Pu/kg bulk)
35	99.4	0.6	15.8	≈1000
15	99.1	0.9	15.8	≈ 792
5	82.7	17.3	(11.0)	(55.6)

(a)   Results in parentheses are from chemical analysis others are from neutron counting.

Table 9:   Magnetic separation results for direct oxide reduction salt