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LA-UR-81-2734

CONF-811049--1

TITLE: THERMAL STABILIZATION OF URANIUM MILL TAILINGS

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SUBMITTED TO: Fourth Symposium on Uranium Mill Tailings Management
Fort Collins, CO 80523

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THERMAL STABILIZATION OF URANIUM MILL TAILINGS

by

David R. Dreesen, Joel M. Williams, and Edward J. Cokal¹

ABSTRACT

The sintering of tailings at high temperatures (1200°C) has shown promise as a conditioning approach that greatly reduces the ²²²Rn emanation of uranium mill tailings. The structure of thermally stabilized tailings has been appreciably altered producing a material that will have minimal management requirements and will be applicable to on-site processing and disposal.

The mineralogy of untreated tailings is presented to define the structure of the original materials. Quartz predominates in most tailings samples; however, appreciable quantities of gypsum, clay, illite, or albites are found in some tailings. Samples from the Durango and Shiprock sites have plagioclase-type aluminosilicates and non-aluminum silicates as major components. The iron-rich vanadium tailings from the Salt Lake City site contain appreciable quantities of α -hematite and chloroapatite.

The reduction in radon emanation power and changes in mineralogy as a function of sintering temperature (500° to 1200°C) are discussed for tailings sands and fines from the Shiprock site. Various tailings materials have been sintered at 1200°C in oxidizing and reducing conditions. Reductions in emanation of more than 99.9% have been found. The mineral forms present in the thermally stabilized tailings are compared with the untreated tailings to determine the high temperature mineral transformations occurring during sintering.

The general technical advantages of thermal stabilization as a remedial action include on-site disposal and minimal cover requirements. Technical questions are presented that require further investigation before a full-scale operation can be designed.

INTRODUCTION

The goal of current uranium mill tailings management technologies is the long-term containment of mobile contaminants. The principal concern is the control of radon-222 releases and water leachable components in tailings. The perceived hazards resulting from such releases have prompted the US Environmental Protection Agency to propose very stringent standards for the ultimate disposal of tailings at inactive mill sites (US EPA 1981). The proposed standards would require a radon flux limit of 2 pCi/m²/s and prohibit the degradation of both surface and ground water.

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The most frequently proposed approach to the management of uranium mill tailings relies on barrier systems to contain these hazardous contaminants and prevent their movement into the environment. The Los Alamos National Laboratory is investigating a different tailings management approach as part of the technology development program of the US Department of Energy's Uranium Mill Tailings Remedial Action Project. The physical structure and/or chemical composition of tailings are being altered to either immobilize contaminants or remove contaminants before disposal. These physicochemical modifications are broadly termed "conditioning" methods.

Our investigations of contaminant immobilization have centered on a process to radically modify the structure of tailings by sintering at high temperatures i.e., thermal stabilization. The mineralogy of untreated and sintered tailings will be discussed as well as the reduction in radon emanation resulting from thermal stabilization.

MINERALOGY OF TAILINGS

The alteration of uranium mill tailings by thermal stabilization is dependent on the structure of the original tailings components. Thus, a critical area of knowledge needed to develop and evaluate this conditioning process is an understanding of major mineral forms present in the tailings and how they can be altered by sintering. Insight into the control of radon emanation at the mineral grain scale will require this information.

Composite tailings representing near surface material from inactive mill sites at Shiprock, New Mexico (SHIP), Salt Lake City, Utah (SLC), Durango, Colorado (DGO), and Ambrosia Lake, New Mexico (AML) have undergone thorough analysis of composition (see Cokal et al. 1981 for description of samples). The major element composition of these materials is reported in Table 1. The principal component in these tailings is Si (19-39%) with variable but minor amounts of Al, Ca, Fe, K, Mg, and Na (all less than 8% except Fe in SLC 5AB). This data indicates that silicates are the predominant component in these tailings with aluminosilicates and metal oxides or salts accounting for much of the remainder.

The mineralogy of the tailings composites (-325 mesh) was assessed on a quantitative basis for quartz, gypsum, clay, illite, kaolinite, and calcite and on a qualitative basis for minerals that have not been standardized on the x-ray diffractometer unit. The diffractometer was operated at 40 kV and 20 mA using a copper target. Noise levels and peak heights were determined by visual inspection of the strip chart record of the x-ray intensity response. A computer program was employed to determine the percentage of standardized minerals present in the tailings samples (Williams 1980).

The mineral composition of tailings is reported in Table 2 along with identified, but unquantified minerals or mineral types. Crystalline quartz was predominant in tailings sands (SHIP Sands, SLC 1AB, and DGO SP Sands) making up more than 70% of the total material. Tailings fines (SHIP Fines, SLC 4AB, DGO SP Fines, and AML Fines) contained substantial crystalline quartz (17 to 46%) with appreciable "non-crystalline" quartz (5 to 12%) which may result from the presence of submicron quartz particles produced during the grinding of uranium ore. Gypsum is present in large amounts in some of the sulfuric acid-leached tailings (SHIP and SLC); this mineral was most likely formed

subsequent to milling. Substantial amounts of clays other than kaolinite and illite were found in fine tailings from SHIP, SLC, and AML. Calcite and albite (sodium aluminosilicate) were also present in the AML Fines. Unquantified minerals, which are apparently present in appreciable quantities, include plagioclase-type minerals in SHIP Fines, DGO LP, and DGO SP Fines. The DGO tailings also contained non-aluminosilicate minerals. In addition, barite was found in DGO SP Fines, which is reasonable considering the high Ba content (2%) of the composite.

The iron-rich SLC 5AB tailings, which we believe represents the "ferrophos" vanadium tailings described by Merritt (1971), contains a moderate amount of quartz and substantial unquantified minerals. Identified mineral constituents include α -hematite, which may represent the principal iron mineral and clino-chloroapatite, which may be the predominant phosphate mineral.

One method of substantiating these mineralogical assays of tailings is to relate our data with the mineralogy of the source ore. For the AML Fines, a fairly complete mineralogical evaluation of the source sandstone ore from the Westwater Canyon Member (Morrison Formation) in the vicinity of Ambrosia Lake, New Mexico has been reported by Squyres (1970). Squyres describes the typical sandstone as containing 50 to 75% quartz (our value 56%), 25% potassium feldspars and sodic plagioclase (our value 18% for albites), a predominance of montmorillonite clay over illite (our clay value 23%, no illite) and authigenic minerals such as calcite and kaolinite (our values 5 and 6%, respectively). The correspondence between Squyres' analysis and our values substantiates the validity of our technique with regard to identification of major mineral forms.

Another piece of substantiating evidence is the electron microprobe elemental analysis of individual particles in size-fractionated SHIP Fines. These data are presented in summary form in Table 3, along with our inferences about the mineral form that might account for these elemental distributions. We have inferred the presence of quartz, gypsum, feldspars and clays, iron oxides, and an organic particle, which might be a coalified, highly altered, humic substance. Again, these electron microprobe data substantiate our x-ray diffraction results, which showed gypsum and quartz predominating with appreciable clay and possible plagioclase content.

RADON EMANATION POWER OF TAILINGS

Emanating and total ^{226}Ra in the composite tailings are reported in Table 4 along with their emanation coefficients. The particle size distribution and quartz content of these tailings are also presented in Table 4. Emanating ^{226}Ra levels range from 39 to 546 pCi/g; total ^{226}Ra levels range from 310 to 2020 pCi/g. Emanation coefficients for Shiprock and Salt Lake City tailings (except SLC 5AB) are appreciably lower (10 to 12%) than those for Durango tailings (19 to 26%). In general, the coarse tailings sands (SHIP SANDS and DGO SP) have lower emanating ^{226}Ra levels than the corresponding tailings fines. However, there is not a great difference in emanation coefficients between sands and fines from the same pile. The emanation coefficient of the iron-rich (ferrophos) Salt Lake City tailings (5AB) is not consistent with those of the "uranium" tailings (1AB and 4AB).

Ryon et al. (1977) report the range of emanation coefficients for four sulfuric acid-leached tailings as 9 to 17% (average 12%) with carbonate-leached tailings having higher emanation coefficients (14 and 45%). These results correspond well with the emanation coefficients in Table 4 for sulfuric acid-leached tailings (10 to 20%) and carbonate-leached tailings (19 to 41%). Macbeth et al. (1978) report emanation coefficients for Salt Lake City tailings (17 to 27%), which are generally higher than our results; these inconsistencies may result from the use of different measurement techniques [gamma counting of de-emanated solids Macbeth et al. (1978) vs alpha counting of ^{222}Rn - this study].

The control of radon flux resulting from the physicochemical conditioning of tailings can be evaluated on a laboratory scale by examination of the reduction in emanating radium or emanation coefficients. Thus, these baseline emanation measurements will form the basis for evaluation of radon flux control. Radon flux is dependent on many factors other than emanating ^{226}Ra (e.g., porosity, diffusion coefficients, moisture content, ...); however, preliminary evaluation of conditioned tailings can be performed in the most direct manner by comparing emanation characteristics.

THERMAL STABILIZATION OF TAILINGS AT 1200°C

In a preliminary series of heat treatments, ^{222}Rn emanation reduction was determined as a function of temperatures ranging from 750 to 1150°C. Significant radon emanation reduction (>95%) was not obtained until temperatures exceeded 1050°C. Because we hoped to achieve a 200-fold reduction, 1200°C was selected as a temperature that (1) could produce such a reduction with some tailings, (2) might be technologically feasible on a large scale, (3) would not subject fire clay crucibles to excessive temperatures, and (4) would permit tailings evaluations under constant conditions.

Both fire clay and graphite crucibles were filled to ~2/3 capacity (100 - 200 g) with each of the tailings composites. The crucibles were loaded into a box furnace preheated to 800°C. The furnace reached 1200°C in about 2 hr and was kept at temperature for ~3/4 hr. The temperature was set back to 800°C and the samples were removed about 1-1/2 hr later when the temperature of the furnace decreased to 800°C.

The sintered tailings could be broken out of the graphite crucibles and residual graphite removed with a file. Some of the tailings fused to the fire clay crucibles (SHIP Fines, SLC 4AB, DGO LP, DGO SP Fines, and AML Fines), which necessitated that the fused tailings and crucible be pulverized together and radon emanation of the combined materials be measured. The radon contribution of a control fire clay crucible was also determined and found to be negligible at <0.01 pCi/g. All the sintered composites were pulverized to pass through a 6.4 mm (1/4 in.) screen and placed in emanation tubes to measure radon emanation power. The emanation results are summarized in Table 5 for oxidizing conditions (i.e., fire clay crucibles) and reducing conditions (i.e., graphite crucibles). Under oxidizing conditions the emanating ^{226}Ra of sintered tailings was reduced by factors from 37 to 1400 with respective emanating ^{226}Ra being 0.27 to 1.58 pCi/g. Under reducing conditions, the emanating ^{226}Ra ranged from 0.12 to 1.72 pCi/g (i.e., reductions of 22 to 1100 fold). Reducing conditions favored lower emanation particularly for the iron-rich SLC 5AB and the DGO SP Fines tailings and

somewhat for SLC IAB. In contrast, oxidizing conditions caused lower radon emanation for SHIP Sands and DGO SP Sands, as well as AML Fines. Replicate emanating ^{226}Ra measurements on the same sample were within 10%; therefore, these differences appear to be real.

The amount of material lost during heating was appreciable for some samples, up to 25% (see Table 5). It is assumed that the material lost would include waters of hydration and volatiles lost as a result of the decomposition of carbonate and/or sulfate salts.

From examining the emanation results in relation to the mineralogy, it is apparent that those samples exhibiting the greatest emanation reduction are generally those with lesser quartz content (i.e., fines), which formed glassy slags. The high quartz tailings (>60%) formed masses of slightly fused sands, which had emanation reduction factors less than 250. The iron-rich SLC 5AB tailings exhibited sintering behavior more characteristic of tailings sands under oxidizing conditions, but formed a glassy slag under reducing conditions. This variable behavior may result from the formation of different high temperature mineral products under different O_2 conditions.

The predominant plagioclase and non-aluminum silicate minerals present in DGO LP and DGO SP Fines appear to have fairly low melting points or undergo slag forming mineral reactions at 1200°C . The AML Fines have considerable clay and albite (mp 1100°C) content along with $\text{NaHCO}_3/\text{Na}_2\text{CO}_3$ (a fluxing agent) from the mill process, which could favor the formation of a glassy slag.

The observations and inferences above concerning the mineralogy of thermally stabilized tailings coincide well with x-ray diffraction results. X-ray diffraction patterns are illustrated in Figure 1 for untreated Shiprock Fines as well as samples heated to 1200° and 1400°C . As is readily apparent, the structure of the tailings has been greatly modified by sintering. The 1200° material shows the disappearance of peaks corresponding to gypsum, clays, illite, kaolinite, the decrease in the peak heights for quartz, and the appearance of anhydrite. In addition, the amorphous region (the baseline corresponding to $2-\theta$ values from 15 to 35) has substantially increased in area. The complete amorphous character of 1400° sample is apparent in Figure 1 with the disappearance of all peaks including quartz.

The reduction in quartz content and increase in amorphous material for the tailings composites heated to 1200°C (in fire clay crucibles) are reported in Table 6. Decreases in quartz content ranged from 5 to 35%; increases in amorphous material ranged from 5 to 65%. The amount of amorphous character was determined as a relative percentage based on the area in the "amorphous region" ($2-\theta$ ranges from about 15 to 35) being 100% for the SHIP Fines sample heated to 1400°C (see Figure 1). This sample showed no discernable mineral content and was thus assumed to be totally amorphous. The origin of this amorphous material was principally quartz for some tailings (SHIP Fines, AML Fines, and DGO SP Sands), but mainly plagioclase for DGO LP and DGO SP Fines. The content of both of these minerals was substantially reduced by heating to 1200°C . Another group of minerals seemed to disappear from the diffraction patterns of the 1200°C samples: gypsum, illite, clays, albites, kaolinite, apatite, barite, and calcite. Some anhydrite (CaSO_4) is present in the thermally stabilized tailings (see Figure 1) and is most likely

produced from gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). In addition, new silicates (e.g., cristobalite), Na or Ca or Fe silicates, and Na or Ca or Fe aluminosilicates are apparently present. Thus, the mineral transformations due to sintering at 1200°C are not easily delineated. The formation of amorphous material and the new minerals produced may cause reductions in emanation power due to the incorporation of ^{226}Ra into these components.

RADON EMANATION AND MINERALOGY AS INFLUENCED BY SINTERING TEMPERATURE

The complex relationship between the reduction in emanation power and changes in mineralogy due to sintering prompted an experiment to investigate these changes as a function of sintering temperature. Sands and fines from the Shiprock and Durango tailings pile were sintered at temperature from 500° to 1200°C as described in the previous section. The emanating ^{226}Ra for both Shiprock and Durango tailings as well as major mineral forms present in the Shiprock samples were determined.

The emanating power of these tailings as a function of sintering temperature is shown in Figure 2 along with the percent reduction in emanating ^{226}Ra at 1200°C . Table 7 summarizes this data in terms of percent reduction in emanating ^{226}Ra . For SHIP Fines, originally 214 pCi/g, most of the reduction occurred from 700 to 1000° (134 to 8.3 pCi/g); however, sufficient reduction (i.e., to 1-2 pCi/g) required temperatures greater than 1100°C for both SHIP Fines and Sands. As seen in Figure 2 and Table 7, the Durango tailings show much greater emanation reduction up to 800°C than the Shiprock samples. From 800° to 1000°C , the reduction in emanating ^{226}Ra was not as great; however, between 1000° and 1200° the emanating ^{226}Ra decreased substantially. As with the Shiprock samples, the Durango tailings required sintering temperatures of 1100° or greater to reduce the emanation power to 1 - 2 pCi/g.

The weight loss due to heating ranged from 11% at 500°C to 24% at 1200°C for SHIP Fines. Corresponding losses for SHIP Sands were 2 to 5%, DGO SP Fines 3 to 6%, and DGO SP Sands 1 to 2%.

The mineral transformations occurring over this range of temperatures was determined by x-ray diffractometry for SHIP Fines and Sands. The inferred changes in the mineralogy of SHIP Fines are as follows:

- (1) gypsum disappears before 500°C (i.e., $\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4$ at 163°C); anhydrite is found at 500° and above, but appears to start decreasing at 1000° and is reduced by ~75% at 1200° ;
- (2) quartz does not change substantially until 1200° where about 60% is transformed perhaps to cristobalite (synthetic SiO_2) or to calcium silicates;
- (3) clay minerals including illite disappear at 900°C ;
- (4) kaolinite seems to disappear by 500°C ;
- (5) new minerals (possibly plagioclase-type) are forming at about 900° where the clay minerals and albite are disappearing;
- (6) the amorphous content seems to substantially increase at 1100° to about twice the original content.

The gypsum and anhydrite response for SHIP Sands parallels that for SHIP Fines. Quartz seems somewhat reduced (~10%) only at 1200°C. Calcium silicates and cristobalite appear to be the high temperature mineral products.

The reduction in emanation power between 700 and 1000° for SHIP Fines seems to correspond with the destruction of clays; however, to reach emanating radium-226 levels of 1 pCi/g apparently requires production of increased amorphous character. In addition, the apparent formation of calcium silicates and/or calcium aluminosilicates at temperatures of 900° or greater could also immobilize radium in structures that limit the escape of radon gas. The more gradual decrease in emanating power for SHIP Sands does not seem to directly relate to changes in mineralogy.

ADVANTAGES OF THERMAL STABILIZATION

The large reduction in the emanating power as well as the anticipated resistance to aqueous leaching of thermally stabilized tailings implies that sintering of uranium mill tailings at the present site could produce a slag or clinker that could be disposed of on-site. The only cover required for a pile of thermally stabilized tailings would be a soil or rock layer to attenuate the gamma radiation field and to act as a substrate for vegetation. The engineering and economic considerations of thermal stabilization are discussed by Thode and Dreesen (1981) for this Symposium. Additional knowledge will be required before thermal stabilization can be applied as a remedial action technology:

- (1) the long-term stability of the sintered material exposed to physical degradation and chemical attack (e.g., solubility of new minerals and amorphous material found in thermally stabilized tailings);
- (2) the interaction of the tailings and the refractories lining a kiln;
- (3) the gaseous and particulate emissions produced during sintering of tailings in a rotary kiln;
- (4) revised engineering and economic analysis of the thermal stabilization process as more complete technical information is developed.

Despite these unknowns, the results of this laboratory study of thermal stabilization as well as the preliminary technico-economic analysis of this process (Thode and Dreesen 1981) indicate that this radically different approach to tailings management may be technically and economically feasible. The advantages of on-site disposal and the independence from barrier systems should decrease the complexity of remedial action and provide for the effective long-term management of tailings.

LITERATURE CITED

- Cokal, E. J., D. R. Dreesen, and J. M. Williams. 1981. The Chemical Characterization and Hazard Assessment of Uranium Mill Tailings. Fourth Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado. October 26-27, 1981. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University.
- Macbeth, P. J., C. M. Jensen, V. C. Rogers, and R. F. Overmyer. 1978. Laboratory Research on Tailings Stabilization Methods and Their Effectiveness in Radiation Containment. Ford, Bacon, and Davis Utah Inc., Salt Lake City, Utah report GJT-21.
- Merritt, R. C. 1971. The Extractive Metallurgy of Uranium. Colorado School of Mines Research Institute, Golden, Colorado. Johnson Publishing Co. Boulder, Colorado.
- Ryon, A. D., F. J. Hurst, and F. G. Seeley. 1977. Nitric Acid Leaching of Radium and Other Significant Radionuclides from Uranium Ores and Tailings. Oak Ridge National Laboratory report ORNL/TM-5944.
- Squyres, J. B. 1970. Origin and Depositional Environment of Uranium Deposits of the Grants Region, New Mexico. Ph.D. Dissertation, Department of Geology, Stanford University.
- Thode, E. F. and D. R. Dreesen. 1981. Technico-Economic Analysis of Uranium Mill Tailings Conditioning Alternatives. Fourth Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado. October 26-27, 1981. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University.
- U. S. Environmental Protection Agency. 1981. Draft Environmental Impact Statement for Remedial Action Standards for Inactive Uranium Processing Sites. EPA 520/4-80-011.
- Williams, J. M. 1980. Qualitative and Quantitative X-Ray Mineralogy: A Layman's Approach. Los Alamos National Laboratory report LA-8409-MS.

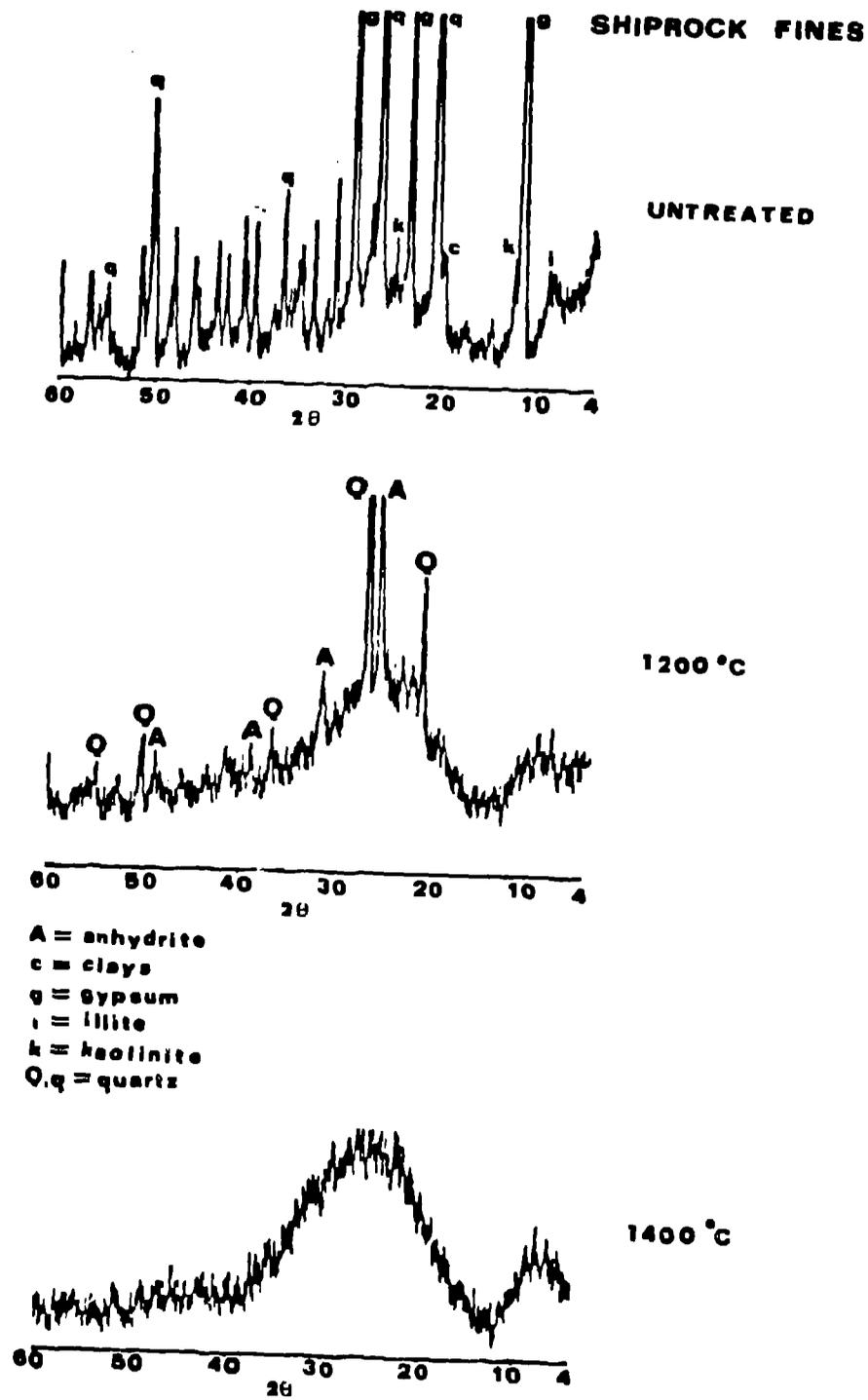


Figure 1. X-ray diffraction patterns for Shiprock Fines, untreated, and sintered at 1200° and 1400°C.

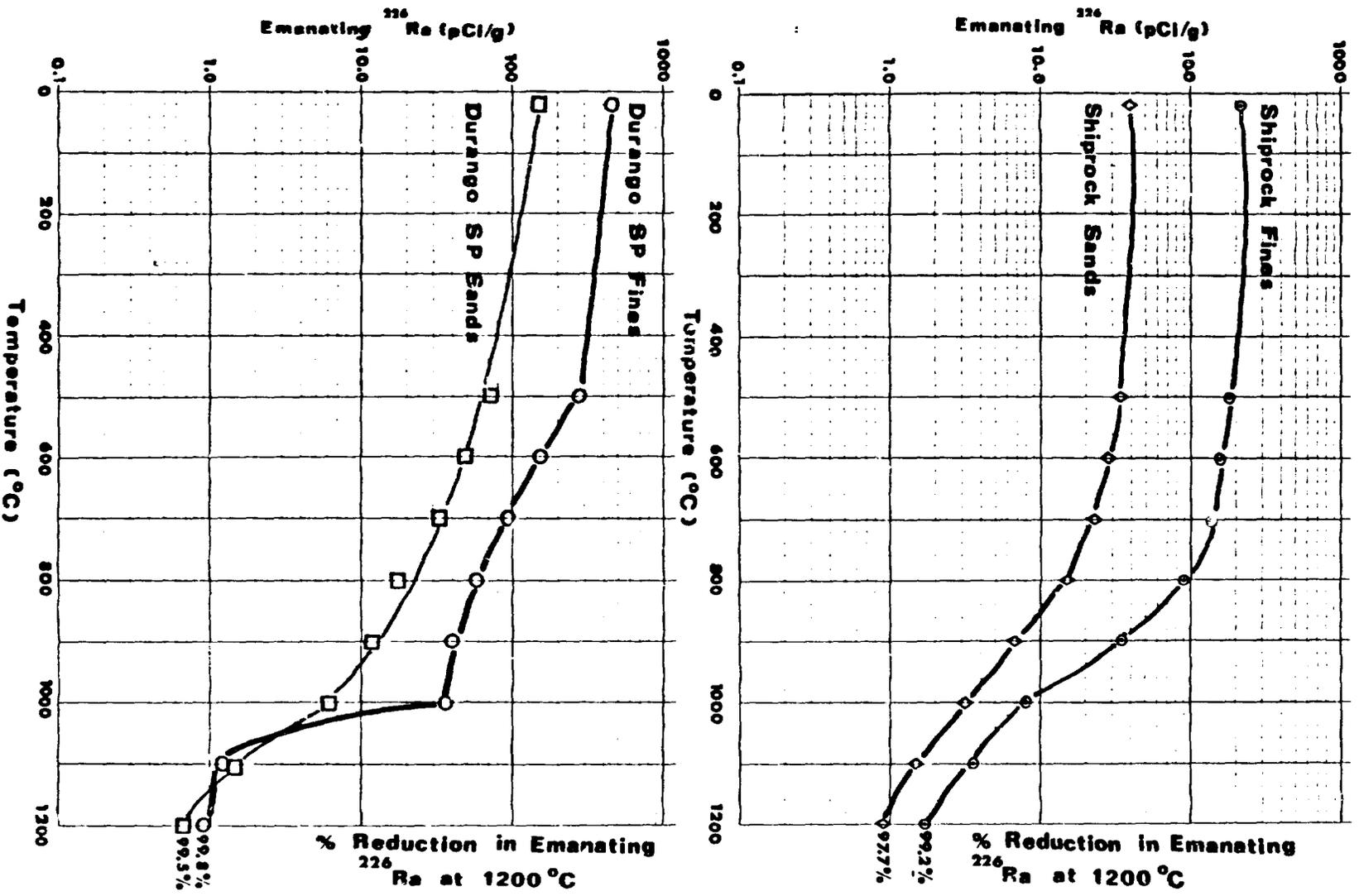


Figure 2. Emanating ²²⁶Ra as a function of sintering temperature for sands and fines from Shiprock and Durango.

Table 1
Major Element Composition of
Uranium Mill Tailings

Site ^a	Composite	% Composition						
		Si	Al	Ca	Fe	K	Mg	Na
SHIP	Sands	39.4	1.3	1.3	0.3	0.8	<0.1	0.1
SHIP	Fines	23.1	4.0	7.7	1.2	1.7	0.5	0.2
SLC	1AB	32.6	3.3	3.8	0.9	2.1	0.3	0.4
SLC	4AB	26.9	5.9	3.4	2.5	2.7	0.6	0.8
SLC	5AB	18.8	2.1	7.7	13.1	1.1	<0.3	1.0
DGO	LP	29.2	5.0	3.0	2.8	<0.5	0.9	3.2
DGO	SP Fines	25.2	6.3	4.2	4.1	0.9	1.1	3.7
DGO	SP Sands	38.1	2.5	1.3	1.4	0.7	0.5	1.2
AML	Fines	-	6.0	3.8	2.5	2.1	0.6	1.3

^aSHIP = Shiprock, New Mexico.
 SLC = Salt Lake City, Utah.
 DGO = Durango, Colorado.
 AML = Ambrosia Lake, New Mexico

Table 2

Mineral Composition of Uranium Mill Tailings Determined by X-Ray Diffraction

		% Composition									Other Identified Minerals Not Quantified
Site	Composite	Quartz		Gypsum	"Clay"	Illite	Kaolinite	Calcite	Feldspars ^a	Unknown	
		Crystal.	Non Crystal.								
SHIP	Sands	90		7					2	1	
SHIP	Fines	23	9	34	12	3	1			18	Plagioclase (low albite?)
SLC	1AB	68		14	5	4	1		7	1	
SLC	4AB	34	12	7	11	11	2			23	
SLC	5AB	34	2	2					3	59	Clino-chloroapatite; α-Hematite
DGO	LP	43	2							55	Mostly plagioclase type aluminosilicates; some non-aluminum silicates
DGO	SP Fines	17	5	2						76	Mostly plagioclase type aluminosilicates; some non-aluminum silicates; barite
DGO	SP Sands	88							11	1	
AML	Fines	46	10		23		6	5	18	8	

^aAlbite or high albite

Table 3

**Composition of Tailings Particles Determined by Electron Microprobe^a
(Shiprock Fines)**

	Particle Classification					
	Silicates	Organic	Potassium Aluminosilicates	Other Aluminosilicates	Iron Oxide	Calcium Sulfate
Si	M	om,o	M	M	o	om,o
O	(M)		(M)	(M)	M	(M)
C	?	M	?	?		?
S		M	o			M
Al	o	om,o	M	M	o	o
K		om,o	M	om,o	o	o
Fe	o	om,o	o	om,o	M	o
Ca		om,o	o	oir		M
Mg	o	o	o		o	
V	o	om,o	o		o	o
Ti	o	o	o			o
P		om,o			o	
Cl		o				
Na			o	om,o		
Ni			o			
Mn					om,o	
F						o
Inferred Mineral	Quartz	Coalified Humic Substance	Feldspar, Illite,Clays	Feldspar Kaolinite,Clay	Iron Oxide	Gypsum

^aM = constant major component
om = occasional major component
o = occasional minor component
? = carbon from epoxy resin on occasional basis
Values in parentheses () indicate variable oxygen response

Table 4

Emanating ²²⁶Ra, Total ²²⁶Ra, Emanation Coefficients and Particle Size Distribution of Tailings Composites

Site	Composite	Emanating ²²⁶ Ra (pCi/g)	Total ²²⁶ Ra (pCi/g)	Emanation Coefficient (%)	Sand (%)	Silt (%)	Clay (%)	Predicted SiO ₂ (%)
SHIP	Sands	39	396	10	77	17	6	90
SHIP	Fines	214	2020	11	10	78	12	53
SLC	1AB	136	1180	12	47	47	6	75
SLC	4AB	125	1070	12	14	76	10	61
SLC	5AB	63	316	20	64	33	3	43
DGO	LP	212	973	22	47	52	1	67
DGO	SP	473	1810	26	11	86	3	57
DGO	Fines							
DGO	SP	140	719	19	81	19	1	87
DGO	Sands							
AML	Fines	546	1330	41	-	-	-	-

Table 5

Radon Emanation from Thermal Stabilized Tailings

Site	Composite	Thermal Stabilization at 1200° C						
		Untreated Tailings			Oxidizing Conditions		Reducing Conditions	
		Emanating ²²⁶ Ra (pCi/g)	Quartz %	% Mass ^a Loss on Heating	Emanating ²²⁶ Ra (pCi/g)	Reduction ^b Factor	Emanating ²²⁶ Ra (pCi/g)	Reduction Factor
SHIP	Sands	39	90	5	1.03	37	1.72	22
SHIP	Fines	214	23	25	0.62	350	0.48	450
SLC	1AB	136	68	12	1.33	100	0.64	210
SLC	4AB	125	34	16	0.44	280	0.44	280
SLC	5AB	63	34	4	0.38	170	0.12	530
DGO	LP	212	43	2	0.27	790	0.32	660
DGO	SP Fines	473	17	7	1.58	300	0.43	1100
DGO	SP Sands	140	88	2	0.75	190	1.71	82
AML	Fines	546	46	9	0.39	1400	0.55	990

^aUnder oxidizing conditions 1200°C.

^bReduction factors = Emanating ²²⁶Ra (untreated tailings)/Emanating ²²⁶Ra (thermal stabilized tailings).

Table 6

Changes in Quartz and Amorphous Material
Resulting from Thermal Stabilization

Site	Composite	Percentage Quartz		Amorphous Material	
		Untreated (%)	1200°C Treatment (%)	Untreated (%)	1200°C Treatment (%)
SHIP	Sands	90	80	20	25
SHIP	Fines	25	10	20	40
			(0) ^a		(100) ^a
SLC	1AB	70	45	20	60
SLC	4AB	35	25	35	60
SLC	5AB	35	30	5	20
DGO	LP	45	25	10	75
DGO	SP	15	15	15	80
	Fines				
DGC	SP	90	65	5	25
	Sands				
AML	Fines	45	10	25	75

^aHeated to 1400°C.

Table 7

Percent Reduction in Emanating ²²⁶Ra
at Temperatures From 500° to 1200°C^a

Sintering Temperature (°C)	SHIP		DGO	
	Sands ^b (%)	Fines ^b (%)	SP Sands ^b (%)	SP Fines ^b (%)
500	15	16	48	61
600	29	27	64	68
700	44	37	76	80
800	63	58	87	88
900	83	84	92	91
1000	92	96.1	95.5	92
1100	96.4	98.8	99.0	99.8
1200	97.7	99.2	99.5	99.8

^a $(1.0 - \text{treated tailings/untreated tailings}) \times 100\%$.

^bOriginal emanating ²²⁶Ra.

SHIP Sands = 39 pCi/g.

SHIP Fines = 214 pCi/g.

DGO SP Sands = 140 pCi/g.

DGO SP Fines = 473 pCi/g.