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APPLICATION OF
MICROWAVE ENERGY FOR
IN-DRUM SOLIDIFICATION OF
SIMULATED PRECIPITATION SLUDGE

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SUBJECT DESCRIPTORS

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NORTH AMERICAN SPACE OPERATIONS
ROCKY FLATS PLANT
P.O. BOX 464
GOLDEN, COLORADO 80402-0464

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for the
Albuquerque Operations Office
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APPLICATION OF MICROWAVE ENERGY FOR IN-DRUM SOLIDIFICATION OF SIMULATED PRECIPITATION SLUDGE

R. D. Petersen, A. J. Johnson, and S. D. Swanson

ABSTRACT

The application of microwave energy for in-container solidification of simulated transuranic contaminated precipitation sludges has been tested. Results indicate volume reductions to 83% are achievable by the continuous feeding of pre-dried sludge into a waste container while applying microwave energy. An economic evaluation was completed showing achievable volume and weight reductions to 87% compared with a current immobilization process for wet sludge.

EXECUTIVE SUMMARY

The application of microwave energy for in-container solidification of simulated transuranic (TRU) contaminated precipitation sludges was studied. Preliminary results indicate that volume reductions to 83% are achievable by the continuous feeding of dried sludge into a waste container while applying microwave energy. An economic evaluation was completed showing achievable volume and weight reductions of 87% compared with a current immobilization process for wet sludge.

Aqueous wastes from the plutonium recovery areas at the Rocky Flats Plant are treated in a hydroxide precipitation process to remove heavy metallic elements. The resultant slurry is passed through a rotary drum vacuum filter, precoated with diatomaceous earth filter media, to remove the solids from the waste stream. A thin layer of filter cake is continuously cut from the drum filter, producing a wet sludge. The wet sludge alone does not meet the Waste Isolation Pilot Plant - Waste Acceptance Criteria (WIPP-WAC) prohibiting the presence of free liquids. In the present operation, a portland cement/diatomite mixture is added to the waste container to absorb free liquids. The

TRU waste forms presently produced at Rocky Flats with the absorbants meet the criteria established by the WIPP-WAC. However, a waste form increasing the waste loading of sludge could significantly reduce the waste generation rate and the associated shipping/storage costs.

The equipment used in this study included: (1) a 6-kW microwave generator, (2) aluminum cavity with turntable, (3) three-stub tuner, (4) waveguides, (5) reflected power meter, (6) infrared thermometer, and (7) screw feeder. Chokes were added to the cavity for mounting the infrared thermometer and screw feeder. The chokes consisted of a 1.25-in. i.d., 8-in.-long aluminum tube, continuously welded to the cavity.

Two methods of feed addition to the microwave cavity were studied: batch and continuous feeding of dried simulated sludge. In the batch-fed method, an initial charge of 2 kg of dry sludge was added to an insulated 8-ℓ stainless steel container. Initial melting occurred within 5 to 10 minutes; the charge was allowed to stand in the microwave field 45 to 60 minutes or until offgassing ceased. Subsequent 2.5-kg additions were made to the container and allowed to heat for the same amount of time. Temperatures of the melt ranged from 1000 to 1300 °C. Densities of the batch-fed samples ranged from 1.0 to 1.44 g/cm³ with an average density of 1.21 g/cm³. The increase in density translates into an average 74.8% volume reduction. Weight reductions for the test runs averaged 16.6%.

The continuous feeding of predried simulated sludge into the waste container resulted in higher densities and greater volume reductions than the batch-fed method. Nine tests were performed, continuously feeding sludge through a screw feeder into an 8-ℓ container. An initial 2-kg charge was added to the container to initiate a melt. After the initial charge

collapsed and temperatures stabilized above 1000 °C, addition was started. After final sludge addition, the cast was left in the cavity for approximately 30 minutes until offgassing ceased. The average density of the casts was 1.92 g/cm³ with an average volume reduction of 81.1%. Table 1 summarizes data collected from the solidification tests.

Trials were also run using fluxes in an effort to decrease the molten viscosity, thereby increasing the density of the waste form. Fourteen trials were made using various fluxing agents, eleven batch fed and three continuously fed. The various fluxes used in the tests included: anhydrous borax, hydrated borax, boric acid, sodium carbonate, trisodium phosphate, lime, and soda lime. Vitrification of the sludge using anhydrous borax produced a waste form with an average density of 2.2 g/cm³.

A general conclusion can be drawn from the bench-scale tests of the microwave system using simulated TRU waste. Waste sludges produced at the Rocky Flats Plant with a high diatomaceous earth content will melt readily, resulting in volume reductions to 83% over that of dried sludge. The process produces a monolith that is free of liquids and excessive particulate meeting criteria established

by the WIPP. The overall volume and weight reductions may exceed the present immobilization system as much as 87% and produce substantial annual operating cost savings.

Work is under way on actual TRU waste to verify the results obtained using the simulated sludge. Characterization of the offgases produced during the melting process are also necessary before scale-up of the process can begin.

INTRODUCTION

Aqueous wastes from the plutonium recovery areas at Rocky Flats Plant are treated in a hydroxide precipitation process to remove heavy metallic elements. The resultant slurry is passed through a rotary drum vacuum filter, precoated with diatomaceous earth filter media, to remove the solids from the waste stream. A thin layer of filter cake is continuously cut from the drum filter, producing a wet sludge. The wet sludge alone does not meet the WIPP-WAC, which prohibits free liquids.¹ In the present operation, a portland cement/diatomite mixture is added to the waste container to absorb free liquids. The TRU waste forms

TABLE 1. Solidification Tests

Trial	Density (g/cm ³)	Reduction		Flux (wt%)	Comment
		(wt%)	(vol%)		
8	1.00	21.1	75.7		Batch Fed
11	1.32	11.6	75.0		Batch Fed
14	1.25	15.3	75.1		Batch Fed
19	0.5	19.1	-3.3	20.0	Trisodium Phosphate
22	0.7	16.4	23.7	20.0	Sodium Carbonate
23	0.9	14.0	62.2	20.0	Lime
24	0.7	14.4	25.3	20.0	Boric Acid
26	1.6	17.0	76.6	10.0	Hydrated Borax
29	1.5	14.0	74.5	10.0	Soda Lime
31	1.9	8.7	81.5		Continuously Fed
33	1.9	10.5	82.0		Continuously Fed
35	1.9	11.3	82.5		Continuously Fed
36	2.3	4.0	83.4	10.0	Anhydrous Borax

presently produced at Rocky Flats with the absorbents meet the criteria established by the WIPP-WAC.

A waste form increasing the waste loading of sludge could significantly reduce the waste generation rate and the associated shipping/storage costs. An ongoing program at Rocky Flats is investigating both microwave and joule-heated glass furnace processes for producing a solidified monolithic waste form.

Microwave technology has been used in the food and chemical industries since the early 1970s with the majority of the work concentrated in drying and vulcanizing rubber.² High-temperature technology was developed by the Japanese for converting plutonium nitrate (recovered from spent fuel reprocessing) to plutonium oxide for nuclear fuel production and for solidifying waste incinerator ash.³ Laboratory-scale vitrification of calcined high-level nuclear wastes using microwave energy was done by the Idaho National Engineering Laboratory. High-level wastes were mixed with a composite of fluxing agents in ceramic crucibles and placed in a microwave cavity. The resulting glass was poured into a metal storage container and allowed to solidify.⁴

Three primary mechanisms are involved in heating with microwave energy. Type I is characterized as the vigorous vibration of a dipole molecule caused by oscillation of the electromagnetic field. The vibration causes frictional heat to build up between the molecules, which elevates the temperature of the material. The simulated sludge used in the tests contains metal oxides (MgO , Al_2O_3 , CaO , and SiO_2), which are normally electrically neutral. However, when placed in an electromagnetic field, they become dipolar.

Type II heating involves substances that are magnetic in nature and couple with the magnetic component of the microwave field. The oscillation of the magnetic component of the field results in hysteresis loss within the material, which generates heat. Ferrites exhibit this property when placed in the microwave field.

Type III heating takes place when an electrically conductive material, such as carbon black, is a com-

ponent of the material being heated. A current is generated throughout the material by the electric component of the microwave field. The material is heated by the current flow through the material resistance.⁵ This paper describes a system for solidifying transuranic aqueous precipitation sludge by sintering or melting the waste to form a solid monolithic product using microwave technology. The work completed includes procedures for simulated sludge makeup, drying tests, equipment description, and melting tests.

SIMULATED SLUDGE

Sludge used in the bench-scale tests was produced to simulate the TRU waste generated in the waste processing facilities at Rocky Flats. Two TRU sludge samples from separate waste streams were taken from the old waste processing facility. Five analyses were performed to characterize the sludge samples:

1. Infrared spectroscopy
2. Emission Spectroscopy
3. Thermal gravimetric analysis
4. Carbon analysis
5. Diatomaceous earth content by X-ray diffraction.

Results of the analyses are presented in Exhibit 1. Simulated sludge was prepared for previous vitrification studies in the 1970s.⁶ The calculated composition is presented in Table 2.

The sludge composition used for the vitrification study was selected as the most easily reproduced waste sludge; however, the formulation was simplified by eliminating minor components. The composition for the sludge used in the microwave solidification study is given in Table 3. Metal oxide amounts in the vitrification studies (Table 2) differ from the microwave studies (Table 3). This is because diatomite used in the current production process and for microwave feed contains higher amounts of metal oxides than the diatomaceous earth used in the vitrification studies.

TABLE 2. Simulated Calcined Waste Sludge (1970 Data)

	wt%
Al ₂ O ₃	6.37
BaO	0.01
CaO	19.33
Cr ₂ O ₃	0.08
CuO	0.28
Fe ₂ O ₃	5.67
K ₂ O	3.62
MgO	6.35
Na ₂ O	11.50
NiO	0.14
PbO	0.71
P ₂ O ₅	1.61
SiO ₂	44.25
TiO ₂	0.06
ZnO	0.02

TABLE 3. Simulated Sludge Used in Microwave Studies

	wt%
Al ₂ O ₃	6.5
NaOH	2.5
CaO	5.5
Na ₃ PO ₄	0.4
MgO	5.5
K ₂ CO ₃	0.9
Fe ₂ O ₃	3.5
NaNO ₃	0.9
Diatomite	74.3

The microwave sludge was produced by adding the compounds to 50 gallons of water and then passing the mixture through an Alar[®] vacuum drum filter precoated with diatomite. The resulting sludge had a moisture content of approximately 52 wt%. Not all of the components added to the solution were removed in the filter. Approximately 87 wt% of the soluble compounds remained with the effluent; the residual solubles remained in the interstitial liquor.

Two dry sludge mixtures were also produced containing 65 and 30 wt% diatomite, respectively. The insoluble components (Al₂O₃, MgO, and Fe₂O₃) were added in the same proportions as the wet sludge. However, the solubles were calculated from retentions in the wet sludge makeups and were added in proportion to the amount of diatomite in the mix. The weight percents of solubles per gram of diatomite are listed in Table 4.

The dry soluble components were added to 1000 g of diatomite in a finned, five-gallon mixing drum and rolled approximately one hour. The contents were then mixed with the remaining diatomite and insolubles in a 55-gallon mix drum and rolled approximately three days to ensure a homogeneous mixture.

MICROWAVE DRYING TESTS

Drying tests were performed to determine the evaporation rate of water from wet simulated sludge containing 52 wt% water. These results are used by dryer manufacturers to size production-scale drying equipment. The tests were accomplished using a 6-kW generator and cavity at Rocky Flats and a size-foot, belt-driven microwave dryer at Cober Electronics, Inc., Stamford, CT.

Experimental work at Rocky Flats included placing known quantities of the sludge in the microwave cavity at one, two, or three inches in depth and varying the power between 2 and 5 kW. At one-minute intervals, the samples were removed from the cavity and weighed. This procedure was

TABLE 4. Solubles, wt% Per Gram of Diatomite

	wt%
NaOH	3.3
CaO	7.4
Na ₃ PO ₄	0.5
K ₂ CO ₃	1.2
NaNO ₃	1.2

continued until the moisture content was within 2 to 5 wt% of the original sludge weight.

Table 5 shows the average evaporation rates (lb/kW-hr) versus the power level (kW) for each depth. The evaporation rate remains fairly constant for each depth over the power range; however, there are slight increases at 3 kW for one-in. depth and 5 kW for two- and three-in. depth.

The drying tests performed at Cober Electronics, using a conveyor dryer, are presented in Exhibit 2. The results from the tests indicate that the sludge dries at an evaporation rate of 5.54 lb/kW-hr and is 84% efficient, which is representative of similar production processes. These data indicate that a production unit would consist of a 10-ft drying unit with a 3- to 5-ft drying section, using 915 MHz microwave energy. This system could process approximately 540 lb/hr of wet sludge at 1-ft/min belt speed.

MELTING TESTS

The objective of the melting tests was to determine the feasibility of adding microwave energy to simulated waste in a metal waste container and solidifying the waste to form either a melt or a sintered waste form. Collection of data important for further development of a microwave system included: (1) simulated sludge feed rate, (2) rate of addition to the waste container, (3) projected volume and weight reductions, and (4) physical properties of the final waste form.

Prior work determined the effectiveness of melting or sintering waste sludge in a gas-fired furnace. The waste form produced by this method was a friable

solid that did not form a cohesive monolith.

Vitrification of precipitation sludge in a joule-heated glass furnace was also done to determine waste loading and final waste form properties. This method produced a vitreous monolith with a waste loading of approximately 67% (Reference 6). Major drawbacks of the vitrification process were the corrosive atmosphere created by the glass melt, its effect on the process equipment, and the need for glass additives to form a pourable mixture.

Addition of microwave energy for solidification includes distinct advantages over other processes; these include: (1) direct addition of energy to the media, (2) in-container processing, (3) remote operation while isolating major pieces of equipment from hostile environments, and (4) containment of high temperatures to the media while maintaining surrounding equipment at relatively low temperatures.

Melting tests using bench-scale microwave equipment were conducted on simulated sludge to determine feasibility of reducing the sludge volume and producing a certifiable waste form. Results indicate achievability of better weight and volume reductions in a waste form meeting present waste criteria. Equipment used in the bench-scale tests include:

1. Cober Electronics microwave generator (6-kW)
2. Aluminum cavity (18 X 10 X 30 in) with a turntable
3. Three-stub tuner
4. Waveguides
5. Reflected power meter
6. Infrared Thermometer
7. Screw feeder

Chokes were added to the cavity for mounting the infrared thermometer and screw feeder. The chokes consist of a 1.25-in. i.d., 8-in. aluminum tube continuously welded to the cavity. The turntable was modified from continuous to intermittent

TABLE 5. Water Evaporation Rate

Depth (in.)	Pounds Per Kilowatt-Hour			
	2 kW	3 kW	4 kW	5 kW
1	1.6	2.2	2.3	—
2	2.4	2.3	2.4	2.8
3	2.4	2.7	2.7	2.9

operation by controlling the on/off switch with a timer. The table rotated approximately one-quarter turn per pulse.

Effective Power Determination

Tests were conducted to determine the power available for melting inside a metal container, termed *effective power*. This data was used to determine an optimum container size versus the amount of input power. Known quantities of water were placed in different-sized stainless steel containers. The containers were placed in the microwave cavity and heated at varying power levels for two minutes. The temperature rise of the water was measured. The effective power into the water was calculated using the equation:

$$q = C \times m/t \times \Delta T \quad (1)$$

where:

C – constant (0.01758 kW-min/lb-°F)

q – power (kW)

m – mass of water

t – time (min)

ΔT – temperature difference (°F)

Water is usually considered the most efficient material in coupling with microwave energy. It was assumed that the simulated sludge in the melting tests would be no more efficient than water in coupling with the available power. Therefore, the effective power using Equation 1 represents the maximum power available for heating inside the metal container.

The average effective power for the different container sizes is shown in Table 6. Figure 1 is a graphic representation of the data. The data curve for each of the containers exhibits a positive, relatively flat slope over the power range. The effective power increases as the container size increases to the 6-l container. The average power for the 6-l container is 5% greater than the 8-l container, suggesting an optimum container configuration where the power efficiency is at a maximum. Table 7 shows the physical dimensions for the metal containers.

TABLE 6. Effective Power (as Percentage of Input Power) Versus Container Size

Power Level (kW)	Effective Power				
	1-l	2-l	3-l	6-l	8-l
1	24.0	17.0	40.0	45.5	56.7
2	28.0	26.0	37.3	55.8	59.2
3		30.3	43.5	63.3	59.2
4		27.0	42.4	62.5	64.0
5		27.8	43.1	72.0	56.7
6		29.0	41.0	76.5	50.0

A test was run to determine if the effective power was the same when simulated sludge was used as the heating medium. A known quantity of 75 wt% diatomite sludge was placed in a metal container in the microwave cavity. The sludge was heated for two minutes at 4 kW and the temperature rise was noted. The specific heat of the sludge was determined using the basic heat transfer equation:

$$q = m \times c_p \times \Delta T \quad (2)$$

where:

m – mass flow rate (lb/hr)

c_p – specific heat (Btu/lb-°F)

ΔT – temperature difference (°F)

Assuming power (q) was the same as calculated in Equation 1, the specific heat (Equation 2) was determined to be 0.25 Btu/lb-°F. This agrees with the manufacturer's data showing a specific heat of 0.23 Btu/lb-°F for diatomite. The effective power was also determined using the radiation equation:

$$q = \epsilon \times \sigma \times A \times T^4 \quad (3)$$

where:

A – surface area (sq. ft.)

ϵ – emissivity

σ – Stefan-Boltzman constant
(0.173×10^{-10}) (Btu/ft²-hr-°R⁴)

T – temperature (°R)

FIGURE 1. Effective Power for Various Container Sizes

TABLE 7. Dimensions of Metal Containers

Volume (ℓ)	Diameter (in.)	Height (in.)	Surface Area (sq. ft.)
1.0	4.0	5.25	0.0873
2.0	4.75	6.75	0.1231
3.0	6.125	7.0	0.2063
6.0	7.1875	9.0	0.2818
8.0	8.0	10.0	0.3491

Emissivity of the sludge was found by measuring the temperature of the melt using a standard type “k” thermocouple and adjusting the emissivity on an infrared pyrometer until the pyrometer temperature agreed with the thermocouple temperature. The effective power calculated using Equation 3, with an average trial temperature of 1210 °C, was 2.63 kW compared with 2.56 kW calculated from Equation 1 at 4 kW in an 8-ℓ container.

Batch Tests

In the batch-fed method, an initial charge of 2 kg of dry sludge was added to an 8-ℓ stainless steel container with 1/2-in.-thick Fiberfrax insulation. The container was centered on the turntable. Input power was set at 4 kW for tests with the 8-ℓ container. Initial melting occurred within 5 to 10 minutes; the charge was allowed to stand in the microwave field 45 to 60 minutes or until bubbling action ceased. Subsequent 2.5-kg additions were made and then heated for the same amount of time. Temperatures of the melt ranged from 1000 to 1300 °C. Table 8 summarizes the data for the batch-fed trials.

Figures 2 and 3 show typical samples of batch-fed casts. In Figure 2, a sintered crust is evident on both the bottom and side of the sample. Figure 3 shows the center of the cast as a vitreous monolith with gas pockets scattered throughout. The sintered bottom crust on the cast is probably caused by insufficient power to complete melting of the sludge at that height in the container. The

TABLE 8. Batch-Fed Trials

Trial	Feed Rate (lb/kW-hr)	Density (g/cm ³)	Reduction	
			(wt%)	(vol%)
7	1.74	1.40	14.5	80.1
8	1.12	1.00	21.1	75.7
9	0.75	1.44	20.6	81.8
10	0.58	1.35	22.6	81.0
11	1.01	1.32	11.6	75.0
12	0.67	1.00	17.5	68.0
13	0.77	1.04	15.0	69.0
14	0.91	1.25	15.3	75.1
15	0.83	1.20	12.3	73.0
16	1.32	1.17	14.5	72.2
17	1.30	1.13	18.0	72.1

FIGURE 2. Batch-Fed Cast. Sample 16.

36002-04

height of the initial charge is sufficient to ensure that the microwave energy does not reflect off the bottom of the container. However, as the temperature of the material rises, the entrained air escapes, decreasing the volume and height of the powder.

At some point, the penetration depth of the microwave is greater than the height of the material, thus allowing a majority of the energy to be reflected off the bottom of the container. As further evidence, the reflected power was higher

FIGURE 3. Batch-Fed Cast. Sample 17.

36002-06

during heating of the initial charge than during subsequent additions.

Final densities for the batch-fed samples ranged from 1.0 to 1.44 g/cm³, with an average density of 1.21 g/cm³. The increase in density from approximately 0.40 g/cm³ for the bulk powder results from removing entrained air and destroying the cell structure of the diatomite, thereby fusing the discrete particles into a single mass. The increase in density translates into an average 74.8% volume reduction.

Weight reductions for the test runs averaged 16.6%. The majority of the loss in weight can be attributed to the evaporation of water from the sample. The feed rate shown in Table 8 was determined by the total amount (pounds) of dry sludge added to the container, input power (kilowatts), and total run time (hours). The feed rate can be used to estimate the total power requirement of the production-scale system. The average feed rate for the batch-fed trials was 1.0 lb/kW-hr.

In general, all the sludge samples behaved similarly when placed in the microwave field. The average

melting times were controlled by the operator who visually inspected the melt, but the melting temperatures remained constant for each trial.

Flux Tests/Continuous Feeding

Two methods were used to increase the density of the final cast. The first was the addition of fluxes to the sludge to decrease the molten viscosity, and the second was to continuously feed the sludge into the container. Fourteen trials were made using various fluxing agents; eleven were batch fed and three were continuously fed. Fluxes used in the tests included: anhydrous borax, hydrated borax, boric acid, sodium carbonate, trisodium phosphate, lime, and soda lime. See Figures 4 through 11. Table 9 summarizes data for the flux tests.

The average volume reduction for the fluxed samples, excluding anhydrous and hydrated borax, was 52.1% compared with 79.0% for the borax. Many gas pockets are noticeable in the non-borate casts, probably due to the breakdown of flux in the melt, which accounts for the lower densities and volume reductions.

FIGURE 4. Batch-Fed Cast Fluxed With Anhydrous Borax. Sample 20.

36002-12

FIGURE 5. Batch-Fed Cast Fluxed With Sodium Carbonate. Sample 22.

FIGURE 6. Batch-Fed Cast Fluxed With Lime. Sample 23.

36002-17

FIGURE 7. Batch-Fed Cast Fluxed With Boric Acid. Sample 24.

36002-18

FIGURE 8. Batch-Fed Cast Fluxed With Hydrated Borax. Sample 26.

36561-14

FIGURE 9. Batch-Fed Cast Fluxed With Trisodium Phosphate. Sample 28.

36561-17

FIGURE 10. Batch-Fed Cast Fluxed With Soda Lime. Sample 29.

36561-19

FIGURE 11. Continuously Fed Cast Fluxed With Anhydrous Borax. Sample 36.

36562-10

TABLE 9. Flux Tests

Trial	Feed Rate (lb/kW-hr)	Density (g/cm ³)	Reduction		Flux (wt%)	Flux
			(wt%)	(vol%)		
18	1.26	0.4	20.1	-15.0	20.0	Trisodium Phosphate
19	1.59	0.5	19.1	-3.3	20.0	Trisodium Phosphate
20	1.35	2.0	8.4	75.0	20.0	Anhydrous Borax
22	1.51	0.7	16.4	23.7	20.0	Sodium Carbonate
23	1.28	0.9	14.0	62.2	20.0	Lime
24	1.31	0.7	14.4	25.3	20.0	Boric Acid
26	1.06	1.6	17.0	76.6	10.0	Hydrated Borax
27	1.26	1.3	12.5	75.0	5.0	Hydrated Borax
28	1.08	1.3	12.4	74.6	10.0	Trisodium Phosphate
29	1.11	1.5	14.0	74.5	10.0	Soda Lime
32	1.32	2.1	6.8	77.5	10.0	Anhydrous Borax
36	1.64	2.3	4.0	83.4	10.0	Anhydrous Borax
38	1.11	2.3	4.6	83.0	10.0	Anhydrous Borax
40	1.39	2.2	3.7	82.2	5.0	Anhydrous Borax

The continuously fed borax samples were higher in density than the batch-fed samples. Excluding the 30 wt% diatomite sample, the average density and resulting volume reduction for the continuously fed samples were 2.25 g/cm³ and 82.9%, respectively, compared with 1.75 g/cm³ and 76.0% for batch-fed samples.

In general, continuous feeding of material into the waste container resulted in higher density and greater volume reduction than batch feeding. Nine tests were performed, continuously feeding sludge through a screw feeder into an 8-l container. An initial 2-kg charge was added to initiate a melt. After the initial charge melted and the infrared thermometer stabilized above 1000 °C, screw-fed addition was started. The screw-feeder hopper was filled with 2 kg of sludge at approximate 60-minute intervals and the sludge was metered in over this period. After the final addition of sludge, the cast was left in the microwave field approximately 30 minutes until bubbling action ceased.

Table 10 shows data collected from the continuously fed tests. The average density of the casts was 1.92 g/cm³ with an average volume reduction of 81.1%. Figure 12 shows a typical continuously fed sludge trial.

TABLE 10. Continuous Feed Tests

Trial	Feed Rate (lb/kW-hr)	Density (g/cm ³)	Reduction	
			(wt%)	(vol%)
30	1.37	1.7	7.2	80.0
31	1.29	1.9	8.7	81.5
33	1.08	1.9	10.5	82.0
35	0.89	1.9	11.3	82.5
37	1.12	1.9	5.3	79.5
39	1.75	2.3	1.9	82.5
41	1.32	1.9	5.1	80.7
42*	1.20	1.9	3.3	80.7
43**	2.66	1.3	0.0	27.0

*65 wt% diatomite

**30 wt% diatomite

Two trials were run using sludge that contained less diatomite to determine the effect on the volume reduction and physical characteristics of the final cast. Sample 42 contained 65 wt% diatomite sludge and Sample 43 contained 30 wt% diatomite sludge. The density and volume reduction of Sample 42 is the same as the other samples; however, Sample 43 exhibits a relatively low density (1.3 g/cm³) and volume reduction (27%).

Two trials were done using carbon steel containers to determine the effect of heating over an extended period. The containers were constructed from 16-gauge carbon steel to simulate metal drums being considered for an upscaled system. Approximately 10% of the metal thickness was oxidized on the section exposed to the melt.

ECONOMIC ANALYSIS

An economic analysis was performed to compare the costs associated with five methods of sludge immobilization. All of these methods eliminated the potential for free liquids and excessive particulate as mandated in the WIPP-WAC. The methods are:

1. Water absorption using a portland cement - diatomite mixture
2. Melting or sintering using microwave technology
3. Cementation into a monolith with portland cement and water
4. Solidification using polyethylene as the binder
5. Solidification using polyester resin as the binder

Table 11 contains the results of the analysis. All costs are based on a production rate of 178,840 pounds of wet sludge per year. The wet sludge contains 66 wt% water and 34 wt% sludge on a dry basis. All processes except the portland cement/diatomite addition assumed a dried product input. Appendix A contains data for 18

FIGURE 12. Continuously Fed Cast. Sample 35.

36562-08

TABLE 11. Economic Analysis of Sludge Treatment Processes

	Processing Systems					
	Present Operation*	Portland Cement/Diatomite*	Microwave	Cement	Polyethylene	Polyester
Properties:						
Density	1.1	1.4	1.9	1.4	1.4	1.4
Waste loading* (% of net weight)	0.4	0.6	1.0	0.4	0.4	0.4
Materials:						
Diatomite (lbs)	134130	59613	0	0	0	0
Cement (lbs)	134130	59613	0	46945	0	0
Polyester (lbs)	0	0	0	0	0	93891
Polyethylene (lbs)	0	0	0	0	93891	0
Water (lbs)	0	0	0	46945	0	0
Sludge (dry lbs)	178840	178840	62594	62594	62594	62594
Net weight: (lbs)	447100	298067	58400	156485	156485	156485
Drums/year:	976	569	123	299	299	299
Total volume: (cu. ft.)	7176	4181	905	2195	2195	2195
Gross weight: (lbs)	539820	352089	70099	184847	184847	184847
Costs:						
Material:						
Diatomite (\$0.11/lb)	\$14,754	\$6,557	\$0	\$0	\$0	\$0
Cement (\$0.05/lb)	\$6,707	\$2,981	\$0	\$2,347	\$0	\$0
Polyester (\$1.00/lb)	\$0	\$0	\$0	\$0	\$42,251	\$93,891
Polyethylene (\$0.45/lb)	\$0	\$0	\$0	\$0	\$0	\$0
Power: (\$0.07/kW-hr)	\$0	\$0	\$4,213	\$0	\$1,000	\$0
No. of shipments:	54	35	7	18	18	18
Shipping: (\$2784/TRUPACT)	\$150,286	\$98,022	\$19,516	\$51,461	\$51,461	\$51,461
Storage: (\$190/cu. ft.)	\$1,363,529	\$794,446	\$172,041	\$417,084	\$417,084	\$417,084
Drums: (\$28.70/drum)	\$28,011	\$16,320	\$3,534	\$8,568	\$8,568	\$8,568
Total:	\$1,563,287	\$918,326	\$199,304	\$479,460	\$520,364	\$571,004
Cost savings:		\$644,961	\$1,363,984	\$1,083,826	\$1,042,923	\$992,283
Equipment/Installation:		\$50,000	\$375,000	\$375,000	\$375,000	\$375,000
Volume reduction:		42%	87%	69%	69%	69%
Weight reduction:		35%	87%	66%	66%	66%

*Present operation and portland cement/diatomite are based on wet sludge

drums from the present operation. The average waste loading of these drums was 38 wt%.

Assumptions

The present portland cement/diatomite process in the old waste processing facility was used as the base case to compare the solidification processes. Other assumptions made for the analysis are listed below:

1. Material costs for cement, diatomite, polyester, and polyethylene were estimated at \$0.05, \$0.11, \$1.00, and \$0.45 per pound, respectively.
2. The cost of shipping was based on \$2784 per round trip for a rectangular TRUPACT.
3. The TRUPACT load limit is 10,000 pounds or 36 drums.

4. Storage costs are based on \$190 per cubic foot.
5. Total equipment and installation costs were estimated to be 0.5 times the equipment cost. Equipment and installation costs were estimated to be \$375,000 for all the processes except the portland cement/diatomite system, which was estimated at \$50,000.
6. Labor and maintainance costs were assumed to be the same for all the processes and were not included.
7. Power costs were taken as \$0.07/kW-hr. All power costs were considered equal for peripheral equipment: only the power consumption for microwave energy and polyethylene immobilization are shown.

Present Operation

In the present operation, a 1:1 mixture of Type I portland cement and diatomite is used as an absorbent in the waste drum. The mixture is intermittently fed into the drum through a screw feeder along with the wet sludge. By intermittently feeding the cement/diatomite mixture, the sludge and absorbent form layers in the drum. The layers act to absorb any water that desorbs from the sludge. The average waste loading for the process is approximately 40 wt% sludge.

Sludge production on the present system is approximately 447,100 pounds (976 drums). The wet sludge content was calculated to be 178,840 pounds by multiplying the waste loading of 0.40 by the net weight of the waste. The total volume was determined by multiplying the number of drums by the volume per drum. Standard 55-gallon drums are used as overpacks for 45-gallon rigid liners in the system; the resulting volume is approximately 7180 cubic feet.

Annual costs include materials, power usage, shipping, storage, and drums. Material costs were estimated at approximately \$6710 for cement and \$14,750 for diatomite. The cost of shipping is based on the number of TRUPACT shipments

required to handle the gross weight. This number (derived by dividing the gross weight by the 10,000-pound payload limit per TRUPACT and the number of shipments) was calculated to be 54. The cost per shipment is multiplied by the number of TRUPACT shipments; for the present operation shipping costs are estimated at \$150,290 per year.

Storage costs were calculated by multiplying the total volume by the unit cost per cubic foot. Storage for the present operation was calculated at \$1,363,530. The cost for drums was assumed to be \$28.70 each or approximately \$28,010 yearly. Total annual operating costs were determined to be \$1,563,290.

Portland Cement/Diatomite

A system to increase the average waste loading using the present processing method was analyzed to determine cost effects compared with the present operation and the other immobilization processes. The system would include a volumetric screw feeder, weigh station, and computer control system.

The net weight, assuming a 60 wt% waste loading of wet sludge, was estimated at approximately 298,070 pounds. A specific gravity of 1.4 g/cm³ was used to determine the weight per drum. Assuming a 45-gallon rigid liner is used as the primary loading vessel, the weight per drum is 526 pounds. The number of drums per year (approximately 569) was determined by dividing the net weight of sludge by the weight per drum. The gross shipping weight was calculated by multiplying the number of drums per year by 95 pounds (the standard weight of the rigid liner and overpack container plus the net weight of sludge). The gross weight is approximately 352,090 pounds. Total volume was calculated to be approximately 4180 cubic feet.

Power usage was determined to be negligible for this process. Material costs were calculated to be \$2980 for portland cement and \$6560 for diatomite. TRUPACT shipments were calculated to be 35 with a resulting \$98,020 shipping cost. Storage costs are \$794,450, and the cost for drums

was calculated to be \$16,320. Total annual operating costs are approximately \$918,330.

The cost savings that could be realized by increasing the average waste loading from 40 to 60 wt% is \$644,960. The volume and weight reductions are 42 and 35%, respectively.

Microwave Solidification

A production-scale microwave sludge solidification process would consist of a surge hopper, screw feeder, microwave cavity, generators, waveguides, tuner, and a drum handling system. The pre-dried sludge is continuously fed into a waste drum inside the microwave cavity. Two 50-kW microwave generators would be needed to process the design feed rate of sludge.

The dry sludge production rate, assuming 65 wt% moisture content, is 62,590 pounds per year, using an average weight reduction of 6.7% after processing through the microwave system; the total net weight of sludge is 58,400 pounds. An average specific gravity of 1.9 g/cm³ was used to determine the number of drums per year required to package the waste. An upper limit of 800 pounds per drum, including the weight of the drum, was used to determine the total gross shipping weight. The number of drums per year was calculated at 123 based on a 30-gallon carbon steel container as the microwave cavity, overpacked with a 55-gallon drum. The resulting weight per drum is approximately 476 pounds. The associated total volume and gross shipping weight are 905 cubic feet and 70,100 pounds, respectively.

Power usage was calculated by dividing the net weight of sludge by an average feed rate of 1.3 lb/kW-hr, then dividing by the efficiency of the magnetron (80%). The cost of electrical power was assumed to be \$0.07 per kW-hr. The annual power usage was calculated to be \$4210. The number of TRUPACT shipments was estimated as 7 for an annual shipping cost of \$19,520. Storage costs were calculated at \$172,040 and the cost of drums approximately \$3530. Total yearly operating costs are \$199,300.

The cost savings associated with the operation of the microwave system was calculated to be \$1,363,980. The volume and weight reductions using this process, compared to the present process, would be 87%.

Cementation

The cementation process used in the cost analysis is based on the current direct cementation process of TRU precipitation sludges from one of the two waste processing facilities. The equipment consists of two storage hoppers for sludge and cement, volumetric screw feeders, mixing screw, drum scale, and a cement storage and transport facility.

The net weight of the waste, assuming a 40% waste loading, was approximately 156,490 pounds. The estimated drums per year is 299 based on using a 45-gallon rigid liner as the primary container overpacked with a 55-gallon drum. Assuming a specific gravity of 1.4 g/cm³, the weight per drum is 526 pounds. The associated total volume is 2195 cubic feet and the gross shipping weight is 184,850 pounds.

The cost for power for the cementation process was considered negligible compared to the microwave system. Material costs for the system would be approximately \$2350 per year. TRUPACT shipments would number 18 with an annual cost of \$51,460. Storage costs were calculated to be \$417,080. The cost of drums is approximately \$8,570. Total yearly operating costs are \$479,460.

The cost savings for the cementation process is \$1,083,830. The resulting volume and weight reductions are 69% and 66%, respectively.

Polyethylene Solidification

Polyethylene solidification is based on work with nitrate salts at Brookhaven National Laboratory.⁷ The process equipment would consist of a polyethylene resin storage and transport system, surge hoppers for the resin and sludge, volumetric screw feeders, heated extruder, and a drum weigh station.

Power usage for the polyethylene system is estimated at 14,290 kW-hr to heat and melt the polyethylene resin including loss of heat through the extruder. The annual cost of power is approximately \$1,000. The material cost for polyethylene resin is \$42,250 per year. The number of TRUPACT shipments is 18 with a shipping cost of \$51,460. Storage costs were calculated to be \$417,080. The cost for drums was determined to be \$8,570. The total annual operating cost is \$520,360.

The cost savings for the polyethylene process is \$1,042,920. The resulting volume and weight reductions are 69% and 66%, respectively.

Polyester Solidification

Polyester solidification is based on the AZTECH process developed by General Electric. The process is used mainly to dewater a liquid waste stream using an azeotropic distillation. The remaining precipitate is solidified using polyester as the binder. Assuming the sludge being introduced into the system would be dry, distillation would not be needed.

The solidification portion of the process would consist of a polyester resin storage and transport system, sludge surge hopper, volumetric screw feeder, mixing screw, and drum weigh station. Power usage for the polyester system was determined to be negligible compared to the microwave or polyethylene processes.

Polyester is a thermosetting resin usually requiring a catalyst for hardening. The cost of the catalyst was assumed to be negligible compared to the cost of the polyester resin and was not added to the material cost. The cost for polyester resin is \$93,890 per year. The number of TRUPACT shipments is 18 with a shipping cost of \$51,460. Storage costs were calculated to be \$417,080. The cost for drums was determined to be \$8570. The total annual operating cost is \$571,000.

The cost savings for the polyester process is \$992,280. The resulting volume and weight reductions are 69% and 66%, respectively.

CONCLUSION

A general conclusion can be drawn from the bench-scale tests of the microwave system using simulated TRU waste. Waste sludges produced at the Rocky Flats Plant with a diatomaceous earth content of 60–65 wt% will readily melt using microwave energy. Volume reductions to 83% over the dry sludge have been achieved. The process produces a monolith that meets the criteria established by the WIPP, namely the absence of free liquids and excessive particulate. The overall volume and weight reductions may exceed the present immobilization system of wet sludge and absorbent by as much as 87%, resulting in substantial annual operating cost savings.

Further work is required on actual TRU sludges to verify the results obtained using the simulated sludge. More data is also required to characterize gases produced during the melting process and determine if offgas treatment is required.

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APPENDIX A.
RFP WASTE PROCESSING FACILITY
DIATOMITE/PORTLAND CEMENT WASTE SLUDGE

Date	Gross Wt (lb)	Tare Wt (lb)	Net Wt (lb)	Net Wt Sludge (lb)	Net Wt Dia./PC (lb)	Time (hr)	Sludge Flow Rate (lb/min)	Dia./PC Flow Rate (lb/min)	Diatomite (wt%)	Sludge (wt%)	Dia./PC (wt%)
9/4/86	425	95	330.0	141.7	188.3	4.42	0.5	17.04	3.5	42.9	57.1
9/4/86	432	95	337.0	113.4	223.6	5.25	0.4	17.04	3.4	33.6	66.4
9/5/86	420	95	325.0	101.4	223.6	5.25	0.3	17.04	3.6	31.2	68.8
9/5/86	462	95	367.0	193.2	173.8	4.08	0.8	17.04	3.2	52.6	47.4
9/5/86	460	95	365.0	144.8	220.2	5.17	0.5	17.04	3.2	39.7	60.3
9/5/86	444	95	349.0	136.0	213.0	5.00	0.5	17.04	3.3	39.0	61.0
9/6/86	390	95	295.0	92.7	202.4	4.75	0.3	17.04	3.9	31.4	68.6
9/7/86	482	95	387.0	191.9	195.1	4.58	0.7	17.04	3.0	49.6	50.4
9/7/86	455	95	360.0	83.1	276.9	6.50	0.2	17.04	3.2	23.1	76.9
9/7/86	500	95	405.0	234.6	170.4	4.00	1.0	17.04	2.9	57.9	42.1
9/8/86	470	95	375.0	108.8	266.3	6.25	0.3	17.04	3.1	29.0	71.0
9/8/86	456	95	361.0	183.4	177.6	4.17	0.7	17.04	3.2	50.8	49.2
9/8/86	454	95	359.0	217.1	141.9	3.33	1.1	17.04	3.2	60.5	39.5
9/9/86	408	95	313.0	64.6	248.4	5.83	0.2	17.04	3.7	20.7	79.3
9/10/86	412	95	317.0	146.6	170.4	4.00	0.6	17.04	3.6	46.2	53.8
9/10/86	380	95	285.0	64.8	220.2	5.17	0.2	17.04	4.0	22.7	77.3
9/11/86	439	95	344.0	88.4	255.6	6.00	0.2	17.04	3.4	25.7	74.3
9/11/86	424	95	329.0	84.1	245.0	5.75	0.2	17.04	3.5	25.5	74.5

EXHIBIT 1

AL 586.0777
October 13, 1986

Characterization of Sludge Samples Intended for Treatment by Microwave System

October 13, 1986

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EXHIBIT 1, CONT'D

AL 586.0777

INTRODUCTION

The Analytical Laboratories (AL) were requested by Waste Operations (WO) personnel to provide analyses support for characterization of Building 774 sludge samples scheduled for microwave drying and melting for the Building 774 immobilization process. The analyses requested were infrared spectroscopy (IR), emission spectroscopy (ES), diatomaceous earth content by X ray diffraction (XRD), weight loss characterization by thermal gravimetric analysis (TGA), and carbon analysis (CA). The initial four samples we received are described below:

Requisition 29303 - 774 sludge sample from 9TK basic waste stream
Requisition 29304 - 774 sludge sample from 10 TK raffs
Requisition 29305 - cold startup sludge sample
Requisition 29306 - cold diatomite sample

This report will detail investigations by all techniques **except** diatomite content by XRD. John Fraser of Building 771 Chemical Operations Support Lab will report those results.

SUMMARY

Analyses results by IR, ES, TGA, and CA indicate major differences between the four samples as well as some similarities. The two hot sludge samples had completely different visual, physical characteristics. 29303 was a light brown color while 29304 was dark black in color. The chemical compositions of these two samples reflected large differences which are due to the sources of the waste streams where these samples originated. 29305 (cold startup sludge) was also unique in chemical composition with some similarities but also large differences when compared to the compositions of 29303 and 29304. The composition of 29306 (cold diatomite) confirmed its identity as a diatomaceous earth.

EXPERIMENTAL

Standard laboratory instrumentation was used on all analyses. IR spectra were recorded on hot and cold Perkin-Elmer IR spectrometers. ES results were obtained using the hot Wadsworth ES for "specs-qual" analysis. TGA was performed on the hot DuPont TGA. CA was performed on the hot LECO carbon analyzer.

RESULTS

Table 1. IR Results

<u>Requisition No.</u>	<u>Composition by IR</u>
29303	silica (SiO_2), possibly small amounts of nitrates or carbonates
29304	nitrates, possibly some carbonates
29305	silica, possibly phosphates, nitrates, and carbonates
29306	silica

EXHIBIT 1, CONT'D

AL 586.0777

Table 2. ES Results (expressed as ppm by weight unless otherwise specified as %)

Element	29303	29304	29305	29306	Element	29303	29304	29305	29306
Mg	200	200	50	<10	Mg	5,000	3%	1%	200
Al	1%	1%	1%	1%	Mn	20	20	50	50
As	<10	<10	<10	<10	Mo	100	<50	<50	<50
B	50	10	100	20	Nb	<100	<100	<100	<100
Ba	50	20	50	50	Ni	100	100	200	50
Be	100	200	2	<1	P	100	<50	5%	50
Bi	<5	<5	<5	<5	Pb	1,000	5,000	200	50
Ca	500	1,000	5,000	100	Sb	50	50	10	10
Cd	50	500	50	<10	Si	2%	500	1,000	2%
Co	<50	<50	50	<50	Sn	10	<10	100	<10
Cr	5	100	100	1	Sr	<500	<500	1,000	<500
Cu	100	100	1,000	100	Te	<10	<10	<10	<10
Fe	3%	2%	3%	1%	Ti	1,000	500	500	1,000
Ga	100	100	500	100	Tl	<50	<50	<50	<50
Ge	50	<5	<5	50	V	10	<10	<10	50
Hg	<5	<5	<5	<5	Zr	<50	<50	<50	<50
In	<10	<10	<10	<10	Zn	100	100	500	<100
K	5%	10%	5%	1%					

Table 3. TGA Results

Requisition No.	Temperature Range(°C)	Weight % Loss	Attributed to:
29303	50 - 130	35.6	water
	130 - 500	1.8	nitrites, carbonates
	500 - 900	7.2	sulfates
29304	35 - 300	49.4	water
	300 - 550	2.3	nitrites, carbonates
	550 - 850	17.4	sulfates
29305	35 - 250	7.7	water
	250 - 310	3.4	nitrites
	310 - 500	3.4	carbonates
	500 - 900	2.4	sulfates
29306	35 - 900	0	

Table 4. CA Results

Requisition No.	Total %C
29303	1.4
29304	3.0
29305	3.0
29306	0.014

EXHIBIT 1, CONT'D

AL 586.0777

DISCUSSION OF RESULTS

ES results provided the most information about the nature of these samples. Data in Table 2 demonstrates the differences as well as some similarities between the samples. The differences in chemical composition of the two hot sludges is due to nature of their different source streams. One interesting result from IR and ES which confirms the findings of the XRD method for quantitative diatomaceous earth content is the large amount of silicon present in 29303. XRD detected significantly lower amounts of silicon in 29304. IR and ES also detected lower amounts of silicon in 29304 compared to 29303. ES detected large amounts of phosphorus present in the cold startup sludge, 29305, that is probably present as phosphates as detected by IR.

CA results indicate that the total carbon detected in samples 29304 and 29305 are very similar. However the carbon detected in these samples is not differentiated between organic and inorganic carbon containing species. 29306 contained only a small amount of carbon as would be expected. 29303 contained only 50% of the total carbon found in 29304 and 29305. The significance of this result is unknown at this time.

TGA results confirm the presence of nitrates and carbonates as reported by IR. The presence of water was also indicated as shown in Table 3. The weight losses at temperatures above 500°C suggest the possibility of sulfates present in the samples. However, this supposition is not confirmed by other analytical methods performed at this time.

EXHIBIT 2

MICROWAVE DRYING OF
SYNTHETIC SLUDGE

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April 17, 1987

EXHIBIT 2, CONT'D

MICROWAVE DRYING OF SYNTHETIC SLUDGE

Objective: To perform drying tests on synthetic sludge in order to determine technical and cost feasibility of utilizing microwave energy for the drying of toxic sludge.

Drying Tests: Curing curves for samples of varying thicknesses were taken in both microwave batch and conveyor oven as a function of power. Since microwave energy can in theory be imparted to a drying process as rapidly as is wished it is necessary to determine the maximum drying rate that the product can withstand for a given process configuration. Preliminary testing was performed on the samples listed in Table 1 with the listed results. The drying curves are shown in Figures 1 and 2 with a plot of the drying effectivities shown in Figure 3. A summary of moisture levels is shown in Table 2.

Discussion: Preliminary results indicate that sludge in a 3" height configuration dries effectively at least at the rate of 5.54 pounds per kilowatt hour in a residence time of 3 minutes (sample 4). Further testing at higher power levels would determine the ultimate drying rate for a 3" height configuration. A calculation in Appendix A indicates that the maximum theoretical process effectivity for sludge drying is 6.25 pounds per kilowatt hour. Thus the conveyor value of 5.54 lb/kWh is running at 84% efficiency, a value which is representative of a production processing operation. The batch effectivity of 56% being lower is not readily explained from cavity size considerations.

Note that the drying curves appear fairly typical with a discernable heat up region at the onset of power (increasing drying rate region). This portion is followed by a constant drying rate region. The tests were terminated before the decreasing drying rate region became prevalent. Note also that Figure 3 shows the usual phenomenon of an increasing process effectivity as the rate and power is increased for a given configuration.

EXHIBIT 2, CONT'D

- 2 -

Cost: Using the experimental value of 5.55 lbs/kWh a 50 kW, 915 MHz power module could process 278 pounds of wet sludge per hour. Assuming a wet density of 36 lb/ft³, a 1 foot wide belt with 3" sludge height could process 540 lb/hr at 1 ft/min belt speed. Thus, a drying system could be quite small; 10 ft in length with a 3-5 ft microwave portion. Cost of such a system would run approximately \$85,000.

EXHIBIT 2, CONT'D

FIGURE 1.

FIGURE 2.

EXHIBIT 2, CONT'D

FIGURE 3.

Sample Number	Microwave System	Net Weight (gm)	Thickness (in)	Drying Time (min)	Process Effectivity (lb/kWh)
1	Conveyor (3 kW)	629.7	3.	5	5.55
2	Conveyor (3 kW)	404.7	2.	4	4.46
3	Conveyor (3 kW)	198.5	1.	2	4.37
4	Conveyor (5 kW)	629.2	3.	3	5.54
5	Conveyor (5 kW)	404.5	2.	2	5.35
6	Batch (3 kW)	1974.7	2.5	25	3.48

TABLE 1

DESCRIPTION OF TEST SAMPLES

EXHIBIT 2, CONT'D

	% Wet Weight	% Moisture Remaining	Moisture Content (%)
From Process	100%	0	51.03
Dry (Sample)			
#6	46.9	53.0	
#2	48.0	52.0	
#4	48.3	51.7	
#5	48.4	51.6	
#3	50.3	47.7	
#1	<u>51.9</u>	<u>48.2</u>	
-			
$\bar{x} =$	48.97	51.03	0
$\sigma =$	1.65	1.60	

TABLE 2

TYPICAL SAMPLE MOISTURE VALUES

EXHIBIT 2, CONT'D

APPENDIX A

MICROWAVE POWER USAGE AND COST WORKSHEET

CUSTOMER	<u>Rockwell International</u>	DATE	<u>3-30-87</u>
ADDRESS	<u>Building 130</u>	CONTACT	<u>Robert Peterson</u>
	<u>Rocky Flats Plant</u>		
	<u>Rocky Flats, CO 80403</u>	PHONE	<u>303-966-4828 or</u>
			<u>303-966-2605</u>

PRODUCT/DESCRIPTION

Calculation of sludge drying rate in terms of pounds of starting
product per hour. Specific heat of dry sludge assumed .2 BTU/LB F,
temperature rise 70 F to 212 F.

I. POWER CONSUMPTION (THEORETICAL)

1. TEMPERATURE RISE (Liquid)

Process Rate 1.0 lb/hr x %H₂O .48 = .48 lb/hr

$$P1 = 2.93 \times 10^{-4} \times \underline{.48} \text{ lb/hr} \times \underline{1.0} \text{ BTU/lb/F} \times \underline{142^0} \text{ F}$$

$$= \underline{.02} \text{ kw}$$

2. TEMPERATURE RISE (Solids)

Process Rate 1.0 lb/hr x %Solid .52 = .52 lb/hr

$$P2 = 2.93 \times 10^{-4} \times \underline{.52} \text{ lb/hr} \times \underline{.2} \text{ BTU/lb/F} \times \underline{142^0} \text{ F}$$

$$= \underline{.004} \text{ kw}$$

3. EVAPORATION

$$P3 = \text{Process Rate } \underline{.48} \text{ lb/hr (liquid)} \times \underline{970} \text{ BTU/lb} \times 2.93 \times$$

$$\times 10^{-4} = \underline{.136} \text{ kw}$$

$$\text{TOTAL POWER} = P1 + P2 + P3 = \underline{.16} \text{ kw}$$

$$\text{PROCESS EFFECTIVITY} = \text{Process Rate} / \text{Total Power}$$

$$= \underline{6.25} \text{ lb/kwh}$$