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AQUEOUS BIPHASIC EXTRACTION OF URANIUM AND THORIUM FROM CONTAMINATED SOILS

FINAL REPORT

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by

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ACRONYMS

ABE	aqueous biphasic extraction
ANL	Argonne National Laboratory
DOE	U.S. Department of Energy
DTPH	dry tons per hour
FCI	fixed capital investment
FEMP	Fernald Environmental Management Project
gpm	gallons per minute
HP	horsepower
ID	Integrated Demonstration, interior diameter
O/F	overflow
O/S	oversize
PEG	polyethylene glycol
psig	pounds per square inch gauge
PTA	phase transfer agent
PZC	point of zero charge
rpm	revolutions per minute
SCFM	standard cubic feet per minute
S.G.	specific gravity
S.S.	stainless steel
STPH	short tons per hour
TDH	total discharge head
TPD	tons per day

TPH	tons per hour
U/F	underflow
U.S.	undersize
USID	Uranium in Soils Integrated Demonstration
V.S.	variable speed
W.V.	weight volume

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ABSTRACT

The aqueous biphasic extraction (ABE) process for soil decontamination involves the selective partitioning of solutes and fine particulates between two immiscible aqueous phases. The biphase system is generated by the appropriate combination of a water-soluble polymer (e.g., polyethlene glycol) with an inorganic salt (e.g., sodium carbonate). Selective partitioning results in 99 to 99.5% of the soil being recovered in the cleaned-soil fraction, while only 0.5 to 1% is recovered in the contaminant concentrate. The ABE process is best suited to the recovery of ultrafine, refractory material from the silt and clay fractions of soils. During continuous countercurrent extraction tests with soil samples from the Fernald Environmental Management Project site (Fernald, OH), particulate thorium was extracted and concentrated between 6- and 16-fold, while the uranium concentration was reduced from about 500 mg/kg to about 77 mg/kg. Carbonate leaching alone was able to reduce the uranium concentration only to 146 mg/kg. Preliminary estimates for treatment costs are approximately $160 per ton of dry soil. A detailed flowsheet of the ABE process is provided.

SUMMARY

In essence, the aqueous biphasic extraction (ABE) technology is based on the selective partitioning of both soluble and refractory particulate uranium contaminants between two immiscible aqueous phases. The contaminated soil is suspended in an aqueous polymer solution (e.g., polyethylene glycol) and is contacted, in a countercurrent fashion, with an aqueous salt solution (e.g., sodium carbonate). The liquid/liquid extraction is carried out in a Karr column because of its ability to handle solids without blockage. During the liquid/liquid contact, heavy metal contaminants, such as uranium, are selectively partitioned from the polymer solution to the salt solution, while the cleaned-soil particles remain dispersed in the polymer phase. Typically, 99 to 99.5% of the soil can be recovered in the cleaned-soil fraction, while only 0.5 to 1% is recovered in the contaminant

concentrate. Dissolved soil organics (e.g., humates) and dissolved uranium species can be recovered from the salt phase by selective precipitation with methanol. This process produces an easily filtered solid residue and can reduce the residual uranium concentration in the salt stream to below 1 mg/kg. The methanol is recovered for recycle from the methanol/salt solution by distillation.

The ABE process is best suited to the recovery of ultrafine, refractory material from soils containing significant amounts of salt and clay. In laboratory-scale tests of the ABE technology with soil samples from the Fernald Environmental Management Project site (Fernald, OH), we were able to reduce the uranium concentration in the -100 mesh soil fraction from about 500 mg/kg to about 77 mg/kg; in contrast, carbonate leaching alone was able to reduce the uranium concentration only to 146 mg/kg. Preliminary estimates for treatment costs, assuming a 480 ton-per-day (TPD) treatment rate, are approximately $160 per ton of dry soil. We are confident that the processing costs can be reduced by further technology development and by further process scale-up to treatment rates of 100 to 200 TPD.

The most expensive component of the flowsheet, in terms of both capital and operating costs, is the methanol precipitation/distillation step. Not only is this operation energy-intensive, it consumes a significant fraction of carbonate from the system. Further development work on alternative methods for the removal of dissolved uranium from concentrated sodium carbonate solutions is recommended. Advances in techniques for radionuclide removal from high-ionic-strength carbonate solutions would be of benefit not only to soil washing, but would also be of use in the treatment of process solutions generated in decontamination and decommissioning operations. In this regard, a new, proprietary solvent extraction process developed at Argonne National Laboratory shows great promise in its ability to remove actinides from concentrated (>5 wt%) carbonate solutions. It should be pointed out that this secondary treatment of the salt-rich phase is necessary only because a significant portion of the uranium present in the Fernald soil is easily dissolved in the salt-rich phase.

A significant finding from the column extraction tests is the fact that ^{234}Th (a daughter product of ^{238}U) was extracted from the soil and recovered in the fraction of solids that partitioned into the salt-rich phase. The thorium was concentrated by 6- to 16-fold, a result that demonstrates that refractory materials can be extracted and concentrated by the ABE process.

1 INTRODUCTION

The former Feed Materials Production Center, now called the Fernald Environmental Management Project (FEMP), at Fernald, OH, produced uranium metal for use in defense reactors until production was halted in 1989. During its operation, the soil at the site became contaminated with uranium from a variety of sources, including deposition of airborne uranium particulates and spills of solvents and process effluents [Lee]. An estimated 2×10^6 yd^3 (1.6×10^6 m^3) of uranium-contaminated soil needs to be treated. Soil cleanup levels have not yet been set [Lee].

The major constituents of the soil at the FEMP site are quartz, calcite, dolomite, and clay [Lee]. Because of the high levels (>80 wt%) of silt (from <53 µm to 2 µm) and clay (<2 µm), this soil is not directly amenable to treatment by conventional soil washing techniques. Buck et al. [Buck-1993, -1994A, -1994B] have identified a number of uranium(VI)-bearing phases in the soil. These phases include uranium silicates, uranium phosphates (e.g., autunites), uranium oxide (UO_3), and uranium associated with calcium fluorite. In addition, Buck et al. identified several uranium(IV)-bearing phases, such as uranium silicide, uranium oxide (UO_2), and uranium phosphite [$U(PO_3)_4$]. While some of the uranyl species are easily leached with aqueous carbonate solutions, some of the uranium phases, like uranium phosphite, are extremely refractory and do not readily dissolve in carbonate solutions even in the presence of an oxidizing agent. The more refractory uranium phases are present as discrete particles with sizes in the micron and submicron range [Buck-1994B].

We are currently evaluating the use of aqueous biphasic extraction (ABE) systems for the recovery of uranium from contaminated soils. The extraction process involves the selective partitioning of solutes, or fine particulates, between two immiscible aqueous phases [Chaiko-1989, -1992, -1993A, -1993B, -1994, -1995A, -1995B, -1995C]. The extraction systems are generated by combining an aqueous salt solution and an aqueous polymer solution. This produces two distinct liquid layers that are as immiscible as oil and water, yet each liquid layer contains at least 70 to 80 wt% water. The biphasic systems that we have been working with consist of immiscible polyethylene glycol (PEG) and salt solutions. Some inorganic salts that promote biphase formation with PEG solutions include the sodium/potassium salts of sulfate, carbonate, phosphate, and hydroxide [Ananthapadmanabhan].

The selective partitioning of particulates in ABE systems is based on physicochemical interactions between the particle surface and the liquid phases, rather than on bulk phase properties such as density. Consequently, particle size should be small enough that particle settling due to gravity is slow compared to the rate of liquid/liquid phase separation. In general, we have found that an upper size limit of about 150-200 µm can be accommodated during continuous, countercurrent extraction.

Bench-scale tests have shown that, in general, ultrafine metal oxide particulates (such as PuO_2, UO_2, CeO_2, Fe_2O_3, TiO_2, and Al_2O_3) partition preferentially into the salt-rich phase in PEG/salt systems [Chaiko-1992, -1993A, -1993B]. The only exceptions to this partitioning behavior that we have found so far are the crystalline silicates (e.g., quartz and cristobalite), layered silicates (e.g., clays such as kaolinite and montmorillonite), and glass. Clays partition into the PEG-rich phase with partition coefficients of about 100, regardless of pH (we looked at pH values ranging from 2 to 12). On the other hand, the partition behavior of crystalline silicates and glass depends the degree of surface ionization. At pH values near the point of zero charge (PZC), these materials partition into the PEG-rich phase, while partitioning into the salt-rich phase occurs when the pH is either above or below the PZC [Chaiko-1993A].

In addition to pH, phase transfer agents (PTAs) can be used to alter the partitioning behavior of ultrafine particulates [Ananthapadmanabhan]. For example, water-soluble complexants, such as Arsenazo III, can be used to selectively transfer PuO_2 or UO_2 particulates from the salt-rich phase into the PEG-rich phase [Chaiko-1992, -1993A]. One can also use PTAs to selectively transfer particles from the PEG-rich phase into the salt-rich phase.

The main advantage of using ABE technology to decontaminate soils is that this process achieves both high decontamination factors and high selectivity. Approximately $\geq$99% of the soil is recovered in the clean fraction, and $\leq$1% of the initial feed is recovered in the contaminant concentrate. The ABE technology can be used to treat ultrafine soil particles, so it is especially attractive for decontaminating soils with a high clay content. In general, the ABE process is ideally suited to removing highly refractory particulate contaminants that are in the micron and submicron size range and that are well liberated from the soil matrix.

2 LABORATORY STUDIES

2.1 BATCH PARTITIONING OF URANIUM

The soil samples used in this work were provided by the U.S. Department of Energy's (DOE's) Fernald Environmental Management Project (FEMP). One set of samples, designated A-14 and A-11, was collected near the waste incinerator. The third soil sample, designated B-14, was taken near the Plant 1 storage pad area. As reported previously [Lee], the uranium concentration in the soil is approximately 500 to 600 mg/kg, with 70 to 80 wt% of the uranium being in the silt and clay fraction.

In model systems consisting of submicron UO_2/clay mixtures processed through a PEG/Na_2CO_3 biphase system, the UO_2 particles partitioned to the salt-rich phase, whereas the clay partitioned to the PEG-rich phase. The partition coefficients for the UO_2 and clay particles were approximately 0.001 and 34, respectively.

Test-tube-scale studies with Fernald soil samples indicated that ABE showed potential for removing both soluble and refractory forms of uranium [Chaiko-1993B, -1994, -1995B]. We examined a number of PEG/salt systems. The salts considered were sodium and potassium carbonate, sodium hexametaphosphate [$(NaHPO_4)_6$], and sodium sulfate [Chaiko-1993B]. In addition, two different PEG molecular weights (1500 and 3400) were used.

We found that the partitioning behavior of solids depends on the choice of salt used to generate the biphase system. With the PEG/carbonate system, approximately 1-2 wt% of the soil is recovered in the uranium concentrate stream (see Table 1). However, with sulfate or phosphate, the amount of solids partitioning to the salt-rich phase is considerably higher. Consequently, the highest degree of partitioning selectivity is obtained in the PEG/carbonate system. The weight loss reported in Table 1 refers to soil components that either dissolve in the biphase system (e.g., humates) or ultrafine soil particles that were not recovered during solid/liquid separation by centrifugation.

When the Fernald incinerator soil (A14) was treated in a PEG/Na_2CO_3 biphase system during batch, test-tube-scale experiments, selective partitioning of particulate uranium into the carbonate phase reduced the uranium concentration in the clean soil fraction from 471 mg/kg to about 138 mg/kg and produced a uranium concentrate that contained about 900 mg U/kg solids [Chaiko-1993B]. However, the storage pad soil (B-14) did not respond as well, producing no selective partitioning of uranium (see Table 2). Analysis of the liquid phases indicated that significant amounts of soluble U(VI) species were being leached form the soils. Typically, 70-80%

TABLE 1 Effect of Salt Phase Composition on Solids Partitioning from Silt and Clay Fraction of Fernald Incinerator Soil (A-14)

	Weight Distribution, %		
System Composition	PEG-Rich Phase	Salt-Rich Phase	Weight Loss
15% PEG-3400/ 10% Na_2CO_3	65.0	1.1	33.9
15% PEG-3400/ 10% $(NaHPO_4)_6$	14.0	58.0	28.0
15% PEG-3400/ 7.5% Na_2SO_4	5.1	76.0	18.9

TABLE 2 Batch Extraction of Uranium from Fernald Soils in a 15% PEG-3400/10% Na_2CO_3 Biphase System at 25°C[a]

	PEG-Rich Phase		Carbonate-Rich Phase	
Soil	Distribution, wt%	Uranium, mg/kg	Distribution, wt%	Uranium, mg/kg
A-14	65.0	138.0	1.1	904
B-14	62.0	245.8	14.0	233.0

[a] Weight distribution does not add to 100% because of soil loss/dissolution.

of the uranium present in the soils dissolved during the time it took to carry out the biphasic partitioning (i.e., 10-15 min). This dissolution occurred not only in biphase systems containing sodium or potassium carbonate but also in those containing sodium sulfate or sodium hexametaphosphate [Chaiko-1993B].

Fortunately, the partition coefficients for soluble U(VI) species are low enough that they do not interfere with the recovery of clean soil from the PEG-rich phase. The partition coefficients for uranyl ion in various PEG/salt systems are listed in Table 3. The coefficients for uranyl sulfate and uranyl carbonate are considerably lower than those for sulfate and carbonate anions alone. We obtained coefficients of 0.25 and 0.15 for sulfate and carbonate, respectively [Chaiko-1994].

TABLE 3 Partitioning of U(VI) between PEG/Salt Phases at 25°C

Biphase System	Partition Coefficient, U
15% PEG-3400/ 10% Na_2CO_3	0.0044
15% PEG-1500/ 10% Na_2CO_3	0.0026
15% PEG-3400/ 7.5% Na_2SO_4	0.086
15% PEG-3400/ 10% $(NaHPO_4)_6$	0.062

We have since found that the choice of salt, PEG molecular weight, and temperature can dramatically affect phase separation times in the presence of suspended solids. Two different PEG molecular weights (1500 and 3400) and four salts [Na_2CO_3, K_2CO_3, Na_2SO_4, and $(NH_4)_2SO_4$] were investigated. In the absence of suspended clay, all the biphase systems exhibited equally rapid phase-separation times (e.g., 10-15 s) at 40°C. This was not true at 25°C. With 1 wt% suspended clay at 40°C, however, rapid phase separation was obtained only in the PEG-3400/$(NH_4)_2SO_4$, PEG-1500/$(NH_4)_2SO_4$, and PEG-1500/Na_2CO_3 systems. Phase-separation times were approximately 10-15 s. At temperatures of 25-30°C, systems with 1 wt% suspended clay had phase-separation times that were as long as in all the other PEG/salt systems. Thus, there is a critical temperature somewhere between 30 and 40°C, above which rapid phase separation can be achieved even in the presence of suspended particles.

Effective treatment of soil by ABE requires (1) rapid liquid/liquid phase separation in the presence of ultrafine solids, (2) low partition coefficients for soluble uranium(VI) species, and (3) a high degree of solids recovery in the PEG-rich (i.e., clean soil) stream. All of these criteria are best met in the PEG-1500/Na_2CO_3 biphase system at temperatures of 40°C or higher.

2.2 SILICA PARTITIONING

In test-tube-scale experiments with model systems, we measured the partition coefficients for various silicate species, including silicic acid, quartz, and clay. The results of these measurements (see Table 4) contradict the partitioning behavior of the crystalline silicates (e.g., quartz with a system pH of 8.5) that we observed in the test-tube-scale soil extraction experiments (described in Section 2.1) and later in continuous, countercurrent soil extraction studies.

We believe that the partitioning of quartz to the PEG-rich phase during biphasic extraction is due to surface activation of these soil particles by adsorbed humic acids. This explanation is consistent with our observation that, when the soil is preleached with Na_2CO_3 (i.e., conditions that cause the dissolution of humic matter), the crystalline silicates, such as quartz, partition selectively to the salt phase. Under these conditions, approximately 11 wt% of the soil was recovered in the salt phase with a uranium concentration of only 15 mg/kg [Chaiko-1993B]. The amount of quartz recovered in the salt phase roughly corresponds to the amount of quartz in the soil. The identity of the mineral phases recovered in the salt phase was verified by electron microscopy [Chaiko-1993B].

TABLE 4 Partitioning of Silica Species in the PEG-3400/Na_2SO_4 System at 25°C

Species	System pH	Partition Coefficient
SiO_2	8.5	<1.0
	2-3	~100
Kaolinite	2-12	~100
Montmorillonite	2-12	~100
$Si(OH)_4$	3	0.64
	6	0.38

The soil organics (i.e., humic and fulvic acids) are believed to have an aromatic ring structure of di- and tri-hydroxyl phenols that are linked by -O-, -NH-, -N-, and -S- bonds [Bohn]. These acids also contain significant numbers of free -OH groups. These materials, with molecular weights ranging from a few hundred to more than 300,000, have a large number of reactive functional groups. It is therefore not surprising that the humic acids adsorb onto mineral surfaces, and, in doing so, can turn hydrophilic surfaces into hydrophobic ones [Abe]. If quartz particles are rendered hydrophobic by the adsorption of humic acids, one can expect them to partition into the PEG phase. In any case, the partitioning of quartz and clay into the PEG phase is an obvious advantage, since this increases the amount of material recovered in the clean soil stream.

2.3 PROCESS SCALE-UP

During FY 1994 and early FY 1995, we began to scale up the biphasic extraction process using a Karr column operated in a continuous, countercurrent fashion. A 3.89-m-tall Karr column with an internal diameter (ID) of 2.54 cm was purchased from the Otto H. York Company (now available from Glitsch Technology Corp., Parsippany, NJ) and installed in our laboratory. The column body is made of borosilicate glass. The top and bottom of the column consist of expanded 5.08-cm ID glass sections. The column is jacketed, and in our studies it was maintained at 40°C by circulating water from a constant-temperature bath. A schematic diagram of the column is shown in Fig. 1.

The extraction zone is agitated by reciprocating vertical strokes of perforated plates that are mounted on a rod. Our column is equipped with a total of 101 stainless steel plates spaced approximately 2.54 cm apart. The maximum reciprocation rate that can be accommodated with the liquid/liquid systems that we are testing is about 1.33 Hz. The column is set up with a fixed stroke length of 1.9 cm.

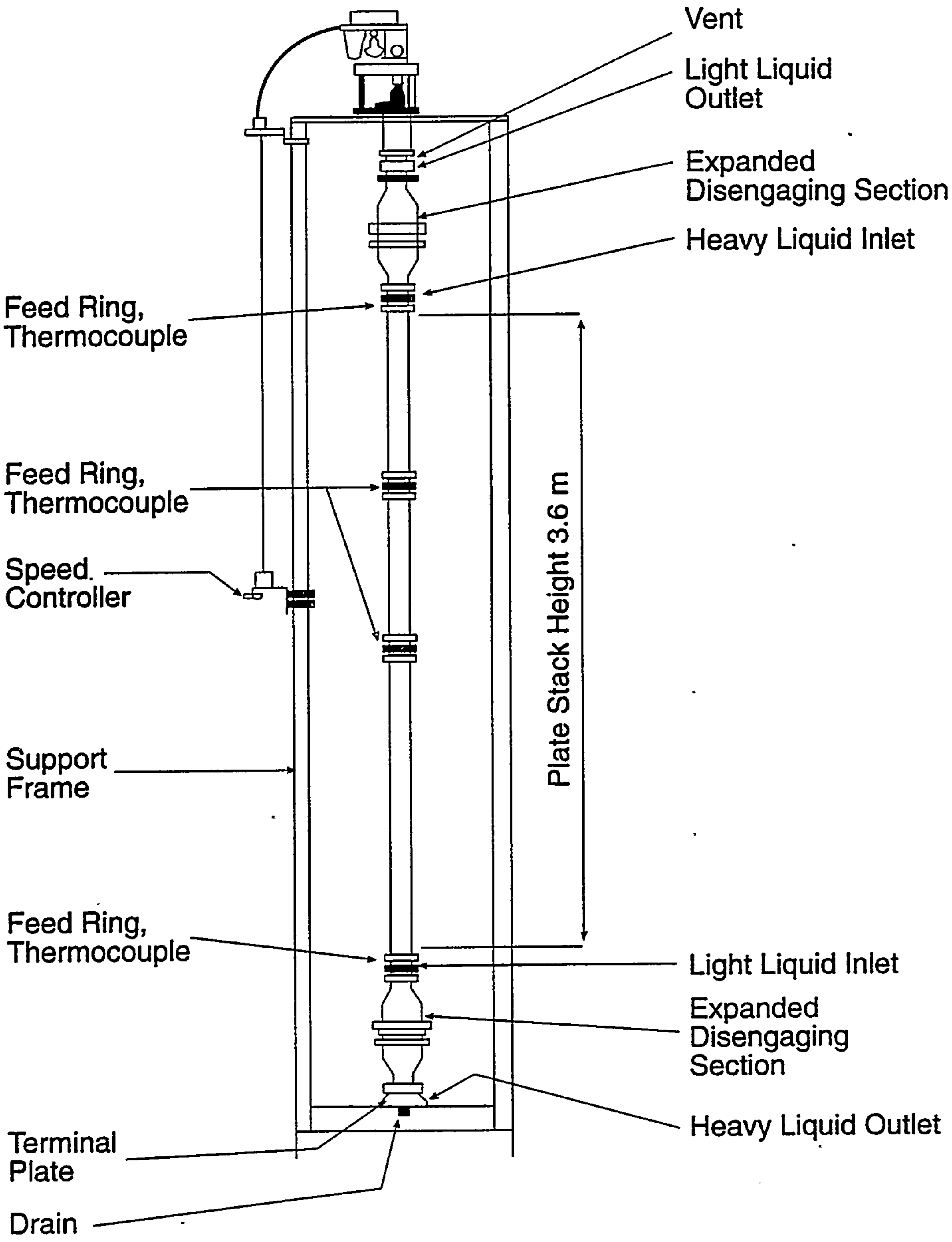

FIGURE 1 Schematic Diagram of Pilot-Scale Karr Column used in Soil Treatment Tests

We operate the column with the less-viscous, salt-rich phase as the continuous phase. Typically, the average diameter of the dispersed-phase droplets is about 1 mm. We have found that, with care, the column can be operated, without flooding, with a liquid/liquid density difference as low as 3-5%. The design of the column, together with its hydrodynamic characteristics, permits rapid transport of fine solid particulates through the column without solids settling within the column. We have estimated the mean residence time of dispersed-phase droplets within the extraction zone to be approximately 2 min.

During extraction, vibration of the dispersed-phase droplets containing suspended soil particles can be seen. In addition, the dispersed-phase droplets continuously undergo a cycle of size reduction and agglomeration. We have found that rapid mass transfer between the two phases can be achieved even with high solids loading (e.g., 30-35 wt%) in the dispersed phase. Efficient mass transfer within the extraction zone of the column is a function of many physical and physicochemical variables. These include the liquid flow rates, degree of agitation in the column, difference in density of the two liquid phases, liquid phase viscosity, interfacial tension, temperature, and the phase-separation time. The effects of most of these variables are interconnected and are discussed in the next section.

2.4 PHASE DIAGRAM AND TIE LINES

Unlike conventional oil/water extraction systems, the two immiscible phases in an aqueous biphasic system share a common diluent—water. Therefore, the potential for process upset due to excessive mass transfer of water should be carefully considered. To prevent the net mass transfer of water between liquid phases, we prepared the PEG-rich and salt-rich phases at compositions defined by the tie lines from the appropriate PEG/salt/water phase diagram.

Figure 2 shows the phase diagram for the PEG-1500/Na_2CO_2 system at 40°C with three tie lines (A, B, and C). The binodal curve (connected triangles in Fig. 2) defines the phase boundary, with the two-phase regime located to the right of the binodal curve and the single-phase regime to the left. The upper and lower intersection points of the tie line with the binodal curve define the compositions of the PEG-rich and salt-rich phases, respectively.

For convenience, we determined the tie lines by using a radiotracer technique with ^{14}C-labeled sodium carbonate and ^{3}H-labeled PEG-4000. The radiotracers enable us to rapidly and easily measure the partition coefficients of carbonate and PEG. The compositions of the two immiscible aqueous phases are then determined from the measurement of the liquid/liquid phase ratio and the appropriate mass balance equations. The procedure is described in detail elsewhere [Chaiko-1992]. Ideally, the tie lines should be determined from chemical analysis of the equilibrated phases. To verify the validity of our approach, we contacted equal volumes of the two phases defined

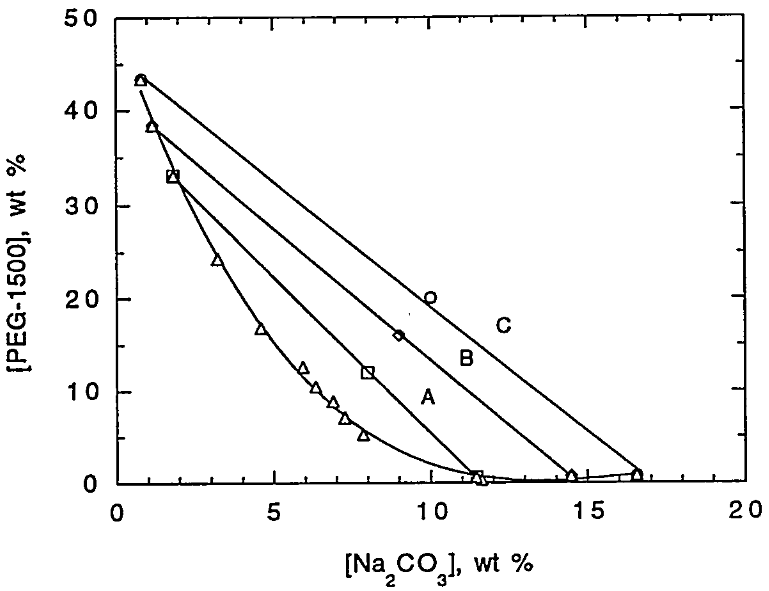

FIGURE 2 Phase Diagram with Tie Lines (A, B, and C) for the PEG-1500/Na_2CO_3/Water System at 40°C

by tie line A in Fig. 2 and measured the change in the liquid/liquid phase ratio. The volume increase or decrease of the two phases, as a percentage of the total volume of the system, was only 2-3%. This small error in the tie line is probably due to slight differences between the partition coefficients of the PEG-1500 tested and the ^{3}H-labeled PEG-4000 used to determine the phase diagram.

A change in temperature will affect the position of the binodal curve and, hence, the performance of the extraction column. An increase in temperature causes the curve to shift slightly to the left, as shown in Fig. 3. Increasing the temperature increases interfacial tension and reduces the viscosity of the liquid phases. Both effects improve phase-separation rates. Therefore, to enhance the rate of mass throughput in the Karr column, we operate it at 40-50°C instead of at room temperature.

Whether tie line A, B, or C is chosen, the viscosity of the salt-rich phase is little changed. However, the viscosity of the PEG-rich phase increases measurably as one moves further away from the critical point (i.e., the point where the length of the tie line is zero). Of course, increasing viscosity would adversely affect mass transport within that phase. Equally important, however, is that increasing viscosity affects the physical entrainment of the salt-rich phase in the PEG-rich stream exiting the column. The liquid-phase viscosity, together with the density difference and interfacial tension, determines the rate at which the PEG droplets arriving at the phase-inversion zone coalesce to form the continuous PEG phase.

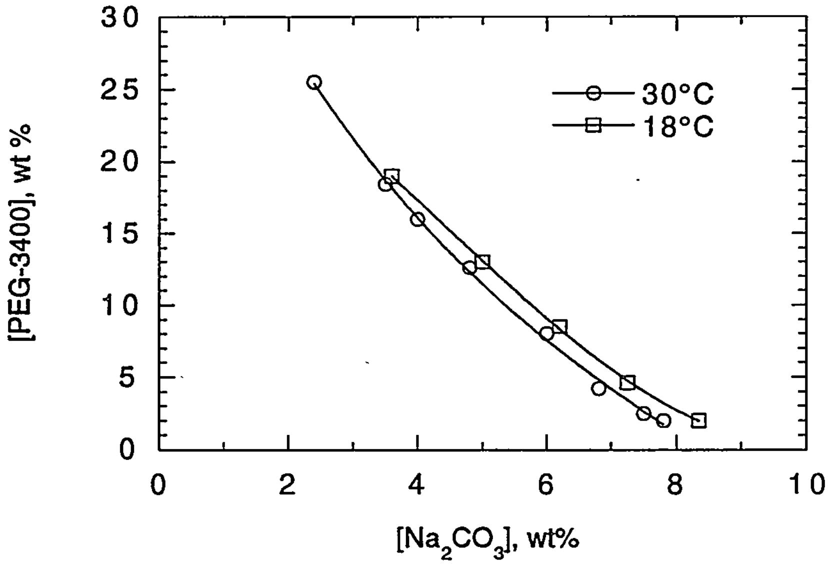

FIGURE 3 Effect of Temperature on Biphase Formation for the PEG-1500/Na_2CO_3 System

The logarithm of the interfacial tension between the PEG and salt phases is proportional to the length of the tie lines [Albertsson]. Therefore, the farther away the system is from the critical point, the greater the interfacial tension. For efficient mass transfer, many droplet dispersion/ coalescence cycles must take place within the column. This is achieved by properly balancing column agitation rate with liquid phase flow rates. The optimum balance point will, in turn, depend on the interfacial tension and the densities of the two phases.

The rate of phase separation, which is dependent on liquid phase viscosities, interfacial tension, liquid phase densities, etc., is an important variable that directly affects column throughput. This parameter [Leonard-1981, -1983] has been characterized by a dimensionless dispersion number (N_{Di}), defined as follows:

$$N_{Di} = \frac{1}{t_{Di}} \sqrt{\frac{\Delta z}{g}} \qquad (1)$$

where t_{Di} is the time for phase separation under gravitational field g, and Δz is the height of the two-phase system. The higher the value of N_{Di}, the higher the process throughput one can expect.

Faster phase separation implies a lower chance for physical entrainment of salt in the PEG outflow. To characterize our extraction system, we determined the dispersion number for the biphase formed by tie line A in Fig 2. Approximately equal volumes (~35 mL) of PEG and salt phases were vortexed together for 1 min and then allowed to separate in a graduated 100-mL cylinder. At 40°C, complete phase separation occurred within 75 s, yielding a dispersion number of 15.5×10^{-4}.

As expected, the dispersion number decreases (i.e., phase-separation time increases) with addition of soil to the biphase system. For example, when 1 wt% (expressed as a percentage of total PEG phase) of Fernald soil was added to the PEG phase, the phase-separation time of the biphase system increased to 120 s, giving an N_{Di} value of 9.7×10^{-4}. With or without solids, however, the dispersion numbers are comparable to those for more common oil/water extraction systems, which usually exhibit N_{Di} values of $1\text{-}15 \times 10^{-4}$.

Because of the need to consider viscosity, interfacial tension, and phase-separation time, selecting a tie line for process operation can be difficult. We have found that tie lines A and B, shown in Fig. 2, permit us to operate the column at reasonable liquid flow rates without flooding. Thus, the determining factor in deciding which of the two tie lines to use is the density difference between the PEG and salt phases. The compositions of PEG and salt phases, along with the corresponding densities of the phases for tie lines A, B, and C, are listed in Table 5.

Clearly, a longer tie line provides a greater difference in the density of the two phases. The manufacturer of the Karr column recommends a liquid/liquid density difference of at least 5%. Therefore, manufacturer guidelines would dictate that tie line A is approximately the shortest tie line permissible for countercurrent extraction with the PEG-1500/Na_2CO_3 system. However, when we apply this liquid/liquid extraction technique for particulate separation, new possibilities arise, as we will describe in the next section.

2.5 CONTINUOUS COUNTERCURRENT TESTS

During the aqueous biphasic extraction process, the clean soil partitions to the PEG-rich phase, while the uranium contaminants partition selectively to the salt-rich phase. Therefore, to

TABLE 5 Composition and Density of Phases on PEG/Na_2CO_3 Tie Lines at 40°C

	PEG-Rich Phase			Salt-Rich Phase		
Tie Line	[PEG-1500], wt%	[Na_2CO_3], wt%	Density, kg/m^3	[PEG-1500], wt%	[Na_2CO_3], wt%	Density, kg/m^3
A	33.11	1.82	1080	0.62	11.45	1120
B	38.46	1.15	1080	0.71	14.48	1150
C	43.33	0.08	1090	0.80	16.56	1180

minimize the amount of mass transfer required for soil decontamination, the soil feed is dispersed in the PEG phase. The effective density (d_e) of the PEG/soil slurry is given by

$$d_e = \frac{100\ d_s\ d_p}{(d_p - d_s)\ W + 100\ d_s} \tag{2}$$

where W is the amount of suspended soil (wt%) in the PEG phase, and d_s and d_p are the densities of soil and PEG phases, respectively.

An average density for the Fernald solid is assumed to be 2500 kg/m^3. Hence, at the critical values of W = 6.3, 10.7, and 13.5 wt% for tie lines A, B, and C, respectively, the density of the PEG-1500 soil slurry is equal to that of the salt phase. This means that, if the column is to be operated with the PEG phase as the less dense phase, the soil loading in the PEG phase must be less than the appropriate critical value of W. This, however, severely restricts the solids throughput of the column.

By loading the soil in the PEG phase beyond the critical value of W, the PEG phase is effectively made heavier than the salt phase. In this approach, the salt-rich phase is introduced to the column from the lower inlet (see Fig. 1), while the PEG-rich phase, containing the contaminated soil, is fed from the upper inlet. As the PEG phase travels down the column, the uranium is extracted into the salt phase, and the density of the PEG phase is gradually reduced. However, because the contaminated soil contains only 100-1000 mg uranium/kg soil [Lee], we expect only a small fraction of the soil mass to transfer into the salt phase.

We carried out experiments to determine the dependence of column operation on the solids concentration in the PEG-rich phase. These tests showed that variation of solids concentration from 1 to 20 wt% had no effect on column performance. When only 1 wt% soil (test condition A) was suspended in the PEG-rich phase, the clean soil was carried upward in the extraction column against the direction of gravity. Therefore, this method of column operation is more suited to treating fine particle sizes (e.g., -200 mesh). However, this limitation is relaxed when the column is operated in the alternative mode described above, with the PEG phase as the more-dense phase. This method works for larger particle sizes because the clean soil moves downward through the column in the direction of gravity. We have since treated Fernald soil with a top particle size of 100 mesh (147 μm) with no apparent problems. The partitioning behavior of the particulate uranium, which is only a few microns in diameter, is unaffected by the larger size of the soil particles.

In FY 1994 we carried out a series of column extraction experiments designed to determine the effect of solids loading on column performance and uranium removal. During those tests, we determined the dissolved uranium content in the salt and PEG phases exiting the column. The results, presented in Table 6, indicate an increase in dissolved uranium concentration with time. In Column Test A, the salt phase was continuously recycled, and, as expected, the uranium concentration in that phase increased progressively. The uranium concentration in the PEG phase, however, remained either below or just at the detection limit of the delayed neutron counting technique used to measure the uranium concentration.

In Column Test A, 60 g of soil was introduced to the column in approximately 5.5 L of PEG phase (1 wt% dispersed solids). Additionally, approximately 7 L of salt phase was used. In Column Test B, 288 g of soil was introduced with only 1.065 L of the PEG phase (20 wt% dispersed solids). The total salt-phase volume, including column holdup, was approximately 7.5 L. Because of the greater amount of soil, the total amount of uranium dissolved and the uranium concentration in the salt phase were higher in Column Test B than in A. However, there is no indication that the salt phases became saturated with dissolved uranium in either experiment. With 20 wt% suspended solids in the PEG feed, the salt-phase recycle was begun at 52 min into the run. The continual buildup of dissolved uranium in the salt phase during the course of the run indicates that the column never reached steady state.

An attractive feature of this extraction system is that the mass of solids recovered in the salt phase is only 1-2 wt% of the initial feed (see mass balance data in Table 7). Complete recovery of

TABLE 6 Dissolution of Uranium during Column Extraction

[U], Column Test A (1 wt% dispersed solids)			[U], Column Test B (20 wt% dispersed solids)		
Time, min	Salt Phase	PEG Phase	Time, min	Salt Phase	PEG Phase
0	0	0	0	0	–[a]
25	1.0	<0.1	15	5.1	
50	1.3	<0.1	30	9.1	
70	1.4	<0.1	52[b]	13.0	
105	1.8	<0.1	85	17.3	
135	2.1	<0.1			
205	2.6	<0.1			
230	3.1	0.1			

[a] The composite PEG phase contained 3.7 mg uranium/kg.

[b] Salt-phase recycle back into the column began at this point.

TABLE 7 Mass Balance on Solids from Column Extraction

	Experiment A		Experiment B	
	Mass, g	[U], mg/kg	Mass, g	[U], mg/kg
Soil feed	60	471	288	471
Uranium concentrate	1	105.9	5	218
Clean soil	49	80.7	175.5	77.7
Column residual[a]	0	---	77.5	88
Soil loss	10	---	30	---

[a] Refers to soil remaining in column after shutdown.

the solids in either the uranium concentrate or clean soil streams was not possible because a portion of the soil (e.g., humic acids) dissolved in the salt and PEG phases, and a portion was recovered separately during column shutdown. Incomplete recovery of ultrafine particles from the aqueous phases would also contribute to the lack of solids mass balance. However, in both column tests, the clean soil recovered with the PEG phase was lower in uranium concentration than the solids recovered from the salt phase, indicating a selective partitioning of uranium species. The uranium concentration in the uranium concentrate was lower than that in the soil feed because of dissolution of uranium into the liquid phases. In effect, the soil is decontaminated during column extraction by two processes: (a) dissolution of soluble uranyl species into the salt and PEG phases, with subsequent selective partitioning to the salt phase and (b) partitioning of refractory uranium particulates into the salt phase. By using this combination of decontamination mechanisms, we can achieve lower residual uranium concentrations in the clean soil than by using carbonate leaching alone. For example, when we leached this soil with 20 wt% Na_2CO_3 at 40°C for 2 h at a liquid/soil weight ratio of 8.8, we were able to reduce the uranium concentration in the soil to only 146 mg/kg.

The experimental results in Table 7 clearly indicate that high solids loading in the PEG phase has little effect on the degree of uranium extraction from the soil. In addition, the high solids loading in Column Test B provided an order-of-magnitude increase in the soil throughput in the column. Our more recent column tests (discussed in Section 2.7) indicate that it is possible to increase the soil loading in the PEG phase to 30-35 wt% and to increase the feed flow rate to at least 24 mL/min. This gives a solids processing capability of approximately 660 g/h with the 2.54-cm ID column. A full-scale column of 1.5 m ID would be capable of handling 2400 kg dry soil/h.

Maximizing extraction efficiency requires minimization of physical entrainment of one phase in the other phase exiting the column (referred to as "other-phase carryover"). This limits the effective partition coefficient, and if the other-phase carryover is excessive, additional unit operations would be required to separate the liquid phases before they could be recycled back to their respective process streams. As shown in Table 8, the entrainment of the PEG-rich phase in the salt-rich phase was below detection limits in both experiments. On the other hand, the amount of salt-rich phase entrained in the PEG phase exiting the column varied from 1 to 7.5 vol%, with an average of 3.9 vol% for the case where the PEG feed contained 1 wt% solids. For the case where the PEG feed contained 20 wt% solids, the salt-phase entrainment in the PEG-phase underflow ranged from 0 to 5.9 vol%, with an average of 3.2 vol%. Interestingly, increased solids concentration does not seem to affect salt-phase entrainment significantly.

2.6 SOLID/LIQUID SEPARATION

Because of the high clay content of the Fernald soil, unit operations devoted to solid/liquid separation are expected to contribute significantly to capital equipment costs. To minimize the size of filtration equipment, we explored the use of flocculants for enhancing the rate of solid/liquid separation. Because most of the soil is recovered from the PEG-rich phase, our initial studies were focused on this process stream. In particular, we wanted to know whether the high PEG concentration in that effluent stream would interfere with flocculant adsorption onto the soil particles. We tested a number of polymeric flocculants that were recommended by Nalco and Cytec (Cytec produces the Magnifloc reagents). A partial list is given in Table 9.

The test procedure involved adding the flocculant to a PEG-1500 phase containing 15 wt% soil. After gently mixing the slurry in a 100 mL graduated cylinder and equilibrating in a 40°C water bath, the settling rate of the soil was measured. In the absence of any flocculant, the settling rate of the soil was only 0.026 m/h (see Table 9). The settling rate was improved little by the Cytec

TABLE 8 Solvent Entrainment during Column Operation

Column Test	Salt Entrainment in PEG Phase, vol%	PEG Entrainment in Salt Phase, vol%
A	3.9 ± 3.1[a]	0
B	3.2 ± 1.9[b]	0

[a] Reported variation represents the standard deviation of five measurements.

[b] Reported variation represents the standard deviation of nine measurements.

TABLE 9 Settling Rate from the PEG-Rich Phase with 50 mg Flocculant/kg Slurry (solids concentration 15 wt%)

Flocculant	Polymer Type	Settling Rate, m/h
None		0.026
Magnifloc 1596C	Cationic polyacrylamide	0.069
Magnifloc 496C	Cationic polyacrylamide	0.091
Magnifloc 1555C	Cationic polyacrylamide	0.249
Nalco 7871	Nonionic, latex	0.207
Nalco 9857	Cationic, latex	0.124
Nalco 7877	Anionic, latex	2.04

flocculants; however, with the Nalco 7877 flocculant, we observed the highest settling rate, which was 2.04 m/h.

We expect the solids content in the filtered cake to be 60-70 wt%. Therefore, the PEG phase entrained in the pores of the filter cake represents 30-40% of the filtrate mass and must be recovered to maintain economic viability. In a full-scale system, a water wash would be used to recover dissolved uranium and PEG from the void volume in the filter cake. The PEG phase can then be recycled after adjustment to the tie-line composition.

In addition to physical entrainment of the PEG phase within the pore volume of the filter cake, another possible mechanism of PEG loss is physical and chemical adsorption of PEG onto soil particles. Initial results of adsorption measurements with ^{3}H-labeled PEG-4000, however, suggested that polymer loss through this mechanism was likely to be less than 20 lb PEG/T soil. With 20 and 30 wt% solids dispersed in the PEG phase (composition given by tie line A in Fig. 2), we found a maximum of 8.4-14 mg PEG adsorbed per gram of soil at 40°C (see Table 10). Also shown in Table 10 are adsorption data for kaolinite. We believe that humate coatings on the soil particles are responsible for the increased PEG adsorption in the Fernald soil.

The data in Table 10 were obtained by measuring the residual activity remaining in solution after equilibration with the soil and kaolinite samples. The adsorption density of PEG was then calculated from a mass balance analysis. In a separate set of experiments, the adsorption densities of PEG were measured by counting the ^{3}H activity in a suspension of the solids directly using ^{3}H-labeled PEG-4000 and PEG-900, with the PEG-900 more closely matching the molecular weight of the unlabeled PEG-1500 used in the biphasic extraction flowsheet. The details of the experimental procedure are provided in Appendix A (Section A.4). Results of the adsorption measurements using PEG-900 radiotracer spiked into a PEG-1500/Na_2CO_3 phase (defined by tie line A in Fig. 2) are shown in Table 11. The solid/liquid equilibration time was 20 min.

Comparison of the adsorption data in Tables 10 and 11 indicates that the density of PEG adsorbed onto soil particles increases with increasing PEG molecular weight. Again, the PEG adsorption densities for the soil were consistently higher than those for the kaolinite. Using the maximum PEG adsorption density of 3.7 mg PEG/g soil, we estimate polymer losses due to irreversible adsorption onto soil particles to be about 7 lb PEG/T soil. This is a worst-case estimate, and actual losses are likely to be about 4 lb PEG/T soil (estimated from the average adsorption density of five independent measurements).

TABLE 10 Adsorption of PEG-4000 onto Soil and Kaolinite at 40°C

Dispersed Solids	Adsorption Density, mg PEG/g solid
Fernald soil[a]	8.4 - 14.2
Kaolinite[b]	1.84 - 2.03

[a] Equilibration time was 20 min.

[b] Equilibration time was 1 h.

TABLE 11 Adsorption of PEG-900 onto Soil and Kaolinite at 40°C

Dispersed Solids	Adsorption Density, mg PEG/g Soil
Fernald soil[a]	1.0 - 3.7
Kaolinite[a]	0.34 - 0.62

[a] Equilibration time was 20 min.

2.7 COLUMN OPERATION FOR IMPROVED EXTRACTION

In column tests performed in FY 1994, we treated a maximum of 400-600 g of soil per test. Because the column feed rates were approximately 660 g dry soil/h, the runs were not long enough to get the system to steady state. We would have liked to carry out long-term (e.g., 6-8 h) column tests to evaluate (a) the effect of uranium buildup on soil decontamination, (b) the effect of humate buildup in the PEG/salt phases on column performance (e.g., phase separation rates) and (if any) on the biphase tie line, and (c) the effects of flocculant use in PEG-phase effluent on column performance/uranium extraction with PEG-phase recycle.

Preliminary column evaluation tests that we carried out at Otto York facilities in Houston showed that extraction performance improved steadily until the column reached steady state (note: the column attains about 90% steady state behavior after three column volumes). In those tests we evaluated the extraction of micron-sized crystobalite from a Mexican clay ore using the PEG-3400/Na_2CO_3 system. The ore contained 12 wt% crystobalite (a crystalline silicate). Samples from the clay product stream showed that the crystobalite concentration steadily decreased until reaching a minimum concentration of 0.03 wt% as the Karr column approached about 95% of steady state. We can expect a similar downward trend in clean soil uranium concentration as the Karr column reaches steady state.

In FY 1995 three column runs were performed in which the following conditions were varied: (a) the soil concentration in the PEG feed, (b) liquid phase flow rates, and (c) column agitation rate. The purpose of this set of experiments was to determine the effect of column length and flow rate on uranium extraction. Each run in this series used Fernald soil A-11 (top size of 150 μm). The experimental details and the results for uranium extraction are discussed below. In addition, data on thorium extraction was obtained in two of the extraction experiments. The experimental setup and procedures for each run are given in Section A.5 of Appendix A.

2.7.1 Uranium Extraction

In the first column run (Column Test C), the soil feed was prepared by adding 2 kg of soil (dry basis) to a PEG/salt solution containing 1545.0 g of PEG-1500, 85.1 g of Na_2CO_3, and 1558.3 g of water. When heated to 40°C, this mixture produced a slurry of 30 wt% (dry basis) soil in a PEG-rich phase whose composition is defined by tie line A in Fig. 2. A schematic flowsheet of the apparatus is shown in Fig. 4.

The purpose of this experiment was to determine the effect of column length on uranium extraction efficiency. To do this, it was necessary to feed fresh salt phase into the column during the entire experiment. If the salt phase had been recycled, the column would not have reached steady state due to a continued buildup of uranium in the salt phase.

In the second experiment of this series (Column Test D), the soil was fed to the column in a 33 wt% slurry (dry basis) and both the flow rates and the agitation rate were increased (see Table 12). In addition, the salt-phase overflow from the column was treated by centrifugation and filtration at 0.14 μm pore size before being recycled into the column. The flowsheet for this test is shown in Fig. 5.

In the third experiment (Column Test E), the feed rate of the PEG/soil slurry to the column was increased slightly (see Table 12), and the treated soil was returned to the column in a batch recycle. The purpose of this test was to see whether the pretreated soil could be fed into the column without significantly disturbing column performance, and to see whether adding an extraction section would further reduce uranium in the cleaned soil. The flow diagram for this test is shown in Fig. 5. A total of 1850 g of soil was processed through the column before treated soil was transferred to the PEG feed tank and recycled into the Karr column.

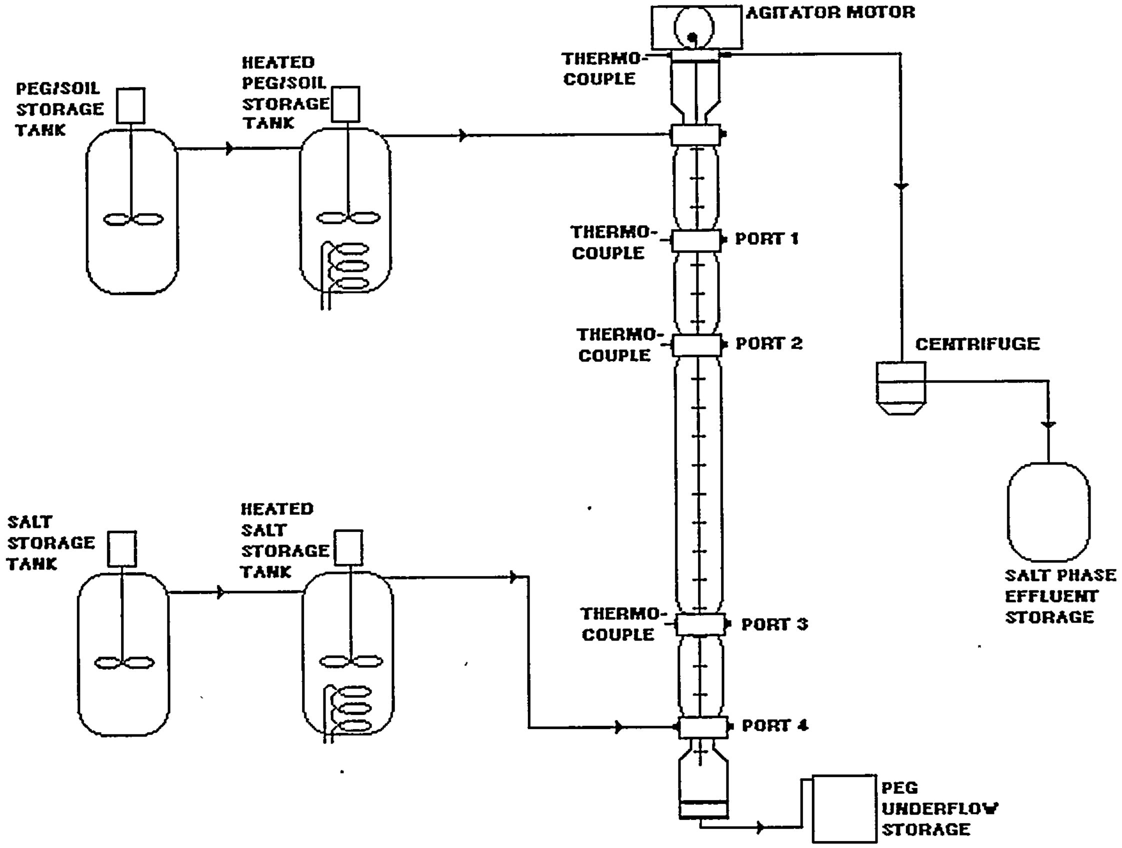

FIGURE 4 Diagram of Equipment Layout for Column Test C

TABLE 12 Summary of Experimental Conditions for High-Throughput Column Tests

Column Test	Soil Concentration, wt%	Flow Rate, g/min PEG Phase	Flow Rate, g/min Salt Phase	Agitation Rate, Hz
C	30.0	24.7	35.1	0.63-1.03
D	33.0	30.0	40.0	1.23
E	33.0	30.8	40.0	1.20

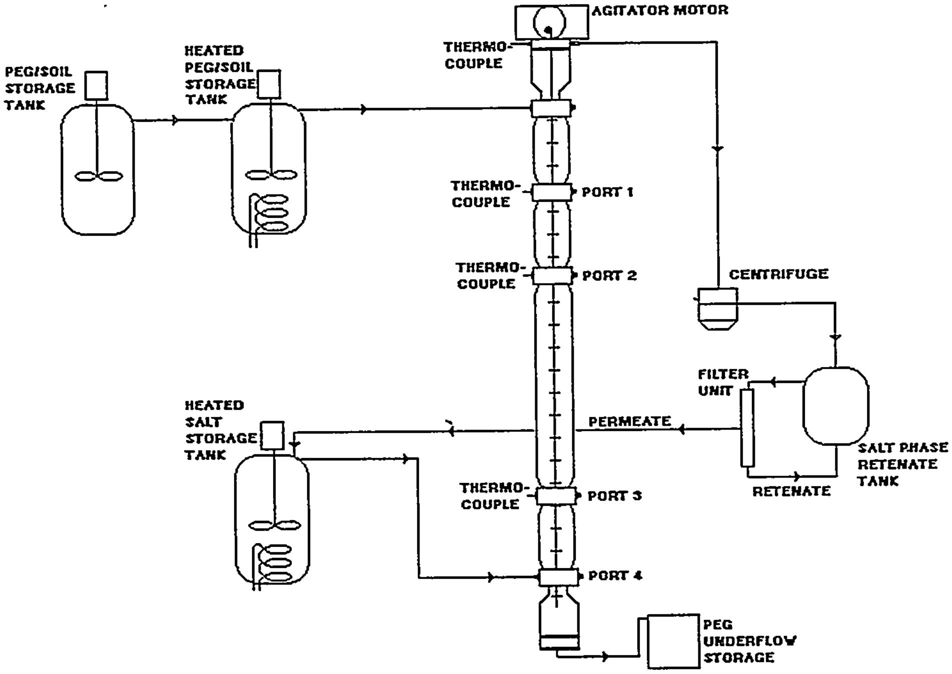

FIGURE 5 Diagram of Equipment Layout for Column Tests D and E

Analysis of the cleaned soil obtained from the column underflow in Column Test C produced an average uranium concentration of 78.6 mg/kg. The uranium concentration in the untreated soil (sample taken from the screened slurry on the same day as the column test) was 545 mg/kg. The total amount of solids extracted from the PEG phase into the salt phase during the column run was 16 g. This represents 1.2% of the 1319 g of soil actually fed into the column. This is the solid fraction that should contain most of the particulate uranium. Analysis of this fraction produced an average uranium concentration of 148 mg/kg.

The results for the samples taken as a function of position in the column are presented in Appendix A. They show that the uranium concentration in the solids varies little as a function of position, suggesting that the rate of uranium dissolution is rapid and that the maximum uranium extraction that can be achieved is obtained within the first 0.6 m (distance from feed port to first sample port) of the column.

During Column Test D, approximately 2 g of soil was recovered from the salt-rich phase overflowing the column. This represents about 0.25% of the soil fed into the column. This dramatic decrease in soil recovery from the column overflow (i.e., salt-rich phase) could be due to the effects of soil loading in the PEG phase. The increase in soil loading raises the effective density of the PEG phase (e.g., see Eq. 2) which should, in turn, improve phase separation and reduce other-phase carryover. However, other-phase carryover in Column Tests C and D was below the detection limit of about 0.1-0.2%. Note that the flow rates of both phases were greater in Column Test D than in

Column Test C, which would lead one to expect the soil carryover in the column overflow to increase. Apparently, the effects of an increased density difference between phases more than compensates for the higher flow rates.

In Column Tests D and E, the salt phase was continually recycled. During Test D, the uranium concentration in the salt phase reached 101 mg/kg by the end of the run. The filtration unit had no detectable effect on uranium concentration of the salt phase. In both of these runs, the residual uranium concentration in the cleaned soil was higher than that obtained when the salt phase was not recycled. The results from the uranium analysis are given in Table 13.

When we attempted to recycle the cleaned soil in Column Test E, the soil began to flocculate while still in the feed tank. This led to phase inversion in the column, with the salt-rich phase becoming the more dense phase. When this occurred, the column run had to be terminated. Prolonged contact of the soil with the biphase system led to significant leaching of humates from the soil, which was accompanied by irreversible flocculation. Resuspension of the soil in a freshly prepared PEG phase did not alter its behavior. On the other hand, we found that it was possible to disperse fresh soil in the recycled PEG phase, suggesting that the problem was not with the PEG phase.

The conclusions drawn from this series of column runs regarding uranium recovery are as follows:

- PEG-phase suspensions of 30-33 wt% solids are easily pumped, and satisfactory column performance with low other-phase carryover can be achieved.

- The uranium concentration in the Fernald soil can be reduced from 545 mg/kg to about 78 mg/kg when the salt phase recycle is uranium-free.

- Full-scale column capacity (1.5 m ID) would be approximately 3100 kg dry soil/h.

- Filtration of the salt phase before recycle back to the Karr column had essentially no effect on the uranium removal from the salt phase.

2.7.2 Thorium Extraction

During Column Tests C, D, and E, we were able to measure between 1000-2000 DPM of β activity in the uranium concentrates by routine survey with hand monitors in the laboratory. Since the untreated soil produced no detectable radiation under similar survey conditions, it was apparent that a weak β emitter had been concentrated during the column extractions. Subsequent analysis of the samples indicated that the species being concentrated was ^{234}Th. Since the half-life of ^{234}Th [Reus] is very short (e.g., 24.1 d) compared to that of the parent, ^{238}U (e.g., 4.47 × 10^9 y), the Th/U pair rapidly reach secular equilibrium. We calculated the ^{234}Th concentration present in the untreated soil using the total uranium concentration and the isotopic abundance of ^{238}U in the soil. With an average uranium concentration of 545 mg/kg in the untreated soil and a ^{238}U abundance of 99.2876 [Chaiko-1993B], we obtain an initial ^{234}Th concentration of 181.8 pCi/g. The ^{234}Th concentrations in the soil recovered from the salt-rich phase, on the day of the column tests, ranged from approximately 1000 pCi/g to 3000 pCi/g. Thus, the ^{234}Th was concentrated approximately 6- to 16-fold (see Table 14).

TABLE 13 Summary of Residual Uranium Concentrations in Treated Soils

Column Test	[Uranium], mg/kg Cleaned Soil	 Uranium Concentrate	 Salt Phase
C	78.5	148.3	
D	112.6	171.8	101
E	96.4		

The difference in partitioning behavior between U and Th is due in part to the fact that the Th species (e.g., ThO_2) are chemically inert in the biphase system, while the UO_2^{2+} species are easily leached from the soil. Thus, this series of column extraction experiments illustrates the performance of which the ABE system is capable, provided the extracted species are particulate and inert.

TABLE 14 Concentration of ^{234}Th in Solids Recovered from the Salt Phase during Column Extraction Tests[a]

Column Tests	[^{234}Th], pCi/g	Th Concentration Factor	Soil Distribution in Salt Phase, Wt%
C	1260	6.9	1.2
D	3004	16.5	0.25
E	1034	5.7	0.37

[a] The initial ^{234}Th concentration in this untreated soil was 181.8 pCi/g.

2.8 SECONDARY WASTE TREATMENT

In one sense, the presence of organic matter in the soil is beneficial in that humic acid coatings cause silica to partition to the PEG phase. However, the humic acids are also a source of concern in that their buildup in process streams could lead to possible process upset. For this reason, we have examined methods of removing dissolved soil organics from process effluents. It is well known [Bohn] that humic acids are readily precipitated from solution at $pH < 3$. However, if we adopt this approach, it would result in the addition of a large amount of mass to the process streams and would alter the composition of the biphase system. It should be noted that below a pH of about 9-10, a biphase is not formed in the PEG/carbonate system. In addition, fulvic acids remain soluble even at low pH.

The conventional method for removing humic acids from drinking water involves coagulation/flocculation by alum, followed by sedimentation. As an alternative, for increased efficiency of humic acid removal, Zhang et al. flocculated the colloidal humic matter with polyaluminum chloride and a polyelectrolyte and then used membrane ultrafiltration to separate the humic matter [Zhang]. They could extract as much as 92% of the humic matter measured by the total organic content, at a permeation flux of 250 $Lh^{-1}m^{-2}$ with a 10^6 molecular weight cut-off membrane. However, their treatment is at a pH of 7, and humic acid content in drinking water supplies is much lower than that in our column effluents. Furthermore, ultrafiltration requires regeneration of the membrane, which would require washing it with, for example, NaOH and a large amount of water.

Our preliminary studies indicate that it is possible to precipitate most of the humic matter from the salt phase by adding Ca^{2+}. This approach is consistent with the results of Orlova et al. [Orlova], who demonstrated that the optically dense humic fraction precipitates with $CaSO_4$ addition. But more importantly, we have found that the optically dense humic-acid fraction, together with the soluble uranium species, can be selectively precipitated from the salt phase with the addition of small amounts (e.g., 20 vol%) of methanol. With higher methanol concentrations, the percent recovery of soluble organics and uranium is dramatically increased. The precipitates are easily filtered and the low boiling point of methanol (65°C) makes the recovery and recycle of the alcohol relatively easy to accomplish.

The data in Table 15 provide a preliminary uranium and carbon mass balance analysis during methanol precipitation. The salt feed was obtained from the salt-phase overflow during a column run in which the soil was fed into the Karr column at 30 wt% suspended solids. The salt phase composition is defined by tie line A in Table 5. The initial uranium concentration in the salt phase was 28.9 mg/kg, which could be reduced to 16.3 mg U/kg solution by microfiltration at a membrane pore size of 0.1 μm. The weight of the organic precipitate was determined after first washing the solids (the major components of which are humates and sodium carbonate) with deionized water and drying at 70°C overnight. The results indicate that (1) approximately 43.6% of

TABLE 15 Precipitation of Humates and Uranium from Salt-Phase Effluent by Methanol at 40°C

[Methanol], vol%	Weight of Solids Generated per 100 mL Feed, before Water Wash, g	Weight of Solids Remaining after Water Wash, g	[U] in Solids after Water Wash, mg/kg	Residual [U] in Methanol-Free Salt Solution, mg/kg
0	–	–	–	28.9
20	0.115	0.040	101	17.5
50	0.136	0.041	85	18.3
100	4.587	0.078	100	11.2
150	9.950	0.142	132	3.25
200	10.912	0.115	126	0.90

the uranium in the salt phase is colloidal and can be removed from the salt-phase column effluent by filtration at 0.1 µm, (2) maximum recovery of humic acids is achieved at a salt-to-methanol volume ratio of 1:1.5, and (3) the concentration of uranium that is precipitated in the humic acid fraction and that remains insoluble during the water wash ranges from 100 to 130 mg/kg of precipitate. Note that the optimum membrane pore size for uranium recovery from the salt phase has not yet been determined. At a salt-to-methanol volume ratio of 1:2.0, we can remove approximately 94.5% of the uranium and 84.2% of the sodium carbonate from the effluent stream, leaving <1 mg U/kg in solution with a residual salt concentration of about 1.9 wt%. This stream could be recycled for washing the +100 mesh soil or discharged to a waste-water-treatment facility.

The precipitation measurements were repeated using the salt feed that was generated from the column extraction experiments described in Section 2.7.1. Because of the higher soil loading and the recycle of the salt phase, the uranium concentration in the salt phase was considerably higher (i.e., 105 mg U/kg salt solution vs. 28.9 mg U/kg salt solution for the case in Table 15). The results are shown in Table 16. It is apparent that the residual uranium concentrations in Table 16 are much higher than those reported in Table 15. Apparently, the equilibration time of 1 min used in the precipitation experiments is not sufficient to reach equilibrium. (Note that the solubility limit of uranium should be the same, regardless of initial uranium concentrations.) Consequently, with longer equilibration time, it should be possible to significantly increase the uranium recovery in the precipitate.

TABLE 16 Precipitation of Uranium from Salt-Phase Effluent by Methanol at 40°C

[Methanol], vol%	Weight of Solids Generated per 100 mL Feed before Water Wash, g	[U] in Solids after Water Wash, mg/kg	Residual [U] in Methanol-Free Salt Solution, mg/kg
0	–	–	105.0
20	0.065	625	107.9
50	0.061	675	112.6.
100	4.455	830	83.0
150	10.08	1040	27.0
200	10.76	1100	9.6

3 ESTIMATED COST OF IMPLEMENTING AQUEOUS BIPHASIC EXTRACTION TECHNOLOGY

A preliminary system flowsheet for uranium removal from soils using the ABE technology is provided in Appendix B. The flowsheet was designed for a dry soil capacity of 20 tons per hour (TPH). Note that scale-up to a larger plant capacity should significantly reduce soil treatment costs. The key features of the process involve storage of the excavated soil on a covered pad to provide a minimum of 2-3 days' feed supply of soil for the processing plant. According to this preliminary flowsheet, the soil is transferred by front-end loader to a feed conveyor and sent to a scalping screen and a series of rotary drum scrubbers where the soil is washed with fresh and recycle salt solution (approximately 1.9 wt% Na_2CO_3) plus fresh water. The cleaned, +2 mm soil is stockpiled for return to the site. It is expected that this cleaned soil fraction will be below 50 mg U/kg soil and that the leachable uranium will be less than 5 mg/kg.

The -2 mm soil is sent to an agitated holding tank, which provides the feed to the Karr columns after making a size split at 100 mesh. The +100 mesh stream is combined with the clean-soil underflow from the Karr column. This combined stream is dewatered by using a thickener and a pressure filter. The filter cake is washed with dilute salt (e.g., 0.91 wt% Na_2CO_3) for recovery of dissolved uranium and residual PEG solution. The first filtrate rinse undergoes a proprietary dewatering step providing a 2:1 concentration factor, which returns the PEG/Na_2CO_3 solution to the appropriate tie line composition. The cleaned soil undergoes a final, fresh-water wash and is then sent for disposal. If necessary, the soil would be treated with a dilute phosphoric acid solution (500 mg/kg) to reduce the concentration of leachable uranium to under 5 mg/kg [Francis]. This acid wash would also reduce the soil pH to near neutral.

The current flowsheet assumes a 20 wt% solids feed to the Karr columns. Our laboratory data indicate that the columns can handle at least 35 wt% solids. Including a dewatering step prior to PEG addition (not currently represented in the flowsheet) would allow a higher solids throughput and reduce the number of Karr columns (based on a 20 TPH throughput) from five to four.

The uranium concentrate in the overflow from the Karr columns is dewatered by using a thickener and a filter press. The solids are then sent for disposal, while the salt phase decant (stream 19) from the thickener is sent for additional processing by methanol precipitation to remove soluble and colloidal uranium and humates. Approximately 88-90% of the time, a methanol-to-salt phase volume ratio of 0.5:1 is used, which results in a 1 wt% loss of carbonate exiting the flowsheet through stream 37. The remaining 10-12% of the time, this salt stream (stream 19) is treated at a methanol-to-salt phase volume ratio of 2:1. This produces a 1.9 wt% salt stream that is free of humates and is expected to contain a residual uranium concentration of less than 1 mg/kg. The amount of salt lost to the uranium concentrate (stream 37) during the high-concentration methanol precipitation approximately equals the amount of fresh salt addition through streams 51, 52, and 55 and thus prevents a buildup of salt in the system.

Our preliminary calculations show that at least 99.5% of the methanol can be recovered from the salt/methanol mixture by distillation. With heat recovery from the Karr columns, the feed temperature would be about 40-50°C. On the basis of vapor/liquid data for methanol/water mixtures from the literature [Hirata], we estimate that a column 6 ft diameter by 28 ft high with 14 trays and a minimum reflux ratio of 1.5 would be required. Given the solubility of sodium carbonate as a function of temperature, precipitation of salt in the reboiler is not expected to be a problem. Note that this is not an optimal column design, and additional work would be required to more accurately estimate distillation column design and performance.

The in-process losses of PEG and sodium carbonate account for approximately 82% of the cost of reagent consumption. This comes to about 6 lb PEG/T soil and 44 lb carbonate/T soil. The PEG losses occur primarily (about 4 lb/T) through irreversible adsorption of PEG onto the soil surface. The losses of carbonate occur primarily through the methanol precipitation step used for soluble uranium recovery from the Karr column overflow. More efficient uranium precipitation at lower methanol concentrations, through the use of either inorganic or organic complexants, would significantly reduce carbonate losses.

Estimates of the daily operating costs for the ABE process are given in Table 17. Assuming a treatment rate of 480 tons per day (TPD), the cost per ton of soil treated is about \$68. Of this, \$23/T is required to cover raw materials and energy costs, while \$45/T covers labor, maintenance, fixed charges and contingency costs (calculated at rate of 25% of direct costs). The fixed capital investment costs are given in Table 18, while the equipment list is provided in Appendix C as Table C-1. The resulting life cycle cost (see Table 19) is estimated to be \$160/T soil processed.

Some of the assumptions used to estimate daily operating costs are:

- Maintenance costs for equipment replacement and repair were estimated at 5.4% of equipment costs (*Chemical Engineers' Handbook* [Perry, pp. 25-30] recommends 4% per year of fixed equipment).

  $$0.054 \times \$4{,}448{,}300 = \$240{,}100/\text{y or } \$686/\text{d}.$$

- Estimated salt make-up based on the use of fresh salt for streams 51, 52, 55; losses from U concentrate filter cake; losses from methanol precipitation; and 3 vol% bleed from stream 19. It is assumed that salt removal by methanol precipitation will balance the amount of fresh salt added in streams 51, 52,

TABLE 17 Daily Operating Costs for the ABE Process[a]

Class	Description	Unit	Unit Cost, $	Quantity/ Day	Subtotal, $	Total, $
Chemical/raw material	Sodium carbonate	ton	381.00	10.63	4,050	
	Makeup methanol	gal	0.75	1,080	810	
	Makeup PEG	lbs	1.00	2,841	2,841	
	Flocculant	lbs	1.80	247	445	
	Bleed solution	gal	0.01	12,960	130	
	Phosphoric acid	lbs	0.34	45	15	
	Makeup water	1000 gal	0.89	180	160	
					Total	**8,451**
Labor, soil loading pad	Soil storage	man-hrs	33.39	24	801	
	Driver	man-hrs	33.39	24	801	
	Radiation monitoring	man-hrs	40.07	24	962	
	Cover personnel	man-hrs	33.39	8	267	
					Total	**2,831**
Aqueous biphasic extraction system	Technicians (7)	man-hrs	33.39	168	5,609	
	Rad. mon. operator	man-hrs	40.07	24	962	
	Cover personnel	man-hrs	33.39	8	267	
	Supervisor	man-hrs	44.41	24	1,066	
					Total	**7,904**
Maintenance	Electrician	man-hrs	33.39	24	801	
	Equipment & subcontracts				686	
	Building				171	
					Total	**1,658**
Electricity	ABE system	lbs	0.004	480,000	1,920	
	Methanol stripping	kwh	0.08	10,838	867	
	Electrical power					
					Total	**2,787**
Operating supplies	Total	day	412.06	1	412	**412**
Fixed charges	Taxes	day	1,418.14	1	1,418	
	Insurance	day	709.07	1	709	
					Total	**2,127**
Contingency	Total	day	6,542.00	1	6,542	**6,542**
Total daily operating cost						**32,712**

[a] Based on treatment rate of 480 tons per day, the cost per ton is $68.

TABLE 18 Fixed Capital Investment for Full-Scale ABE Process (20 TPH)

Item	Symbol	Description	Formula	Value, $
1	E	Equipment costs	E	4,448,300
2	LAB	Cost of installation labor	.40E	1,779,320
3	IC	Instrumentation and controls	.13E	578,279
4	I	Insulation costs (for equipment and piping)	.05E	222,415
5	P	Piping	.16E	711,728
6	Q	Labor for installation of piping	.40P	284,691
7	F	Electrical installation	.15E	667,245
8	B	Buildings including services (labor, material, etc.)	---	1,500,000
9	Y	Yard improvements	.10E	444,830
10	S	Service	.55E	2,446,570
	D	**Direct Plant Cost**	**Sum of 1-10**	**13,083,378**
11	ES	Engineering and supervision	.60E	2,668,980
12	C	Construction expenses	.25E	1,112,000
	I	**Indirect Plant Cost**	**ES+C**	**3,780,980**
13	CF	Contractor's fee	.05(D+I)	843,218
14	CO	Contingency (unpredictable events)	.20(D+I)	3,372,871
	FCI	**Fixed Capital Investment**	**D+I+CF+CO**	**21,080,447**

and 55. This will require approximately 10-12% of stream 19 being treated with 2:1 methanol precipitation:

Fresh salt addition through stream 51 and 52 at 1.9 wt%,

$$12.558 \text{ TPH} \times 0.019 \times 24 \text{ h/d} = 5.73 \text{ TPD}$$

Fresh salt addition through stream 55 at 0.91 wt%,

$$8.401 \text{ TPH} \times 0.0091 \times 24 \text{ h/d} = 1.83 \text{ TPD}$$

Salt loss through entrainment in uranium concentrate filter cake,

$$0.1371 \text{ TPH} \times 0.1145 \times 24 \text{ h/d} = 0.376 \text{ TPD}$$

3% bleed from stream 19,

$$32.5874 \text{ TPH} \times 0.03 \times 0.1145 \times 24 \text{ h/d} = 2.69 \text{ TPD}$$

TABLE 19 Life-Cycle Cost for the ABE Process

FCI	$21,080,447
Start-up cost	$ 2,108,044
Yearly operating cost	$11,449,200

Year	Cost, $
0	23,188,491
1	11,449,200
2	12,021,655
3	12,622,733
4	13,253,864
5	13,916,552
6	14,612,374
7	15,342,986
8	16,110,129
9	16,915,629
10	17,761,404
11	18,649,466
12	19,581,932
13	20,561,021
14	21,589,063
15	22,668,507
16	23,801,924
17	24,992,010

Total cost	$319,038,940
Cost/ton of soil processed	$160

Total salt loss per day,

$$5.73 + 1.83 + 0.38 + 2.69 = 10.63 \text{ TPH.}$$

- Estimated methanol losses occur primarily through incomplete methanol recovery from the distillation step (assume 99.5% methanol recovery by distillation of stream 39 and 88% recovery of methanol from uranium concentrate [stream 37]).

  – 88% of stream 39 is treated at 0.5:1 methanol:salt ratio,
  299.52 GPM × 0.88 × 0.33 × 0.005 = 0.44 GPM

- 12% of stream 39 is treated at 2:1 methanol:salt ratio,
  299.52 GPM × 0.12 × 0.66 × 0.005 = 0.12 GPM

- Total loss from distillation step is 0.56 gallons per minute (GPM) or 806.4 gallons per day (GPD)

- Estimated total methanol losses are 1080 GPD.

Some of the assumptions used to arrive at life-cycle costs include the following.

- A soil density of 74 lb/ft^3 is assumed, or 1 yd^3/T soil. Consequently, there are 2,000,000 tons of soil to be processed.

- A 70% utilization factor for plant operations at the full-scale treatment facility is assumed. The remainder of the time is devoted to maintenance and repairs. The plant is assumed to operate 24 h/d (3 shifts) for 350 d/y. The estimated amount of soil to be treated annually is:

  20 T/h × 24 h/d × 350 d/y × 0.70(utilization factor) = 117,600 T/y.

- In year 0, the costs incurred will be the fixed capital investment and startup expenses. Years 1 through 17 will consist of operating costs for a full-scale facility and include an inflation rate of 5% per year.

A detailed equipment list and a mass balance estimate are provided in Appendix C and Appendix D, respectively.

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APPENDIX A:

EXPERIMENTAL PROCEDURES

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EXPERIMENTAL PROCEDURES

A.1 REAGENTS

Polyethylene glycol, with an average molecular weight of 1500, was purchased from Aldrich Chemical. Sodium carbonate and sodium pyrophosphate were purchased from Fisher Scientific. All chemicals were reagent grade. Radiolabeled PEG-900 and PEG-4000 were purchased from DuPont NEN.

A.2 SOIL PREPARATION

The uranium-contaminated soil used for testing was obtained from FEMP. The soil was collected near the waste incinerator at the Fernald site and is designated as Fernald A-11 soil. The soil obtained by FEMP was in raw form, containing rocks, pebbles, and even glass. The raw soil was mixed with water and sodium pyrophosphate (used as dispersant) in roughly the following batch sizes:

1.0 kg of Fernald A-11 soil
2.0 L of deionized water
0.6 g of sodium pyrophosphate (200 ppm).

Each batch was tumbled in a ball mill for 15 min and then wet-sieved using a 100 mesh screen. As a rough guess, approximately 95 vol% of the raw soil passed through the 100 mesh screen. Water was decanted from the screened fraction after the soil had settled (several days), and the resulting slurry was stored at approximately a 40 wt% moisture content. Analysis of this soil indicated an average uranium concentration of 544 ppm.

A.3 SAMPLE ANALYSIS

Uranium concentrations in solid and dried liquid-phase samples were determined by delayed neutron counting with a detection limit of 0.1 mg/kg. The analyses were performed by Activation Laboratories, Ltd., Ancaster, Ontario. All uranium concentrations for the soil samples are reported on a dry-weight basis. Salt-phase uranium concentrations are reported on a wet-weight basis. All soil samples were washed twice with deionized water before being sent for analysis.

Both alpha and gamma spectra analyses were performed on the salt-phase solids obtained from column runs C, D, and E. In addition, an alpha spectrum for the untreated soil (-100 mesh fraction) was measured to compare total alpha activity before and after ABE treatment. These analyses were performed by the Analytical Chemistry Laboratory, Argonne National Laboratory.

Measurement of the alpha spectra involved repetitive leaching of the soil samples with a mixture of nitric and hydrochloric acids. The actinides and lanthanides were separated as a group from the other matrix constituents on an extraction chromatographic column consisting of TRU™ resin (Eichrom, Darien, IL). The samples were then electrodeposited prior to alpha spectrometry. The results from the alpha spectra are shown in Tables A-1 and A-2. Since tracers were not added to the sample, standard alpha sources were counted in the detector to define the proper energy calibration.

The ^{234}Th concentrations in the salt-phase effluent samples were determined by gamma spectrometry. The gamma data were corrected for decay to obtain the ^{234}Th concentrations present on the day that the respective column extractions were performed. The ^{234}Th concentration in the untreated sample was estimated from the ^{238}U concentration by using the assumption that the two radionuclides were in secular equilibrium. The isotopic distribution of uranium was reported previously (Chaiko-1993B). The results from the ^{234}Th analyses are reported in Table 14.

A.4 POLYETHYLENE GLYCOL ADSORPTION

The PEG adsorption densities on Fernald soil and kaolinite were determined by two techniques. In both approaches, soil samples were equilibrated with an aqueous phase containing 33.11 wt% PEG-1500 and 1.82 wt% Na_2CO_3 at 40°C (i.e., PEG-rich phase used in the column extractions). In our first attempt, the adsorption densities were measured by equilibrating (20-60 min) soil samples (1-10 mg) with the aqueous PEG phase (1 mL) containing a known activity of ^{3}H-labeled PEG-4000. The solids were centrifuged to the bottom of the test tube, and aliquots of the supernatant were removed and counted. The weight of PEG adsorbed into the soil particles was then determined from the residual activity in the supernatant and a mass balance calculation. The results from these measurements are reported in Table 10.

Occasionally, we obtained residual liquid phase activities that were higher than what we started with due to adsorption of water by the solids. Another problem was the difference in PEG molecular weight for the radiotracer and the unlabeled PEG (later measurements showed that the PEG adsorption was dependent on its molecular weight).

The experimental protocol was then modified to include direct measurement of the activity adsorbed into the solids and use of a ^{3}H-labeled PEG-900 tracer (unfortunately, labeled PEG-1500 is not available commercially). Soil samples of known weight (5-25 mg) were equilibrated with

TABLE A-1 Results from Alpha Spectra Analysis for Solids from Salt-Phase Effluent and Untreated Soil

Sample	Peak Energy, MeV	Isotope[a]	% Activity[b]
Column Test C	4.01	Th-232	2
	4.18	U-238	42
	4.40	U-235/236	3
	4.76	Th-230	53
	5.42	Th-228	1
Column Test D	4.10	U-238 Th-232	31
	4.63	Th-230 U-235/236	68
	5.43	Th-228	2
Column Test E	4.18	U-238 Th-232	39
	4.36	U-236/236	2
	4.69	Th-230	58
	5.31	Po-210	<1
	5.43	Th-228	1
Untreated soil	4.14	U-238 Th-232	46
	4.33	U-235/236	2
	4.71	Th-230	51
	5.36	Po-210	1

[a] Because no elemental separations were performed, alpha emitters of equivalent energies may be present in the spectra, and, therefore, more than one alpha emitter may be listed for each peak.

[b] This value is based upon the ratio of the counts under the individual peak to the total counts of all the peaks. This value also assumes equivalent electrodeposition efficiencies for all analytes, which is only true to a gross approximation for different elements.

TABLE A-2 Estimated Total Alpha Activity in Solids from Salt-Phase Effluent and Untreated Soil

Sample	Activity, DPM/g
Column Test C	362 ± 54
Column Test D	675 ± 101
Column Test E	628 ± 94
Untreated soil	833 ± 125

2 mL of the PEG solution at 40°C. After centrifuging, the PEG solution was decanted, 6 mL of deionized water was added, and the sample was vortexed to redisperse the solids. This procedure was repeated for 3-4 cycles to remove all activity originating from unadsorbed PEG. After the final wash, a small amount of acetone was added to disperse the soil. Soil samples were then transferred to weighted scintillation vials by pipetting a 20 mL portion of the soil. A drop of acetone was added to the transferred sample, and the sample was taken to dryness under a stream of nitrogen. The scintillation vial was capped and reweighed to determine the weight of soil transferred. Then, a few drops of a 0.1 wt% NaOH solution were added to disperse the soil.

Finally, 10 mL of Ultima Gold scintillation cocktail (Packard, Westmont, IL) was added, the vials were capped and placed in a sonicated water bath for 30 min to ensure complete dispersion of the solids in the cocktail. The samples were then counted in a Tri Carb-2400 scintillation counter (Packard Instruments). Multiple samples with differing amounts of soil were counted for each experiment to ensure that there were no problems with quenching. The results of these measurements are presented in Table 11.

A.5 COLUMN TEST PROCEDURES

Three column extraction runs were performed in FY 1995. For these tests, the Karr column was modified by changing the plate spacing from fixed 2.54-cm spacing to a dual-zone spacing sequence. The plate spacing was kept at 2.54 cm for the first 0.6 m below the top feed inlet. The remainder of the plate stack was spaced at 5.18 cm. The stroke length was fixed at 1.9 cm, and the stroke frequency was varied as described below. The glass sections of the column were covered with pipe insulation that could be removed easily for inspection of the column during an experimental run. The disengaging sections at both ends of the column are not jacketed, so they were wrapped with heating tape (Thermolyne, Dubuque, IA) to maintain a 40°C operating temperature in these regions. In addition, Septa seals were placed inside modified fittings at four places along the column to allow samples to be withdrawn during operation. A 16-gauge needle was used to withdraw samples. Thermocouples were also placed at five locations along the column. A diagram of the Karr column showing the locations of sample ports and thermocouples is given in Fig. A-1.

A total of 2 kg of Fernald soil (A-11, top size of 150 μm) was used in each of the column runs in this series of experiments. The soil was wet-sieved with a 100-mesh screen and stored as a paste with a 42.5 wt% moisture content.

In the first experiment (Column Test C) the effect of column length on extraction efficiency was examined by taking soil samples from different positions in the column as a function of time. After the column had filled with salt phase, a salt phase flow rate of 35.1 g/min was established. The agitator stroke rate was set at 1.03 Hz. At 12:15 p.m. on the day of testing, the PEG/soil feed was introduced at the top of the column at a flow rate of 24.7 g/min. To accurately determine the effect of column length on extraction efficiencies, it was necessary to feed fresh salt phase into the column. If recycled salt phase had been used, the column would not have reached steady state due to the increase in uranium concentration in the salt phase. After an interface had formed at about 10 cm

<u>DISTANCE FROM PEG FEED</u>

PORT #1:	0.61 m
PORT #2:	1.22 m
PORT #3:	3.05 m
PORT #4:	3.66 m
BOTTOM:	3.90 m

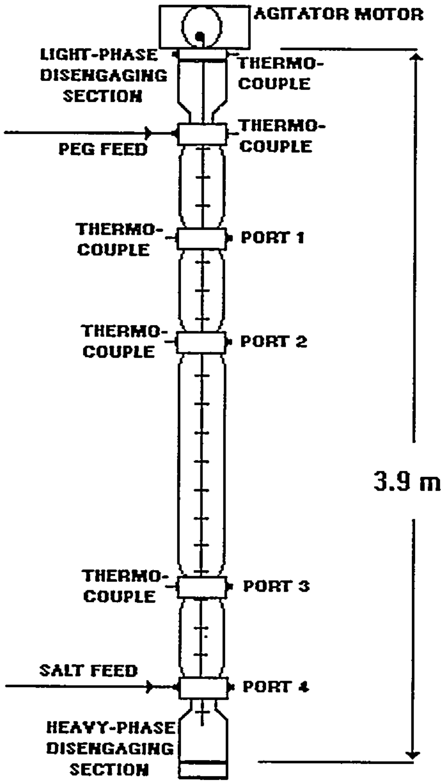

FIGURE A-1 Schematic Diagram of Karr Column Showing Placement of Sample Ports and Thermocouples

high in the bottom disengaging section, the underflow PEG/soil pump was turned on and set to maintain a steady interface position. At 1:45 p.m. the agitator stroke rate was decreased to 0.63 Hz to determine the effect on PEG/soil phase droplets — the droplet size did appear to increase, especially near the top of the column. The PEG/soil feed was shut down at 3:13 p.m. Column operation lasted 178 min, with 1319 g of soil being processed during the run.

For Column Test D, 2000 g of -100 mesh soil (dry basis), which was previously prepared and stored as an aqueous slurry with 33.9 wt% moisture, was added to an aqueous solution containing 1344.5 g PEG-1500, 74.0 g sodium carbonate, and 1616.8 g of water. This mixture resulted in a 33 wt% soil loading in the PEG phase having a composition given by tie line A in Fig. 2. The column was filled with salt phase, and a salt phase flow rate of 40.0 g/min was established. The agitator stroke rate was set at 1.23 Hz before the PEG/soil feed (from top) was introduced at a flow rate of 30.0 g/min. The PEG/soil feed was turned on at 2:05 p.m. The salt-phase overflow from the column was centrifuge-filtered (IEC Chemical Centrifuge) before being sent through the 0.14 μm filter (Carbosep M14 membrane, Rhone-Poulenc, Cranbury, NJ). The permeate from the membrane was sent back to the column as recycle, while the retained material ("retentate") was sent back to the column overflow holding tank.

The PEG/soil feed was shut down at 3:25 p.m. due to a leak in one of the fittings to the membrane filtration unit. The column was operational for 80 min, and 792 g of soil was processed.

During Column Test E, the PEG/soil feed was prepared in exactly the same manner as for Test D, with 2000 g of soil (dry basis) fed at 33 wt% loading in the PEG phase. The salt phase flow rate was set at 40.0 g/min after the column had filled. The agitator stroke rate was set at 1.2 Hz. The PEG/soil feed flow rate, turned on at 9:55 a.m., was increased slightly over that of Test D, to 30.8 g/min. The salt-phase filter membrane was used as in Test D.

At 12:57 p.m., the PEG-phase underflow from the column (up to that point) was recycled as the PEG/soil feed. The purpose of recycling the PEG-phase underflow was to see if further uranium extraction was possible. A total of 1850 g of original soil was processed in the time before the recycle. The recycled PEG/soil feed was used until 1:45, when the salt phase depleted. A total of 488 g of recycled soil was processed from 12:57 to 1:45 p.m.

Results from sample analyses for uranium concentrations from Column Tests C, D, and E are given in Tables A-3, A-4, and A-5, respectively.

TABLE A-3 Results of Uranium Analysis from Samples Taken during Column Test C

No.	Sample Description[a]	[U], mg/kg
1	Soil sample from port #4 at 1:26	89.0
2	Soil sample from port #4 at 1:28	98.5
3	Soil sample from port #3 at 1:29	95.0
4	Soil sample from port #3 at 1:31	89.0
5	Soil sample from port #2 at 1:33	89.2
6	Soil sample from port #2 at 1:35	91.0
7	Soil sample from port #1 at 1:36	86.5
8	Soil sample from port #1 at 1:37	89.4
9	Soil sample from port #4 at 2:13	91.0
10	Soil sample from port #3 at 2:14	93.7
11	Soil sample from port #2 at 2:16	91.5
12	Soil sample from port #1 at 2:17	93.5
13	Soil sample from port #4 at 3:05	95.9
14	Soil sample from port #3 at 3:06	109
15	Soil sample from port #2 at 3:08	90.7
16	Soil sample from port #1 at 3:10	91.9
17	Bottom taken at end of run	84.0
18	Bottom taken at end of run	73.2
19	Salt phase solids (solids from centrifuge)	153
20	Salt phase solids (solids from centrifuge)	151
21	Salt phase solids (solids from centrifuge)	141

[a] The start time was 12:15 p.m.

A.6 SOIL FLOCCULATION TESTS

The effect of various flocculants on the settling rate of Fernald A-11 soil suspended in a 33.11 wt% PEG-1500 plus 1.82 wt% Na_2CO_3 aqueous solution was examined to determine the feasibility and efficiency of using thickeners for treating effluents from the ABE process.

The soil was prepared by first weighing out a 1-kg sample. After the rocks and pebbles were removed from the raw soil, 2 L of deionized water along with 25 mL of 0.03 wt% aqueous sodium pyrophosphate (dispersant) was added to the soil. The mixture was then placed in a ball mill, tumbled for 15-20 min, and then wet-sieved through a 200 mesh Tyler screen. The soil that passed through was air dried, crushed, and then dry-sieved through the 200 mesh screen again.

TABLE A-4 Results of Uranium Analysis from Samples Taken during Column Test D

No.	Sample Description[a]	[U], mg/kg
1	Salt phase membrane retentate taken at 2:22	10.7
2	Salt phase after centrifuging at 2:22	25.7
3	Soil sample from bottom at 2:26	122
4	Salt phase membrane permeate taken at 2:35	24.8
5	Soil sample from bottom at 2:50	110
6	Soil sample from port #1 at 2:50	116
7	Soil sample from port #2 at 2:53	100
8	Soil sample from port #3 at 2:58	92.2
9	Soil sample from port #4 at 3:00	106
10	Salt phase membrane permeate taken at 3:00	51.8
11	Salt phase after centrifuging at 3:01	78.9
12	Salt phase membrane retentate taken at 3:02	55.8
13	Salt phase membrane retentate taken at 3:12	77.9
14	Soil sample from bottom at 3:16	107
15	Salt phase membrane permeate taken at 3:22	88.2
16	Soil sample from bottom at 3:23	120
17	Soil sample from bottom at 3:46	111
18	Salt phase solids (solids from centrifuge)	164
19	Salt phase solids (solids from centrifuge)	173
20	Salt phase solids (solids from centrifuge)	166
21	Salt phase solids (solids from centrifuge)	184
22	Salt phase liquid after run	101

[a] The start time was 2:05 p.m.

TABLE A-5 Results of Uranium Analysis from Samples Taken during Column Test E

No.	Sample Description[a]	[U], mg/kg
1	Salt phase membrane permeate at 10:41	32.9
2	Salt phase membrane permeate at 11:10	70.0
3	Soil sample from bottom at 11:17	110
4	Soil sample from port #1 at 11:19	98.1
5	Soil sample from port #3 at 11:21	95.7
6	Soil sample from port #4 at 11:23	91.6
7	Soil sample from bottom at 11:42	115
8	Soil sample from bottom at 11:54	109
9	Soil sample from bottom at 12:21	110
10	Soil sample from port #1 at 12:26	92.7
11	Soil sample from port #2 at 12:28	95.4
12	Soil sample from port #3 at 12:30	102
13	Salt phase after centrifuging at 12:40	45.7
14	Soil sample from bottom at 12:44	109
15	Soil sample from bottom from 1st cycle container	96.4
16	Salt phase after centrifuging at 12:45	157
	*****2nd cycle feed (recycle soil) started at 12:57*****	
17	Soil sample of feed for 2nd cycle	105
18	Salt phase after centrifuging at 12:58	163
19	Soil sample from bottom at 1:09	105
20	Soil sample from port #3 at 1:10	99.2
21	Soil sample from port #1 at 1:11	111
22	Soil sample from port #2 at 1:14	100
23	Soil sample from port #4 at 1:19	104
24	Soil sample from bottom at 1:20	94.5
25	Soil sample from bottom at 1:50	104

[a] The start time was 9:55 a.m.

All flocculants were diluted to a 0.1 wt% solution in deionized water. After 0.25 g of flocculant was added to a weigh boat, 250 g of deionized water was used to wash the flocculant off the weigh boat into a glass container. A stir bar was placed in this 0.1 wt% flocculant solution, and a slow vortex was created by the stir plate. Each flocculant required a different length of time to dissolve, but generally the liquid polymers dissolved in about 10-30 min, while the solid polymers required a few hours. Approximately 100 mL of this homogeneous solution was saved — the preparation of the excess was to reduce weighing errors with the small mass of flocculants added.

The desired PEG/salt/water concentration, taken from the tie-line composition used in column extraction tests, is as follows:

A)	33.108 wt%	PEG-1500
	1.823 wt%	Na_2CO_3
	65.069 wt%	Deionized H_2O

So, if 88 g of the above composition solution was used, it contained:

B)	29.137 g	PEG-1500
	1.602 g	Na_2CO_3
	57.262 g	Deionized H_2O

To achieve a flocculant concentration of 50 ppm for the entire PEG/salt/H_2O/soil system, it was necessary to add 5.449 g of the 0.1 wt% flocculant solution. Since this 5.449 g of solution is essentially all water, this amount of water was deducted from the water contained in 88 g of the solution described on tie line A. Therefore, from the 57.262 of water on tie line B, we deducted 5.449 g, giving 51.813 g of H_2O. Now the new composition of the PEG/salt/H_2O becomes:

C)	35.295 wt%	PEG-1500
	1.940 wt%	Na_2CO_3
	62.764 wt%	Deionized H_2O

Note that this solution is no longer a tie-line composition, so when using this solution for testing it was mixed very well prior to transfer.

Along with a stir bar, 82.55 g of PEG/salt/water solution of composition given by tie line C was placed in a glass beaker. To this, 15.53 g of 200 mesh Fernald A-11 soil was added and mixed thoroughly. When the solution appeared homogeneous, 5.449 g of 0.1 wt% flocculant solution was added. This mixture was stirred slightly and then transferred to a glass 100 mL graduated cylinder. The cylinder was inverted 8-10 times and placed in a 40.0°C temperature bath. The initial volume of this (15% soil, 50 ppm flocculant) solution was approximately 89 mL. Settling rate measurements were started when the settling solids reached the 85 mL marking. This extra time was used to allow the contents to reach 40.0°C. Elapsed time was recorded at each 0.075 in. (0.190 cm) increment (i.e., each 1 mL marking on the cylinder).

The settling data obtained from these tests were converted to a dimensionless form by dividing the settled distance by the initial height (h_0). A linear curve fit was used to calculate an average settling rate. The data are listed in Table A-6.

The curve fit to the graph for Nalco product 7877 did not include the last two points measured (at t = 103 s and t = 158 s). These two points were excluded because, in this range, the compression zone was reached. Each point on the graph for Nalco 7877 was measured at an interval of 0.375 in. (0.952 cm). This was because the soil settled too rapidly to accurately measure at 0.075 in. (0.190 cm) intervals. This flocculant produced large, fairly stable masses. The 50 ppm polymer dose translates into 0.66 lb (0.30 kg) flocculant per ton of soil.

TABLE A-6 Soil Settling Rate from PEG-Rich Phases at 40°C

Flocculant	Comment	Settling Rate ft/h	 m/h
None		0.082	0.026
Magnifloc 491C	Cationic, polyacrylamide	0.513	0.156
Magnifloc 494C	Cationic, polyacrylamide	0.250	0.076
Magnifloc 496C	Cationic, polyacrylamide	0.299	0.091
Magnifloc 1555C	Cationic, polyacrylamide in water-in-oil emulsion	0.819	0.249
Magnifloc 1591C	Cationic, polyacrylamide in water-in-oil emulsion	0.220	0.067
Magnifloc 1592C	Cationic, polyacrylamide in water-in-oil emulsion	0.249	0.076
Magnifloc 1594C	Cationic, polyacrylamide in water-in-oil emulsion	0.239	0.073
Magnifloc 1596C	Cationic, polyacrylamide in water-in-oil emulsion	0.227	0.069
Magnifloc 1596CSP	Cationic, polyacrylamide in water-in-oil emulsion	0.243	0.074
Magnifloc 1598C	Cationic, polyacrylamide in water-in-oil emulsion	0.209	0.064
Magniflox SD2061	Cationic, polyacrylamide in water-in-oil emulsion	0.203	0.062
Magnifloc SD2080	Cationic, polyacrylamide in water-in-oil emulsion	0.486	0.148
Excel Ultra 5000	Cationic, liquid polyacrylamide	0.219	0.067
Magnifloc 2535CH	Cationic, modified polyacrylamide in water	0.522	0.159
Magnifloc 1885A	Cationic, polyacrylamide in water-in-oil in emulsion	0.341	0.104
7871	Nonionic, latex	0.678	0.207
7877	Anionic, sulfonated latex	6.69	2.04
7878	Anionic, latex	0.244	0.074
9825	Anionic, latex	0.735	0.224
9857	Cationic, latex	0.408	0.124

APPENDIX B:

FULL-SCALE FLOWSHEETS FOR AQUEOUS BIPHASIC EXTRACTION

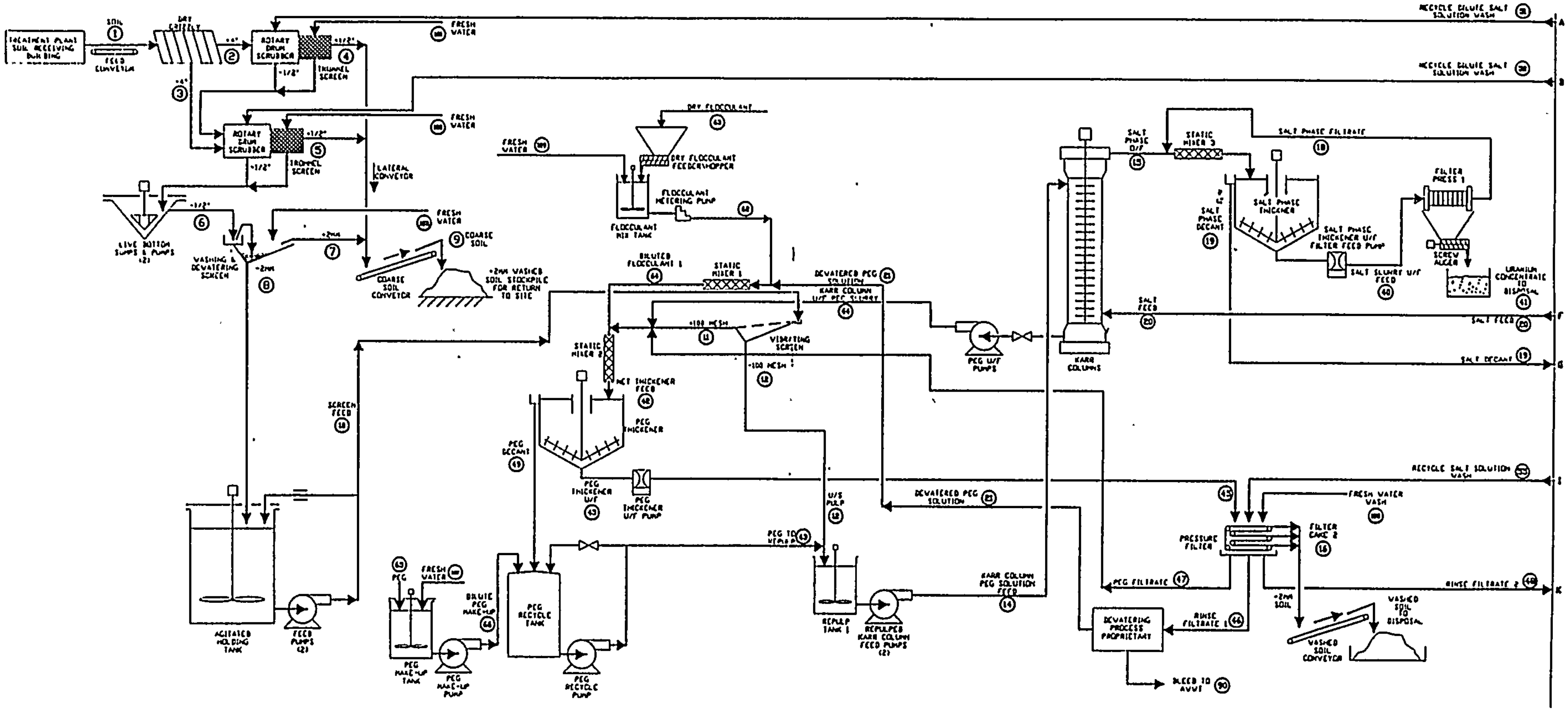

FIGURE B-1 Aqueous Biphasic Extraction for Liquid-Solid Separation and Uranium Concentration of Fernald Soils

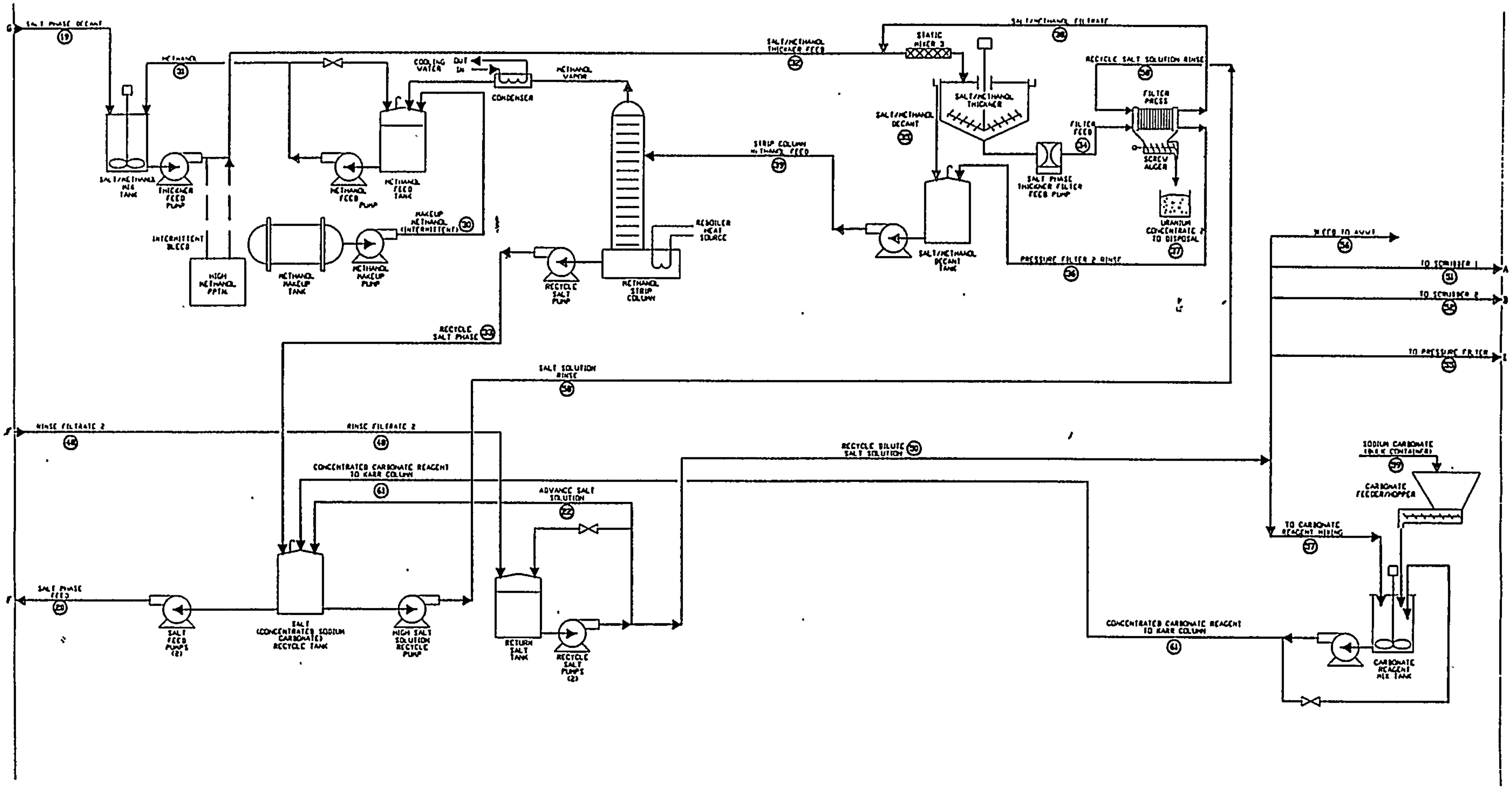

FIGURE B-2 Aqueous Biphasic Extraction with Solubilized Uranium Removal Reagant Recycle for Treatment of Fernald Soils

APPENDIX C:

EQUIPMENT LIST FOR FULL-SCALE AQUEOUS BIPHASIC EXTRACTION TREATING 20 TONS PER HOUR

TABLE C-1 Equipment List for Full-Scale ABE Process Treating 20 TPH

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Grizzly Feed Conveyor	1	Feeds soil from excavation stockpile to elevated grizzly. Flexible belt, segmented pocket type. Rises 16' in 60' length angled section (15° slope).	24"W x 100'L with 4" high sidewalls and pocket separators. In "Z" configuration with 20' horiz. sections at both ends of rise section.	KAMFLEX Carol Stream, IL C/O John Tomacca 800-323-2440 CAMBELT INT. Salt Lake City, UT 801-972-5511	$60,000
Dry Grizzly	1	Separates oversize rocks, twigs, roots and other trash materials from feed soil. Oversize (+4") flows directly to Drum Scrubber 1 via rails discharge chute. Undersize feeds Drum Scrubber 2 via 6' x 8' x 4' truncated frustrum cone and 2' x 2' enclosed chute.	6' x 8' sloped entry with rails mounted at 4" spacing.	PORTEC Kolberg Yankton, SD	$40,000
Drum Scrubber 1	1	Heavy-duty drum scrubber with ½" punched plate trommel screen discharge. Has drum flush water dewatering section and separate trommel screen wash spray collection section. Both U/F's report to Drum Scrubber 2 by gravity flow. O/S is discharged by chute to coarse soil transport conveyor to stockpile on pad.	4'D x 6'L with 6' trommel section.	McLANAHAN Holidaysburg, PA	$90,000
Drum Scrubber 2	1	Heavy-duty drum scrubber with ½" punched plate trommel screen discharge. Has drum flush water dewatering section and separate trommel screen wash spray collection section. Both U/F's report to live-bottom sump & pump by gravity flow. O/S washed soil is discharged by chute to coarse soil transport conveyor stockpile on pad.	6'D x 8'L with 6' trommel section.	McLANAHAN Holidaysburg, PA	$150,000

[a] Acronyms are defined in the list at the beginning of this report.

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
O/S Soil Transport Conveyor	1	Transport O/S (+½") washed soil from drum scrubber trommels and 2mm screen to washed soil stockpile. Flexible belt, segmented pocket type. Rises 16' in.	24"W x 100'L with 4" high sidewalls and pocket separators.	KAMFLEX Carol Stream, IL C/O John Tomacca 800-323-2440 CAMBELT INT. Salt Lake City, UT 801-972-5511	$60,000
Washing & Dewatering Screen	1	Elevated screen with slotted vee-shaped, upward sloping discharge urethane deck and O/F slurry feed distributor. Receives -1/2" slurry from live-bottomed sump & pump and rinses and dewaters +2.0mm O/S with fresh water sprays. O/S also is discharged by chute to flexbelt pocket conveyor to stockpile. U/S (-2.0mm) flows by gravity to agitated holding tank, which feeds downstream fine soil circuit.	6' x 8' screen deck with linear, high-frequency motion.	DERRICK MANUF. Buffalo, NY 716-683-9010 BRANDT SCREENS Conroe, TX	$40,000
Slurry Pump & Sump	2	Combination sump & slurry pump (live-bottomed sump configuration) which receives soil slurry underflow from drum scrubbers (-½") and pumps it to elevated 2mm dewatering screen. SALA type pump/sump combination with clearances to handle -3/4" slurry. One pump operating, one pump installed standby.	Sized for 150 gpm, 50' TDH, S.G. slurry 1.500. Pump impeller 18" dia. conical. Sumps have 1.0 yd^3 capacity each. Nominal 3" discharge.	SALA PUMPS ALLIS MINERAL SYSTEMS York, PA Gary Sellman Houston, TX 713-771-1200	$7,000
Agitated Holding Tank	1	Agitated holding tank which receives -2mm screen underflow slurry and provides surge capacity for downstream circuit feed. Agitator is low-shear, axial-flow impeller with minimized horsepower requirements for slurry suspension. Cylindrical with cover, baffles & flat bottom.	Nominal 15,000 gal maximum working vol. Normal holding time= 60 min. or 8,100 gal. 14'D x 16' high. 3/8" carbon steel shell, ½" x 6" rubber-dipped baffles.	Estimated (Incl. mixer bridge)	$20,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Holding Tank Agitator	1	LIGHTNING mixer with low-shear, axial-flow pumping impeller.	Model 16-Q-15 with 15 Hp motor, 56 rpm, 72" dia. S.S. A-310 impeller. Shaft 3"D x 12' long S.S. Mounted on 9" x 3.5" steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$14,600
Feed Pumps	2	Centrifugal slurry pumps with cone-type vee-belt adjustment variable-speed drive. Pumps soil slurry to 100 mesh (m) screen and provides recirculation back to Holding Tank (controlled by pinch valve).	250 gpm maximum output, 4" x 3" with 12" dia. semi-open impeller, rubber-lined mild steel casing. 65' TDH with S.G. 1.350 slurry, 20 hp, 2500 rpm	GALLIGHER PUMPS Salt Lake City, UT	$9,000
Vibrating Screen	1	Derrick Model K-48X96-M3S 100 mesh slotted urethane deck provides cut on soil feed @ 100 mesh. Equipped with washing sprays and totally enclosed. Underflow discharges to Repulp Tank. Screen -2.0mm + 100m. O/S is mixed with PEG filtrate from filter, Karr Column PEG U/F and diluted floc in screen discharge launder and flows by gravity through Static Mixer 2 as feed to PEG Thickener. A conical feed launder is provided for mixing components prior to Static Mixer 2 stand pipe. Mounted 12' elevation above PEG Thickener feed well.	Model K, 48" x 96" linear motion screen with laser-cut .175mm x 10mm slots, which give 100 mesh cut point. 3.5 hp high-frequency drive motor.	DERRICK MANUF. Buffalo, NY 716-683-9010	$40,000
Static Mixer 1	1	LIGHTNING Turbulent/Laminar static mixer, which mixes dewatered Rinse Filtrate 2 dissolved flocculant to obtain dilution to approximately 0.10% or less prior to mixing with soil slurry as feed to PEG Thickener.	1½" x 18", 316 S.S. shell and 24 internal elements, 50 gpm, $\Delta P = 10$ psig, with flanged connections.	MIXING EQUIP. CO. Rochester, NY	$1,500

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Static Mixer 2	1	LIGHTNING Turbulent/Laminar static mixer, which mixes all feed (slurry, floc, etc.) to thickener to obtain optimal floc performance. Mounted at bottom of 4" NPS x 10' high stand-pipe with conical feed hopper (2'D x 18"H).	4" x 24", 300 gpm max., 4.0 psig (8') Delta P with 24 element internals. Shell and internals 316 S.S. with flanged connections.	MIXING EQUIP. CO. Rochester, NY	$5,000
Dry Flocculant Hopper/Feeder	1	Volumetric feeder/hopper for dry floc feed to initial mixing tank. Approximately 0.65 lb floc/ton soil solids design. Variable-speed capacity for single helical screw feeder 0.018-0.90 ft^3/hour.	Example: Acrison Model 120C with 5.0 cubic feet hopper, and 50:1 turn-down ratio. (0.018 ft^3/hr or 1.0 lb/h precision.)	ACRISON, INC. Moonachie, NJ 201-440-4939	$15,000
Flocculant Mix Tank	1	Flocculant mix tank to produce 1.0 wt% liquid flocculant for feed to Karr Column U/F PEG slurry. Approximately 10 lb/floc required/hour or 125 gal of 1.0% solution. Mix capacity for 4 hours inventory provided. Equipped with low-shear V.S. agitator.	6'D x 6'H cylindrical mix tank with flat cover, with 4-1/4" x 4" side baffles, conical bottom (5° slope), 1000 gal WV, 316 S.S. Reinforced rim and cross channel to support mixer.	Estimated (Incl. mixer bridge)	$2,700
Flocculant Mix Tank Agitator	1	Flocculant mix tank agitator, which mixes dry floc to initial dilution (1%) and keeps it fluid for delivery by metering pump. LIGHTNING variable-speed mixer (AC) with low-shear (A-310) impeller, pumping type.	Model 16-Q-5 with 5 hp AC V.S. motor, 0-100 rpm, 30" dia. A-310 impeller. Shaft 1½" x 6' long S.S. steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$10,000 (Incl. AC VS)
Flocculant Metering Pump	1	Flocculant metering pump, dual-diaphragm type with ball check valves. Variable-speed delivery from 0-170 gph each element. Equipped with a 2 hp, variable-speed drive.	DurcoMeter P/D Metering Pump Model L1-13116, 0-160 gpm, 3/4" S.S. check valve.	DURIRON CO. Angola, NY 716-549-2500	$17,500

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
PEG Thickener	1	Receives Karr Column U/F PEG slurry, recycle pressure filter initial dewater filtrate, dewatered filtrate 1 as floc dilution and 100 mesh screen O/S (+100m) soil. Fed through gravity fed Static Mixer 2. Overflow decant returns to PEG Recycle Tank, underflow soil is fed to the pressure filter. Sized on the basis of 1.0 m/h (0.055 ft/min) fall velocity and 250 gpm feed.	Conventional thickener 28.0 ft diameter, 10' cylindrical sidewalls, overflow lip and launder, 3.0 rpm rake, 15 hp, with hydraulic lifting mechanism, conical bottom (30°) and deep feed well (8').	DORR OLIVER Stamford, CN	$150,000
PEG Makeup Tank	1	Receives fresh PEG from 3000 gal PEG delivery truck trailer used as PEG storage. Mixes PEG with dilution water (fresh or 2% carbonate). Equipped with high turnover, pumping impeller (A-315 or equivalent).	6' x 8' cylindrical tank with baffles, 1000 gal W.V., 316 S.S. with reinforced rim and cross channel to support mixer. Flat cover with view port.	Estimated (Incl. Mixer bridge)	$3,000
PEG Makeup Tank Agitator	1	LIGHTNING mixer with low-shear, axial-flow pumping impeller.	Model 16-Q-5 with 5 hp AC V.S. motor, 0-100 rpm, 30" dia. A-310 impeller. Shaft 1½" x 6' long S.S. Mounted on 6" x 2.5" steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$10,000 (Incl. AC VS)
PEG Makeup Pump	1	Transfer pump for diluted PEG makeup to PEG Recycle Tank. Centrifugal, fixed-speed, 200 gpm, 65' head.	3" x 2" with 10" dia. impeller, mild steel casing. 65' TDH with S.G. 1.000 15 hp, 2500 rpm.	DURIRON CO. Angola, NY 716-549-2500	$5,000
PEG Recycle Tank	1	Cylindrical steel tank with conical cover and flat bottom. Vented through flash-proof vent. Receives overflow decant from PEG thickener and makeup diluted PEG.	Sized for 9,000 gal maximum inventory, 4,500 gpm W.V. 12'D x 12'H carbon steel		$10,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
PEG Recycle Pumps	2	Transfer pump for PEG recycle to the PEG Repulp Tank. Centrifugal, fixed-speed, 225 gpm, 65' head. Net flow controlled by recycle control valve to PEG recycle tank.	3" x 2" with 10" dia. impeller, mild steel casing. 65' TDH with S.G. 1.000 15 hp, 2700 rpm.	DURIRON CO. Angola, NY 716-549-2500	$5,000
PEG Repulp Tank	1	Accepts PEG decant from PEG thickener and -100 m soil slurry underflow from the vibrating sizing screen. Repulps the PEG as feed to the Karr Column. Equipped with V.S. pumping agitator.	6' x 8' cylindrical tank with baffles, 1000 gal W.V., 316 S.S. reinforced rim and cross channel to support mixer. Flat cover with view port.	Estimated (Incl. mixer bridge)	$3,000
PEG Repulp Tank Agitator	1	LIGHTNING mixer with low-shear, axial-flow pumping impeller.	Model 16-Q-7.5 with 7.5 hp AC V.S. motor, 0-100 rpm, 30" dia. A-310 impeller. Shaft 1½ " x 6" x 2.5" steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$11,000 (Incl. AC VS)
Repulped Karr Column Feed Pumps	2	Centrifugal slurry pumps with cone-type vee-belt adjustment variable-speed drive. Pumps PEG soil slurry to Karr Column feed plate.	350 gpm maximum output, 4" x 3" with 12" dia. semi-open impeller, rubber-lined mild steel casing. 65' TDH with S.G. 1.350 slurry, 20 hp, 2700 rpm.	GALLIGHER PUMPS Salt Lake City, UT	$9,000
Karr Columns	5	Multiplate Karr Columns for PEG and salt phase contacting. Receives repulped PEG feed and concentrated (approx. 15% sodium carbonate) salt phase. Sizing based on 3.0 TPH solids each column at approximately 30 wt% solids in column. Net flow is 340 gpm (250 + 90).	6'D × 15'H contact section, with plate rotating drive (5 hp) and top and bottom disengagement sections.	OTTO YORK Glitsch Corp. Persipany, NY C/O Don Glatz 201-299-9200	$380,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Karr Column PEG U/F Pumps	2	Centrifugal slurry pumps with cone-type vee-belt adjustment variable-speed drive. Pumps PEG U/F soil slurry to thickener feed (Static Mixer stand pipe).	350 gpm maximum output, 4" x 3" with 12" dia. semi-open impeller, rubber-lined mild steel casing. 65' TDH with S.G. 1.350 slurry, 20 hp, 2700 rpm.	GALLIGHER PUMPS Salt Lake City, UT	$9,000
Static Mixer 3	1	LIGHTNING Turbulent/Laminar static mixer, which mixes all feed (salt phase O/F, recycle salt phase filtrate) to obtain blended feed to Salt Phase Thickener. It is assumed that no flocculant will be required for thickener.	3" x 24", 150 gpm max., 5 psig (10') Delta P with 24 element internals. Shell and internals 316 S.S. with flanged connections.	MIXING EQUIP. CO. Rochester, NY	$4,500
Salt Phase Thickener (for concentrate)	1	Receives Karr Column O/F salt phase slurry. Fed through Static Mixer 3, which mixes salt phase with recycle filtrate from plate-and-frame Pressure Filter. Feed is into deep discharge feed well. Sizing based on 1.0 m/h (0.055 ft/min) fall velocity and maximum 150 gpm feed.	Conventional thickener 20.0' diameter, 8' cylindrical sidewalls, overflow lip and launder, 3.0 rpm rake, 10 hp, with hydraulic lifting mechanism, conical bottom (30°) and deep feed well (6').	DORR OLIVER Stamford, CN EIMCO Salt Lake City, UT DENVER EQUIP. CO. CO Springs, CO	$95,000
PEG Thickener Underflow Pumps	2	Dual diaphragm slurry pumps for pumping PEG thickener underflow slurry (40-50% solids) to the horizontal pressure filter. Pumps are positive displacement with integral line flush. Uses wash solution for the flushing between slurry load cycles. Mounted on "Y" discharge from thickener cone to facilitate dual operation with spare or change-over.	12" diameter diaphragm pumps, 100 psig, driven by compresses air (@ 150 psig). Variable-speed 0-75 gpm. Carbon steel with butyl rubber diaphragms.	WARREN RUPP Sandpiper	$5,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Salt Thickener Underflow Pumps	1	Dual diaphragm slurry pumps for pumping Salt thickener underflow slurry (40-50% solids) to the recessed plate filter. Pumps are positive displacement with integral line flush. Uses salt decant for line flushing between slurry load cycles. Mounted on "Y" discharge from thickener cone to facilitate dual operation with spare or change-over.	8" diameter diaphragm pumps, 100 psig, driven by compressed air (@ 150 psig). Variable-speed 0-20 gpm. Carbon steel with butyl rubber diaphragms.	WARREN RUPP Sandpiper	$2,500
Recessed Plate Concentrate Filter	1	Recessed plate filter press with auger-screw cake handling discharge for loading uranium concentrate into disposal containers. Model EPF 470/32-14 with 14-32"x32" plates each with 2.1 ft^3 net cake capacity. Equipped with hydraulic ram and auto-open mechanism.	DURCO Model EPF 470/32-14 with 8" dia screw-auger live-bottom discharge Vee hopper. 5 hp hydraulic system, 27.3 total ft^3 capacity.	DURIRON CO. Angola, NY 716-549-2500	$20,000
Horizontal Pressure Filter	2	Horizontal belt semi-continuous belt filters (2 each, alternating fill cycle) with recycle salt and fresh water washing cycles. Capacity of 0-20 DTPH solids feed as a thickened (40-50% slurry). Equipped final air-blow cycle to discharge semi-dry soil cake (>40% moisture). Nominal capacity 16 TPH (8-12 TPH each), single-end discharge. Fully contained with leak sump, recycle pump, side enclosures, etc.	LAROX Model PF-16 with 409 ft^2 filter area. Sizing based on 50 $lb/hour/ft^2$ filter area required. Filter takes up 376 ft^2 floor space each, 25 hp each.	LAROX INC. Columbia, MD 301-381-3314	$400,000 each (complete)
Washed Soil (-2 mm) Conveyor	1	Takes washed soil filter cake from filter discharges to washed soil stockpile. Flexible, segmented pocket type. Rises 16' in 60' length angled section (15° slope).	24"W x 100'L with 4" high sidewalls and pocket separators. In "L" configuration with 40' horiz. section at filter discharge end.	KAMFLEX Carol Stream, IL C/O John Tomacca 800-323-2440 CEMBELT INT. Salt Lake City, UT 801-972-5511	$60,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Salt/Methanol Mix Tank	1	Accepts salt phase decant from salt phase thickener and mixes methanol with it to precipitate the dissolved uranium. Normally, the mixing is a 1:0.5 salt phase:methanol ratio. This only partially precipitates the uranium, but only ppts. 5% of carbonate. Recycled salt phase reports to salt recycle tank (high carbonate recycle). The other 1/3 of the time, the methanol is added in a proportion 1:2 and virtually all uranium precipitated to 2.0% remaining in salt phase. This, after methanol stripping, reports to return salt tank for use as low-carbonate scrubber wash and PEG dilution. Design of pptn. circuit is based on 1:2 ratio for correct sizing of equipment for worst case. Equipped with V.S. pumping agitator.	8' x 8' cylindrical tank with baffles, 2000 gal W.V., 316 S. S. with reinforced rim and cross channel to support mixer. Flat cover with view port. Vented through flash protector.	Estimated (Incl. mixer bridge)	$5,000
PEG Repulp Tank Agitator	1	LIGHTNING mixer with low-shear, axial-flow pumping impeller.	Model 16-Q-10 with 10 hp AC V.S. motor, 0-100 rpm, 42" dia. A-310 impeller. Shaft 2" x 8' long S.S. Mounted on 8" x 3" steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$13,500 (Incl. AC VS)
Salt/Methanol Thickener Feed Pumps	2	Centrifugal slurry pumps with cone-type vee-belt adjustment variable-speed drive. Pumps PEG U/F soil slurry to thickener feed (Static Mixer stand pipe).	350 gpm maximum output, 4" x 3" with 12" dia. semi-open impeller, rubber-lined mild steel casing. 65" TDH with S.G. 1.100 slurry, 15 hp, 2500 rpm.	GALLAGHER PUMPS Salt Lake City, UT	$9,000
Static Mixer 4	1	LIGHTNING Turbulent/Laminar static mixer, which mixes all feed (salt/methanol from pptn. and recycle salt/methanol filtrate) to obtain a blended feed to the Salt/Methanol Thickener. It is assumed that no flocculant will be required for thickener.	3" x 24", 250 gpm max., 5 psig (10') Delta P with 24 element internals. Shell and internals 315 S.S. with flanged connections.	MIXING EQUIP. CO. Rochester, NY	$4,500

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Salt/Methanol Thickener	1	Receives salt/methanol precipitate slurry fed through Static Mixer 4, which mixes salt/methanol phases with recycle filtrate from precipitate filter press. Feed is into deep discharge feed well. Sizing based on 1.5 m/h (0.080 ft/min) fall velocity and maximum 250 gpm feed.	Conventional thickener 20.0' diameter, 8" cylindrical sidewalls, overflow lip and launder, 3.0 rpm rake, 10 hp, with hydraulic lifting mechanism, conical bottom (30°) and deep feed well (6').	DORR OLIVER Stanford, CN EIMCO Salt Lake City, UT DENVER EQUIP. CO. CO Springs, CO	$95,000
Salt/Methanol Thickener Underflow Pumps	2	Dual diaphragm slurry pumps for pumping salt thickener underflow slurry (40-50% solids) to the recessed plate filter. Pumps are positive displacement with integral line flush. Uses salt decant for line flushing between slurry load cycles. Mounted on "Y" discharge from thickener cone to facilitate dual operation with spare or change-over.	8" diameter diaphragm pumps, 100 psig, driven by compressed air (@ 150 psig). Variable-speed 0-20 gpm. Carbon steel with butyl rubber diaphragms.	WARREN RUPP Sandpiper	$2,500
Recessed Plate Precipitate Filters	2	Recessed plate filter press with auger-screw cake handling discharge for loading uranium concentrate into disposal containers. Model EPF 470/32-14 with 14-32"x 32" plates each with 2.1 ft^3 net cake capacity. Equipped with hydraulic ram and auto-open mechanism. Two installed, one loading, one discharging mounted in parallel over common live-bottom screw-auger cake transport system.	DURCO Model EPF 470/32-14 with 8" dia screw-auger live-bottomed discharge Vee hopper. Single 5 hp hydraulic system for both filters. Total 54.6 ft^3 capacity.	DURIRON CO. Angola, NY (716) 549-2500	$18,000
Air Compressors	2	Air compressor (150 psig) and receiver system to supply air for filter blow down and air-driven pumps. Capacity of 150 SCFM provided through plant air distribution system. Equipped with dryers and receiver tanks.	50 hp reciprocating air compressors with 150 SCFM @1500' capacity and single 500 ft^3 receiver tank, dryer system.	GARDNER-DENVER AZ Pneumatic Sys. Tucson, AZ	$48,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Methanol Feed Tank	1	Receives methanol makeup and condensed and cooled methanol from methanol strip column condenser. Designed to hold 1 hour inventory of methanol during maximum (1:2) addition rate. Cylindrical carbon steel tank with conical top and flash-proof vent. Working volume of 12,000 gal.	Nominal 15,000 gal maximum volume. Normal holding time = 50 min or 12,000 gal. 14'D x 16' high. 3/8" carbon steel shell, 3/16" top with flat bottom.	Estimated	$20,000
Methanol Precip. Feed Pump	2	Transfer pump for methanol feed to Salt/Methanol Mix Tank. Centrifugal, fixed-speed, 300 gpm, 65' head. Advance rate controlled by recycle control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 65' TDH with S.G. 1.000, 15 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Methanol Makeup Pump	1	Transfer pump for methanol makeup to Methanol Feed Tank. Centrifugal, fixed-speed, 300 gpm, 65' head. Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 65' TDH with S.G. 1.000, 15 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Methanol Makeup Tank	1	Tanker truck trailer (3000 gal) used as storage container for makeup methanol to precipitation.	3,000 gal tank truck trailer. 316 S.S.		$13,000
Salt/Methanol Decant Tank	1	Receives salt/methanol decant from salt/methanol thickener and also salt rinse filtrate. Designed to hold 1 hour inventory of salt/methanol solution during maximum 1:2 addition rate. Cylindrical C.S. tank with conical top and flash-proof vent. Working volume of 12,000 gal.	Nominal 15,000 gal maximum volume. Normal holding time = 60 min or 12,000 gal. 14'D x 16' high. 3/8" carbon steel shell, 3/16" top with flat bottom.	Estimated	$20,000
Methanol Strip Column Feed Pumps	2	Transfer pump for methanol feed to Salt/Methanol Mix Tank. Centrifugal, fixed-speed, 300 gpm, 65' head. Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 65' TDH with S.G. 1.000, 15 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Methanol Strip Column	1	Multi-plate methanol stripping column (16 trays) with 2000 gal reboiler. Heat input rate (based on 262 cal/g and 44 ton/h methanol volatilization rate) app. 20 MM BTU/h. Inlet feed used to cool vapor discharge from column and to preheat column feed. Includes reboiler and condensers. (Note: No provision made for steam generation or water cooling tower, if required.)	10'D x 32'H methanol stripping column with 16 perforated trays. Sizing based on 2.0 gpm/ft^2 tray area average liquid specific flow rate. 2000 gal reboiler with 20 MM BTU/h heat input rate as condensing steam.	Estimated (by scaling from similar design)	$200,000
Recycle Salt Pumps	2	Transfer pump for salt solution return to either Concentrated Salt Recycle Tank or lower (2%) concentration Salt Return Tank. Pumps are centrifugal, fixed speed, 300 gpm 100' head (S.G. 1.000). Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Recycle Salt Solution Pumps	2	Transfer pump for salt solution recycle to drum scrubbers, filter wash, etc., from the lower (2%) concentration Salt Return Tank. Pumps are centrifugal, fixed speed, 300 gpm 100' head (S.G. 1.000). Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
High Solution Recycle Pump	1	Transfer pump for high conc. salt solution recycle to filter press (salt/methanol) or pressure belt filter wash solution from high concentration Salt (Carbonate) Recycle Tank. Pumps are centrifugal, fixed speed, 300 gpm 100' head (S.G. 1.000). Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia. impeller, mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
High Solution Recycle Pump	1	Transfer pump for high conc. salt solution recycle to filter press (salt/methanol) or pressure belt filter wash solution from high concentration Salt (Carbonate) Recycle Tank. Pumps are centrifugal, fixed speed, 300 gpm 100' head (S.G. 1.000). Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia impeller mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Karr Column Salt Solution Feed Pumps	2	Transfer pump for high conc. salt solution feed to Karr column from the high-concentration Salt (Carbonate) Recycle Tank. Pumps are centrifugal, fixed speed, 300 gpm 100" head (S.G. 1.00). Advance rate controlled by pump discharge control valve.	4" x 3" with 10" dia impeller mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Concentrated Carbonate Reagent Pump	1	Transfer pump for high conc. salt solution makeup solution from the Carbonate Reagent Mix Tank to the Salt Recycle Tank. Pump is fixed speed, 300 gpm, 65' head.	4" x 3" with 10" dia impeller mild steel casing. 100' TDH with S.G. 1.000, 20 hp, 2500 rpm.	DURIRON CO. Angola, NY (716) 549-2500	$6,000
Salt (High-Carbonate) Recycle Tank	1	Receives salt recycle from salt/methanol strip bottoms and also concentrated salt makeup solution. Designed to hold 2 hours inventory of salt concentrated solution. Cylindrical C.S. tank with conical top and flash-proof vent. Working volume of 12,000 gal.	Nominal 12,000 gal maximum volume. Normal holding time = 60 min or 12,000 gal. 14'D x 16' high. 3/8" carbon steel shell, 3/16" top with flat bottom.	Estimated	$20,000
Return Salt (Low-Carbonate) Tank	1	Receives salt recycle from salt/methanol strip bottoms when high 1:2 methanol precip. is used. Designed to hold 2 hours inventory of salt concentrated solution. Cylindrical C.S. tank with conical top and flash-proof vent. Work volume of 12,000 gal.	Nominal 12,000 gal maximum volume. Normal holding time = 60 min or 12,000 gal. 14'D x 16' high. 3/8" carbon steel shell, 3/16" top with flat bottom.	Estimated	$20,000

TABLE C-1 (Cont.)

Equipment Item	Number	Description	Size	Vendor	Est. Cost (Each)
Carbonate Makeup Tank	1	Received bulk sodium carbonate from carbonate bulk feeder/hopper, which uses Tote (6 yd^3) containers as storage feed hopper. Mix tank equipped with high turnover, pumping impeller (A-315 or equivalent).	6' x 8' cylindrical tank with baffles, 1000 gal W.V., 316 S.S. with reinforced rim and cross channel to support mixer. Flat cover with view port.	Estimated (incl. mixer bridge)	$3,000
Carbonate Reagent Tank Agitator	1	LIGHTNING mixer with low-shear, axial-flow pumping impeller.	Model 16-Q-5 with 5 hp AC V.S. motor, 0-100 rpm, 30" dia. A-310 impeller. Shaft 1-1/2" x 6' long S.S. Mounted on 6" x 2.5" steel channel bridge.	MIXING EQUIP. CO. Rochester, NY	$10,000 (Incl. AC VS)
Bulk Carbonate Storage Containers	12	Tote type containers (316 S.S. sheet) with rigid angle support frame. Each equipped with manual-hydraulic slide-gate dump valve on bottom to mate with screw feeder/hopper.	6 yd^3 containers approximately 6'x6'x6' with conical discharge.	TOTE Systems Fort Worth, TX C/O Herb Roorda (817) 447-9110	$3,500 (each)
Bulk Carbonate Screw Feeder	1	Volumetric feeder, which mates to Tote hopper for feed to carbonate mixing tank. Feeds carbonate to tank based on makeup conc. Variable-speed capacity for single helical screw feeder 3.2-160.0 ft^3/h. Hopper fits above auger-screw. Timer controls net feed to mix tank.	Example: Acrison Model 101M with 5.0 ft^3 hopper, and 50:1 turn-down ratio. (3.2 ft^3/h or 120.0 lb/h precision.)	ACRISON, INC. Moonachie, NJ (201) 440-4939	$15,000
TOTAL CAPITAL EQUIPMENT COST:					**$4,448,300**

APPENDIX D:

MASS BALANCE ESTIMATES FOR FULL-SCALE AQUEOUS BIPHASIC EXTRACTION

TABLE D-1 Mass Balance for ABE Process for Soil Washing at 20 DTPH Soil Input, Coarse Separation and Karr Column Feed[a]

Stream Number	Stream Description (Based on Flexmet Balances)	Solids S.G.	Liquid S.G.	Slurry S.G.	Bulk Density	Wt.% Solids	Solids (STPH)	Liquid (STPH)	Total (STPH)	Tot. GPM (yd^3/HP)	Stream Number
1	Soil Feed Grizzly	2.500	1.000	2.119	90.0	88.00	20.0000	2.7270	22.7270	(18.70)	1
2	Grizzly Oversize (+4") to Scrubber 1	2.500	1.000	2.119	132.2	88.03	0.2000	0.0272	0.2272	0.43	2
3	Grizzly Undersize (-4") to Scrubber 2	2.500	1.000	1.923	132.1	88.00	19.000	2.0000	22.4998	42.43	3
4	Trommel Oversize (+½") from Scrubber 1	2.500	1.000	1.923	84.0	80.00	0.2000	0.0500	0.2500	(0.22)	4
5	Trommel Oversize (+½") from Scrubber 2	2.500	1.000	1.000	84.0	80.00	0.3000	0.0750	0.3750	(0.33)	5
101	Scrubber 1 Wash Water	---	1.000	1.000	62.4	0.00	0.0000	2.2050	2.2050	8.81	101
102	Scrubber 2 Wash Water	---	1.000	1.037	62.4	0.00	0.0000	2.2050	2.2050	8.81	102
51	Scrubber 1 Recycle Carbonate Solution	---	1.037	1.053	84.7	0.00	0.0000	6.2790	6.2790	24.18	51
52	Scrubber 2 Recycle Carbonate Solution	---	1.053	1.457	65.7	0.00	0.0000	6.2790	6.2790	23.33	52
6	Washing and Dewatering Screen Feed	2.500	1.029	1.923	90.9	49.91	19.6000	19.5700	30.0700	107.14	6
7	Screen O/S (+2mm) to Stockpile	2.500	1.000	1.337	84.0	80.00	1.5000	0.3750	1.8750	3.90	7
8	Screen U/S (-2mm) to Holding Tank	2.500	1.021	1.000	83.4	40.00	18.0000	27.0000	45.0000	134.42	8
103	Screen Wash Water	---	1.000	1.023	62.4	0.00	0.0000	7.8040	7.8040	31.18	103
9	Combined (+2mm) O/S to Disposal Stockpile	2.500	1.000	1.337	119.9	80.00	2.0000	0.5000	2.5000	5.19	9
10	Net Feed to 100 mesh Screen	2.500	1.021	1.337	83.4	40.00	18.0000	27.0000	45.0000	134.42	10
11	Screen O/S (+100 mesh) to PEG Thickener	2.500	1.021	1.337	83.4	40.00	2.0000	3.0000	5.0000	14.93	11
12	Screen U/S (-100 mesh) to PEG Repulp Tank	2.500	1.021	1.000	83.4	40.00	16.0000	24.0000	40.0000	110.45	12
63	Dry Flocculant	1.800	1.000	1.000	112.3	100.00	0.0052	0.0000	0.0052	(0.0034)	63
100	Dry Floc Dilution Water	---	1.000	1.004	62.4	0.00	0.0000	0.5160	0.5150	2.08	109
62	Initial Diluted Floc Mixture (1% Soln.)	1.800	1.000	1.115	62.6	0.00	0.0052	0.5150	0.5202	2.07	82
21	Floc Dilution (from PEG Dewatering)	1.800	1.115	1.103	69.6	0.00	0.0000	4.2010	4.2010	15.06	21
64	Diluted Floc to Static Mixer	1.800	1.103	1.314	83.4	40.00	0.0062	4.7160	4.7212	17.10	64
44	Karr Column PEG Phase-U/F to Static Mixer	2.500	1.092	1.000	62.0	30.00	15.6600	36.5870	52.2870	158.87	44
47	Pressure Filter PEG Filtrate to Static Mixer	2.500	1.049	1.250	67.9	0.00	0.0000	12.0920	12.0020	44.38	47
42	Net Feed to PEG Thickener	2.500	1.089	1.000	78.5	29.87	17.6650	58.3840	74.0790	235.21	42
49	PEG Thickener Decant to Recycle Tank	2.500	1.089	1.220	67.9	0.00	0.0000	34.7790	34.7790	127.63	49
84	Makeup PEG	---	1.220	1.000	78.1	0.00	0.0000	1.0000	1.0800	3.54	64
107	PEG Makeup Dilution Water	---	1.000	1.220	62.4	0.00	0.0000	0.0000	0.0000	0.00	107
43	Net Recycle PEG to Repulp Tank	2.500	1.093	1.093	68.1	0.00	0.0000	35.3540	35.8590	131.12	43
14	PEG Slurry Feed to Karr Column from Repulp	2.500	1.064	1.211	75.5	21.09	16.0000	59.8590	75.8560	250.35	14
45	U/F from PEG Thick to Pressure Filter	2.500	1.089	1.459	91.0	45.00	17.6850	21.5150	39.3000	107.58	45
55	Recycle Dilute Salt Soln. Wash on Filter	2.500	1.021	1.021	63.7	0.00	0.0000	3.4010	8.4010	32.87	55
108	Fresh Wash Water on Pressure Filter	---	1.000	1.000	62.4	0.00	0.0000	16.8020	16.0020	67.12	108
48	Filtrate 1 (from Oil Salt Soln. Wash)	2.500	1.062	1.062	66.2	0.00	0.0000	8.4010	8.4010	31.61	40
46	Recycle Dilute Salt Soln. Wash on Filter	2.500	1.025	1.0258	63.9	0.00	0.0000	16.8020	16.8020	65.48	48

[a] Based on initial mass balances for Revision 1ABE Flowsheet(12/19/94) and maximum 40% solids in screen feed.

TABLE D-1 (Cont.)

Stream Number	Stream Description (Based on Flexmet Balances)	Solids S.G.	Liquid S.G.	Slurry S.G.	Bulk Density	Wt.% Solids	Solids (STPH)	Liquid (STPH)	Total (STPH)	Tot. GPM (yd^3/HP)	Stream Number
80	Bleed from Proprietary Dewater Process	2.500	1.000	1.000	62.4.	0.00	0.0000	4.2000	4.2000	16.78	90
16	Washed Filter Cake (-2mm) Soil to Disposal	2.500	1.008	1.638	102.2	65.00	17.6850	9.5230	27.2080	(19.7115)	16
14	PEG Slurry Feed to Karr Column from Repulp	2.500	1.023	1.1240	77.4	21.09	16.0000	50.8590	75.8590	244.33	14
44	Karr Column PEG Phase U/F to Static Mixer	2.500	1.002	1.314	62.0	30.00	15.0000	36.5870	52.2070	158.87	44
20	Concentrated Carbonate Salt Solution Feed	2.500	1.287	1.000	82.4	0.00	0.0000	9.4526	9.4520	37.78	20
15	Salt Phase Column U/F of Thickener	3.000	1.123	1.000	43.9	0.97	0.3200	32.7246	33.0440	131.16	15
136	Net Feed to Thickener	2.500	1.000	1.000	43.9	0.95	0.3200	33.0874	33.3874	132.62	136
19	Salt Decant from Thickener	2.500	1.123	1.000	62.4	0.00	0.0000	32.5874	32.5874	130.10	19
40	Thickener U/F Slurry to Filter	2.500	1.123	1.000	62.4	40.00	0.3200	0.4800	0.0000	3.20	40
18	Filtrate from Thickener	3.000	1.123	1.123	70.0	0.00	0.0000	0.3429	0.3429	1.22	18
41	Uranium Concentrate (from PEG Column)	3.000	1.123	1.123	70.0	70.00	0.3200	0.1371	0.4571	(0.48)	41
30	Methanol Makeup	3.000	0.500	0.800	49.9	0.00	0.0000	0.0000	0.0000	0.00	30
148	Recycle Methanol from Strip Condenser	3.000	0.500	0.800	34.9	0.00	0.0000	32.5874	32.5874	162.73	148
138	Net Feed to Precipitation	3.000	0.885	0.885	55.2	0.00	0.0000	65.6540	65.6549	295.43	138
139	Precipitation Outflow	3.000	0.885	0.000	56.7	3.72	2.4420	63.2129	65.6549	288.66	139
30	Filtrate Recycle	3.000	0.885	0.885	55.2	0.00	0.0000	2.6154	2.6164	11.81	30
32	Net Feed to PPTN. Thickener	3.000	0.885	0.908	66.6	3.58	2.4420	65.8293	68.2712	300.48	32
35	PPTN. Thickener O/F Decant to Meth. Strip Feed	3.000	0.885	0.885	65.2	0.00	0.0000	62.1663	62.1863	280.68	35
34	Uranium PPT. Filter Cake	3.000	0.885	1.233	76.9	40.00	2.4420	3.6629	6.1048	19.79	34
145	Filter Cake after Dewater	3.000	0.885	1.747	109.0	70.00	2.4420	1.0466	3.4855	(2.37)	145
58	Salt Solution Wash	3.000	1.023	1.023	63.8	0.00	0.0000	4.1862	4.1862	18.35	58
38	Rinse Filtrate	3.000	1.023	1.023	63.8	0.00	0.0000	4.1862	4.1862	18.35	38
37	Uranium Precipitate to Disposal	3.000	1.023	1.399	118.4	70.00	2.4420	1.0406	3.4885	(2.18)	37
39	Net Feed to Methanol Strip Column	3.000	0.885	0.365	55.2	0.00	0.0000	66.3526	66.3520	299.52	39
33	Recycle Salt Solution	3.000	1.023	1.023	63.8	0.00	0.0000	33.7651	33.7651	131.91	33

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Aqueous Biphasic Extraction of Uranium and Thorium from Contaminated Soils
Final Report

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