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Engineering Evaluation of Solids/Liquids Separation Processes Applicable to Sludge Treatment Project

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Abstract: This engineering study looks at the solids/liquids separation unit operations after the acid dissolution of the K Basin sludge treatment. Unit operations considered were centrifugation, filtration (cartridge, cross flow, and high shear filtration) and gravity settling. The recommended unit operations for the solids/liquids separations are based upon the efficiency, complexity, and off-the-shelf availability and adaptability. The unit operations recommended were a Robatel DPC 900 centrifuge followed by a nuclearized 3M™ cartridge filter. The Robatel DPC 900 has been successfully employed in the nuclear industry on a world wide scale. The 3M™ cartridge filter has been employed for filtration campaigns in both the government and civilian nuclear arenas.

Christine Willingham
Release Approval

AUG 25 1998
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ENGINEERING EVALUATION OF SOLIDS/LIQUIDS SEPARATION PROCESSES APPLICABLE TO SLUDGE TREATMENT PROJECT

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1.0 INTRODUCTION

Trade studies have been performed to determine likely unit operations and methods required to support the removal, storage, treatment and disposal of solids/liquids present in the K Basins at the Hanford Site. The conceptual sludge treatment chemical flow sheet for the entire process is included, for information, in Appendix A. It should be noted that the conditions ascribed to streams KE1 and KW2 are considered bounding for all five waste streams. This trade study addresses solids/liquids separation methods to be used to separate undissolved solids remaining after the sludge dissolution step. The solids/liquids separation operations will include steps to wash the solids to remove any interstitial liquids such that the solids, after leaching can be mixed with grout and solidified, may be disposed of in the Environmental Restoration Disposal Facility (ERDF) on the Hanford Site.

1.1 Background

The K East (KE) and K West (KW) Basins are water-filled concrete pools that contain over 2,000 ton of N Reactor fuel elements stored in aluminum or stainless steel canisters. During the time the fuel has been stored, approximately 50 m^3 of heterogenous solid material or sludge has accumulated in the basins. The sludge is a mixture of fuel corrosion products, metallic bits of spent fuel and zirconium cladding, iron and aluminum metal corrosion products, silica from sand filters and migration sands (Pearce 1998). Polychlorinated biphenyls (PCBs) have been determined to be present in the K Basins and are suspected to have adhered to the surface of the sludge. The sludge and dissolver solution requires pretreatment to meet waste acceptance criteria for storage. The key control parameters for the Tank Waste Remediation System (TWRS) acceptance are pH, particle size, uranium 235 enrichment levels, and neutron absorbers.

The estimated sludge volumes are 43.83 m^3 for K-East and 6.75 m^3 for K-West (Pearce 1998). However, a nominal value of 50 m^3 will be for purposes of this study. The approximate mass of sludge to be treated is 76,339 kg.

1.2 Overview

Three primary methods of solids/liquids separation were evaluated as part of this trade study-centrifugation, filtration and solids settling. Recommendation of methods to be used to support K Basin sludge treatment were based on sludge removal efficiency, sludge particle size, prior use and experience in radioactive environments, operations and maintenance experience, and impact on upstream and downstream process steps.

1.3 Conclusions/Recommendations

Based upon the selection criteria a centrifuge was chosen as the best method of solids/liquids separation to support the resin separation step. Also, based upon the selection criteria, a centrifuge followed by a final filtration step was chosen to remove solids remaining after dissolution.

Based upon experience a Robatel DPC900 centrifuge is recommended for the centrifuge step. A 3M™ Corporation melt-blown polypropylene nuclearized cartridge filter is recommended for the final filtration step. The number and configuration of the filter will be defined as the design develops.

2.0 DESCRIPTION OF REQUIREMENTS

2.1 Requirements for Liquid Stream

Due to the stringent requirements for TWRS acceptance of PCBs, the liquid stream must contain no more than 0.5 ppb and associated solids must contain no more than 2 ppm of PCBs.

2.2 Requirements on Solids

In solids/liquids separation processes, the interest is in obtaining a stream that is devoid of as many solids as possible to transfer to TWRS. In the treatment flowsheet for K Basins, the interest is not only in intercepting as many solids as possible, but also to obtain as dry a cake as possible. That is to remove as much of the interstitial liquid as possible from the solid mass while allowing as few of the solids as possible to be transferred with the liquid stream to TWRS due to PCBs .

2.3 Other Possible Constraints

Criticality

The operations in this process must provide an adequate margin of subcriticality to ensure criticality safety. Criticality control in the dissolution step is based on limits for the mass of fissile material in a batch and soluble poisons. Therefore, criticality control for later processing steps, including the Separation Process, is established by the controls used to limit the batch mass in the dissolver, provided multiple batching and fissile material buildup in equipment is prevented and the soluble poisons are not lost.

Studies are being conducted for safety under as low as reasonably achievable (ALARA) and criticality for the sludge treatment and will be issued under a separate document.

Operations and Maintenance

Since the K Basin sludge streams will be highly radioactive both maintenance requirements and ALARA principles will be adhered to. Selection of equipment will be predicated upon the anticipated service life and remotization of equipment. The campaign to treat the K Basin sludge is anticipated to be a 2 year effort. Equipment chosen must be able to perform during the campaign with minimal maintenance. The design must be as uncomplicated as possible and the equipment be remotized.

3.0 REVIEW OF AVAILABLE TECHNOLOGIES

This section will consider the following technologies: centrifugation, filtration, and settling (gravity thickening).

3.1 Centrifugation

3.1.1 Description of Technology

This is a mechanical method of separating immiscible solids from liquids by the application of centrifugal force. (The force applied by a centrifuge may be many multiples of gravity, therefore those separations which occur via gravitational forces overtaking inertial forces are enhanced by many orders of magnitude with a centrifuge.) For the selection of a centrifuge, consideration must be given to the particle size, solids concentration, differences in specific gravity of liquids and solids and the liquid viscosity. Bowl centrifuges (such as the Robetal DPC) are able to capture particle diameters of approximately 1 micron. Centrifuge efficiencies are predicated upon the considerations above, densities of particles, liquid, etc. Centrifuges range in efficiencies from 50% to as high as 100%, depending upon the processing conditions (Leung).

Centrifuges can be divided into the following categories:

1. Filtering (Solids/Liquids). This unit uses a cylinder or cone which has surface holes or slots. Over this surface is placed a screen or screens, with openings to restrict the passage of the solid material but allowing the liquid phase to pass freely. The solids/liquids slurry is introduced into the rotating body of the centrifuge via a feed pipe. The centrifugal force pushes the slurry to the side, forcing the liquid through the perforations in the basket while the solids are retained within by means of a fine screen. The remaining solids (cake) may then be washed and spun at higher G forces to achieve a relatively dry cake. The resultant cake is then discharged though the bottom of the basket by means of a single motion plow mechanism.

2. Sedimentation (Solids/Liquids). This unit uses a cylinder or cone but has an imperforate solid wall basket. This unit is used for solids which are very fine or have poor filtering characteristics. The slurry is introduced into the rotating basket by a feed pipe. The slurry is then driven to the

basket wall and the lighter liquid is forced to escape by overflowing the top of the basket while the heavier solids are retained within. The solids are collected on the wall of the centrifuge and must be periodically or continuously removed.

Initially, with fine solids, the centrifuge will not yield a clarified effluent. Therefore, it is usually necessary to recirculate the filtrate to allow a cake of the solids to build. After the cake builds up, either through recirculation or over a short process time, the solids separation will improve.

3.1.2 Application to K Basin Sludge Treatment

Samples of K Basin sludge were dissolved in nitric acid (to simulate the acid dissolution step in the flowsheet) and subjected to a particle volume analysis. This is representative of the feed stream to the centrifuge in the K Basin sludge treatment flowsheet. Both the particle size distributions indicate the following range, 0.15 µm to 5 µm, 2.76% for sample 98-04209 and approximately 4.13% in the same range for sample 98-04208. The remainder of the particles, for both samples, ranged from 4 µm to 400 µm with the largest concentration between 50 µm and 150 µm (Appendix D). The type of centrifuge that would yield the highest efficiency of separation based upon the particle size analysis would be the sedimentation centrifuge.

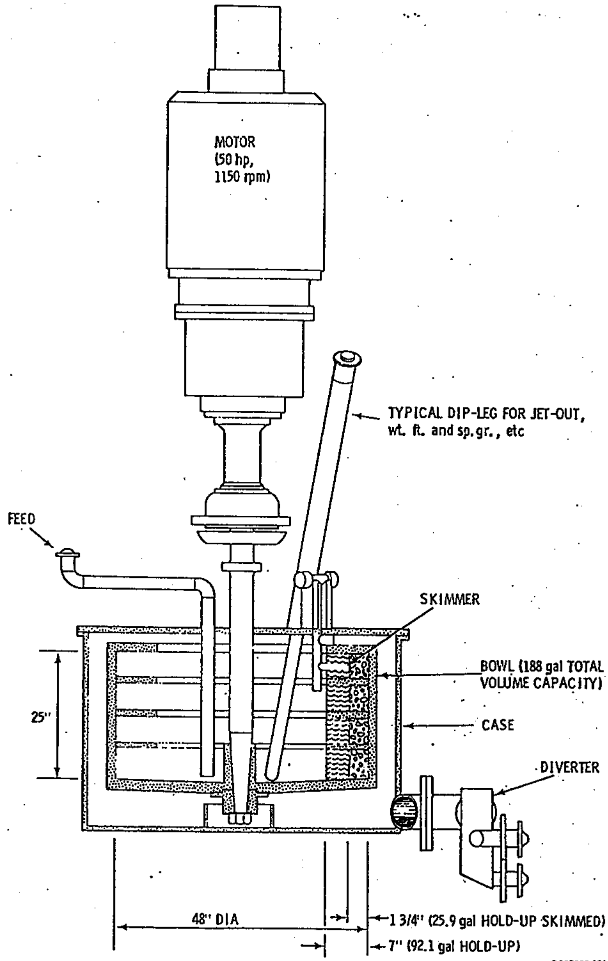
3.1.3 Department of Energy and French Experience With Centrifuges in Nuclear Operations

On the Hanford Site, Koegler (1985) reported that there were three 40 -inch diameter bowl centrifuges in use at B Plant to separate strontium and cesium solids for current acid waste and the Plutonium Uranium Extraction (PUREX) acidified sludge. They were typically operated at 8 gpm and 1740 rpm. The solid particles were forced to the bowl wall and the supernatant liquid was removed by a skimmer. When 15 gallons of solid material had collected on the wall (determined by calculation) the feed was stopped and the bowl was cleaned with high pressure water. The B Plant centrifuges were non-continuous batch process sedimentation centrifuge. Unfortunately, there was no particle size data taken on the feed to the centrifuges or the effluent.

The PUREX plant used two centrifuges (Bird) to remove uranium terafluoride from Zirflex coating wastes (Figure 3.1.3-1). Each centrifuge used a cylindrical bowel, 48 inches in diameter, spinning volumes of 90 gallons (341 liters) and exerted a 900 G force at the working speed of 1150 r/minute (WHC-SP-0479).

An important centrifuge auxiliary was the high-pressure spray for dislodging or washing down the solids. During operation, the feed was introduced via a dip tube near the bottom of the rotating bowl. After the solids collected on the bowl wall, they were removed by spraying, slurrying, and jetting.

Figure 3.1.3-1 Purex Centrifuge



A problem encountered during the slurrying and solids removal process was the motor heating which led to reduced life. The reason for the problem was that the centrifuge would be started a number of times from stop to only 10 to 80 r/minute.

DOE has tested various centrifuges at the Hanford Site with varying rates of success. The tests were conducted on synthetic materials and the particle size distributions were not reported.

That is, those centrifuges that obtained close to 100% efficiency may well have been challenged with a stream of particles several hundred microns in diameter and above. Also, there is no mention of nuclearization of the centrifuges in the reports. The remotization and nuclearization of a piece of equipment such as a centrifuge is time consuming, as well as requiring dedicated monies to the effort.

In France, the Robatel (Appendix C) centrifuge has been developed to be remotized and nuclearized to serve in a hot cell environment for the processing of HLW. This centrifuge has an efficiency of 100% for particles greater than 5 μm. Tests with SiO_2 were conducted in France and the results from the Robatel DPC 900 are:

Particle Size	Efficiency
1.3 to 1.6 μm	82 to 91 %
1.6 to 2 μm	93 to 97%
2 to 10 μm	> 99%

Also, the Robatel DPC 800 has been in service at the La Hague UP2-400 for 20 years with no significant bowel or mechanical problems. The Robatel DPC 900 has been in service at the La Hague UP3, UP2-800 and Marcoule for more than 8 years without mechanical problems. Appendix C has more particulars around the Robatel models and schematics of the Robatel DPC 800 and DPC 900.

3.1.4 Advantages/Disadvantages

The following sections delineate general advantages and disadvantages for classes of centrifuges.

3.1.4.1 Advantages

Filtration Centrifuge -- Advantageous for those streams that contain large particles, usually greater than 100 microns.

Sedimentation Centrifuge -- There is much experience in the nuclear arena with this type of centrifuge. Some equipment has been specifically designed for this type of centrifugation and would be directly applicable for our purposes. This would save program dollars and reduce risk.

Sedimentation centrifuges allow a good compaction of the solid cake. Therefore a high solid concentration is present in the cake, approximately 80% would be expected. However, since there have been no tests applicable to K Basin sludge, a conservative estimate of 60% can be considered.

Due to the high solids loading of the cake, a drier cake is possible. This will obviate wash volumes in the process flowsheet that would otherwise be necessitated with a wetter cake and more interstitial liquids. Washing and dilution steps can be carried out in the same centrifuge which limits solids transfers and ancillary support equipment.

Throughput is on the order of 1 cubic meter per hour, which is well within the range of the throughput needed for the process. Finally, there is no waste production. A centrifuge is an expensive piece of equipment. It is to be noted that development has already been made with the Robatel DPC 800 and the Robatel DPC 900. Neither of these centrifuges require extra piping and valves as does cross flow filtration or precoat filtration.

3.1.4.2 Disadvantages

Filtration Centrifuge -- Due to the presence of small particles, the filter screen or media would be expected to be quickly blinded. This would render the centrifuge quite useless in the K Basin sludge flowsheet.

Sedimentation Centrifuge -- Centrifugation is not efficient for small and low dense particles (<0.2 microns). For the K Basin sludge flowsheet it is estimated (Appendix D) that approximately 5% of the particles are within this range. Therefore, there will be a need for additional separation for the clarified liquid going to Tank Farms. The efficiency may be improved by the addition of a flocculent.

3.1.5 Conclusion /Recommendation

The Robatel DPC 900 would be the centrifuge of choice for the reasons mentioned above around efficiency, nuclearization, and service record. The Robatel DPC 800 and 900 centrifuges are currently in service in the nuclear industry in France (1-DPC 800, 5-DPC 900), Japan (2-DPC 900), and England (3-DPC 800). There have been no reports of mechanical or bowl problems at any site. The DPC 800 at LaHague has been in operation for 20 years with bowel replacement or mechanical problems. Five DPC 900's have been in operation for over 8 years without mechanical problems. At the time of this study, the years in service at the other sites have not been made available.

A final polishing filter will be needed to ensure particles do not escape the separation process in the clarified liquid stream.

3.2 Filtration

For the purposes of this study, filtration will be divided into two categories. Dead-end and cross flow as depicted in Figures 3.2-1a and 3.2-1b, respectively. The following categories are discussed in terms of filtration media with configurations as subsets or in terms of the filtration configuration. For example, under metal filter media, dead end filtration and cross flow filtration are discussed. Under high shear filtration, only that configuration is discussed as several filtration media may be employed. When the term membrane is used, it is used in the context of media applicable to the nuclear industry, that is metal, radiation hardened polymers, etc.

There are however, some common attributes to most filtration mechanisms that affect performance of the filtration mechanism.

Concentration Polarization

Concentration Polarization (CP) is a boundary layer phenomenon in which solutes retained by the membrane accumulate at the membrane surface and are not scoured back into the bulk solution. The CP boundary layer produces two adverse effects: a reduction of flux and a change in particle selectivity. The boundary layer resistance to permeation can become much larger to that of the membrane and therefore degradation of flux is observed. As the concentration of retained solute increases at the membrane surface, the pressure required for permeation of the solvent and permeable solutes through this layer increases. Thus adversely affecting the membrane separation capability.

Fouling

Although concentration polarization maybe thought of as dynamic fouling, other types of membrane fouling will adversely affect membrane performance and in some cases on a permanent basis. This type of fouling may be composed of material adsorbed directly on the membrane (chemisorption), or may accumulate on the surface where it is difficult to control or remove (physisorption). Fouling is a boundary layer or sub-boundary layer phenomenon, which may or may not be exacerbated by CP. Once fouling occurs, the unit must cease operation, be brought off line and cleaned.

Cleaning

Although it is effective at reducing fouling, cross flow alone is often insufficient to eliminate fouling. If fouling at some level occurs, the only practical way to reverse its effect is to perform a cleaning on the membrane. Cleaning of membranes typically is *in situ* at an elevated temperature, using either acids, caustics, or oxidizing agents or a combination of these. Although the objective of cleaning is to chemically remove foulants and restore the flux to previous states, it must be remembered that cleaning causes wear and tear on the membrane and ultimately degrades performance and limits membrane life.

Figure 3.2-1(a) Dead End Filtration

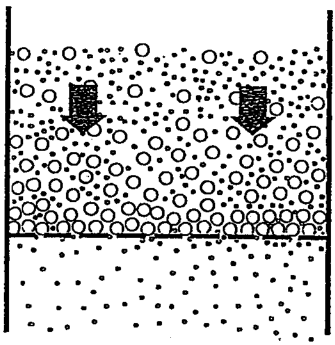
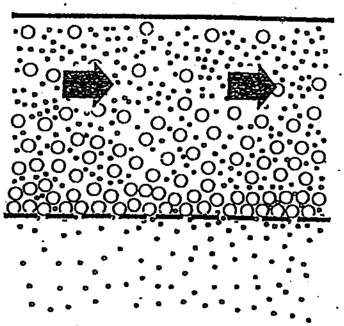


Figure 3.2-1 (b) Cross Flow Filtration



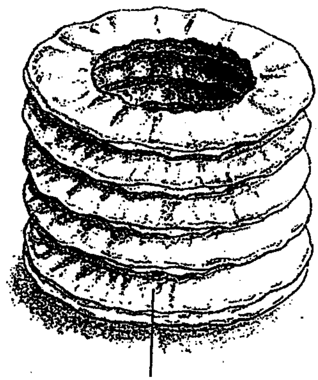
3.2.1 Cartridge Filtration

This configuration is supplied with various filtration media and hydraulic configurations. The media may range from polypropylene either spun woven or melt blown for chain randomization and absolute pore size control to cellulose esters. Filtration occurs on a process stream delivered inside the cartridge to the outside, entraping and entraining the solids in the lumen of the cartridge. (Figure 3.2.1-1)

The choice of cartridge filtration is limited to fluids containing approximately 0.02% solids and where cake handling is unnecessary. Particles to be removed from liquids by cartridge filters range from submicron to above 40 mm. These fine particles produce a impermeable cake with unusually high resistance (for its thickness). Therefore, cartridge filtration is used primarily to clarify low-solids-containing fluids.

Figure 3.2.1-1 3-M Filter

	Filter Cartridges		
Comparative Measure	**3M™ High Flow Filter System**	**String Wound**	**Pleated**
Typical number of cartridges to handle 550 gpm	11 each x 40 in. length	54 each x 40 in. length	54 each x 40 in. length
Total filtering surface area	2200 sq. ft.	140 sq. ft.	1080 sq. ft.
Expected dirt holding capacity	242 lb.	14 lb.	43 lb.



The patented radial pleat design allows greater packing of usable filter media into each cartridge.

3.2.2 Experience in the Nuclear Arena

The efficiency of cartridge filters range from 99% to 99.999% depending upon filter media, particle distribution and flow rates. A filter manufactured by the 3M Company was used at N Reactor Spent Nuclear Fuel Basin to remove particulate matter from the water for clarification purposes. The efficiency of that filter was 99% in the removal of suspended particulate matter. The particle size distribution at N Basin was similar to that of KE basin. (Table 3.2.2-1)

The filter is manufactured in an encapsulated configuration which is used in a remotized nuclear operation applications by GE Nuclear in commercial reactors within high radiation areas. The filter was also used by Centac under US DOE oversight to filter and clarify water in a North Korean Spent Nuclear Fuel Basin much like the Hanford N and K Spent Nuclear Fuel Basins.

Table 3.2.2-1 Particle Diameter vs. Filtration Efficiency

Particle Diameter (micron)	Efficiency
5	99%
2	99%
0.5	60%

The efficiency at the lower micron level will increase as the cake builds on the membrane surface which enhances filtration of the process stream. Complexity is not an issue, as there is no maintenance around the encapsulated cartridge filter or its housing. The filter is a valve in and valve out with quick disconnects.

3.2.3 Advantages and Disadvantages

3.2.3.1 Advantages

The advantages of a nuclearized cartridge filter are a high solids holding capacity and high efficiency. The filter manufactured by 3M™ has a capture capability of approximately 494 g/m^2 of filter media area. It is available in an encapsulated configuration for remotized nuclear operations.

3.2.3.2 Disadvantages

The major disadvantage of a cartridge filter is the inability to engage in backwashing the filter to retrieve the filter cake. Also, the amount of interstitial liquid with the cake can be rather high. For example, the 3M™ filter, depending upon the speciation of the solids, will contain 12 to 40%

of interstitial liquid on a wt/wt basis. However, it will only contain less than 0.24 liters of free drainable liquid (Kinard, 1998).

3.2.4 Metal Filter Media

Metal filters are available in both dead end and cross flow configurations. Metal microfiltration membranes are made from sintered stainless steel, other grades of metals, or ceramics. The usual methods of preparation give membranes with fairly large pores 1 to 100 μm. However, by partially filling the surface layer with zirconium oxide or other inorganic materials, asymmetric membranes with controlled pore sizes are obtained.

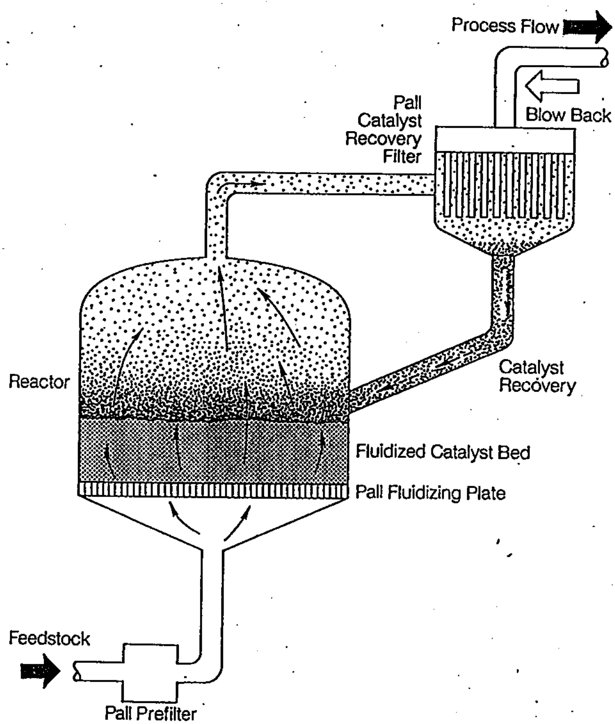
The metallurgical filters have been used to:

- separate iron oxide (95% less than 1 μm) from water and concentrate to a consistency of toothpaste, and

- separate and concentrate titanium dioxide (100% 0.1 to 0.3 μm) from water.

Figure 3.2.4-1 is a schematic of a metal filter for recovering catalyst from a process. The application to the K Basin sludge treatment process would be the capture of solid particles after solids liquid separation. The schematic also indicates a backpulse to clean the filter media.

Figure 3.2.4-1 Pall Corporation Metal Filter



Typical schematic of
fluidized bed reactor system.

3.2.4.1 Experience in the Nuclear Arena

There have been many applications of metal filter media both in dead end and cross flow filtration configurations. Studies at Hanford and Savannah River have employed different iterations of this filtration media for the filtration of tank waste. For example:

In 1991, testing was conducted to demonstrate that simulated NCAW solids can be removed using a pneumatic hydropulse (PHP) sintered metal filter (King, 1991). The purpose of the test was to determine if the sintered stainless steel PHP type filters were capable of removing 7% solids in the transuranic extraction (TRUEX) feed stream. The filter membrane tested was a 5 μm absolute pore size PHP filter. The surface area of the filter was 1.35 square feet. The results of the testing indicated that the filter would be able to process the solution at a minimum of 0.6 gpm per square foot of filter surface area at an operating pressure of about 30 psi.

In 1986, tests were conducted with simulated NCAW to determine the optimum operating parameters for removing NCAW solids with the inverted pall hydropulse (I-PHP). Parameters investigated include diatomaceous earth (DE) precoat and DE body feed. The test apparatus was a 1.9 square foot sintered metal Mott Metallurgical Corporation Multi Mode Process Filter Model 8704001. The range of DE precoat varied from 11 to 85 gm/ft^2 and the body feed ranged from 1 to 4 parts NCAW per part DE. The tests indicated that using a precoat of 42 gm/ft^2 and a body feed of 1 part DE to 4 parts NCAW resulted in a 500% increase in solids filtered per cycle. It was recommended that the filter cycle be terminated and backwashed when a delta P of 35 psi was reached. This prevented the formation of large masses of agglomerated solids in the backflush solution.

In 1978, a Mott cross flow filter was tested on synthetic Hanford PUREX and REDOX sludge (Koegler, 1978). The study showed that the filtration rate decreased with increasing slurry concentration.

Savannah River performed a demonstration test to remove radioactive cesium from high level liquid waste (Snell, 1983). A Mott metal media unit was used with 200 square feet of filter area. The filtration rate ranged from 7.5 to 10.5 gallons per hour (0.125 gpm to 0.175 gpm) with a recycle rate of 125 gallons per minute. The filtration rate dropped significantly as the solids concentration increased above 4%.

3.2.4.2 Advantages and Disadvantages

3.2.4.1 Advantages

The media (especially in the cross flow configuration) presents a very efficient solids separation unit operation. The addition of a filter aid, either as a precoat or a body feed, will enhance the filtration capability of the media. In the case of the K Basin Sludge flowsheet, a precoat may aid in the removal of PCBs from the liquid stream. Efficiencies of 99% can be obtained by coupling centrifugation and cross flow filtration. The problem that will be encountered is the lag storage needed due to the large differences in production rate.

3.2.4.2. Disadvantages

Unfortunately, a major drawback to the metal filter media is the surface and subsurface fouling that is encountered during filtration with a concomitant decrease in the flux. When this occurs chemical cleaning is recommended to restore the flux value. Also, flux values are not high with cross flow filters as reported above. As the solids build up on the membrane, the flux will decrease to the point of bringing the system off line and instituting cleaning procedures.

Experience at STE3 at La Hague indicates there is a complexity of piping, valves and automated system to transfer the precoat filter removal from the filter.

The choice of a precoat is difficult, it must be a material that is easily transported by pipes and easily implemented in the delivery to the filter media. As of yet, there has been no precoat identified that would be adequate to the K Basin sludge flowsheet.

Nuclear experience is quite limited. As mentioned above, LaHague does have a cross flow filter. Few of the metal filters have been demonstrated in a nuclearized operations mode.

This approach of a metal dead end or cross flow filter would be a rather complicated process to institute behind a hot cell for K Basin Sludge processing.

3.2.5 High Shear Filtration

The high shear membrane process is basically like that of conventional membrane systems with the exception of the rate at which the process fluid is recirculated. Since the cross flow velocity is controlled by a force input rotating the membranes, the recirculation flow rate is set based on the amount of permeate removed. Therefore, the dependence of pressure is decoupled from the feed flow rate for transmembrane flux. This allows more control over the driving force pressure and independence of control over cross flow velocity.

Some common attributes for all the high shear filtration units are:

• High Rates - These units average 10 times higher than competing membrane technologies such as cross flow filtration.

• Fouling Resistance - These systems use a shear process to keep the membrane surface clean. Processes such as dewatering, counter current washing and size classification all benefit from this shearing action.

• High Solids - Systems which rely on the feed flow to create shear become increasingly inefficient as the feed stream concentrates. They stop operating as the stream becomes too viscous. Because these units rely on external force applied to the membrane surface to create shear it is able to achieve very high concentrations while retaining fouling resistance. The only solids limit is the ability to discharge the material. . Because high shear membranes do not depend on the shearing forces of the feed flow, the slurry can become extremely viscous and still be successfully dewatered.

• High Efficiency - In high shear filtration systems, shear is focused on the membrane surface allowing for a high energy conversion to shear. In typical cross flow systems where only 10% of the energy is actually converted to shear, most of the energy is spent overcoming pressure drops associated with flow turnarounds and screens.

• Membranes - Membrane pore size can be varied from reverse osmosis membranes (rejection of everything except water molecules), ultrafiltration (rejection of molecules of 100 MW to 1 Million MW), microporous membranes (0.1 μm to 10 μm), and woven screen which extend from 1 μm to standard mesh sizes.

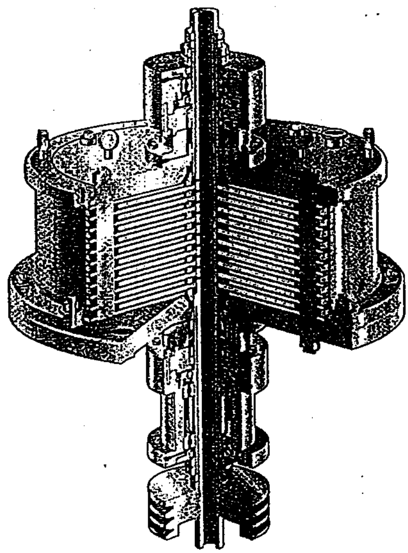
There are several manufacturers that have brought the high shear filtration to a marketable product. They are SpinTek, Vsep, and Pall-Sep. These will be discussed individually.

3.2.5.1 SpinTeK II High Shear Rotary Filter (Figure 3.2.5.1-1)

The SpinTek II High Shear Rotary Filter uses rotating disks, coated with either flat sheet membrane or creamic membrane material. The disks mount on a common rotating shaft. The entire stack of membrane disks are enclosed within a pressure vessel.

The feed fluid enters the vessel, flows between disks across the membrane surface, where permeate flows through the membrane. The concentrate exits the system at the opposite end. The fluid is recirculated as in conventional crossflow systems, but not at as high a rate.

Figure 3.2.5.1-1 SpinTek High Shear Rotary Filter



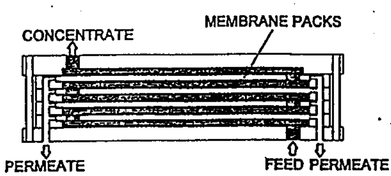


Figure 7 - Plate and Frame Membrane Housing

Stationary disks oppose the rotating membrane disks and provide a means for prohibiting fluid rotation and promoting turbulent flow if desired. The stationary disks may have vane-like protrusions to enhance fluid flow in and out of the channel. The stationary disks increases the shear rate, or change in the velocity per distance from the membrane surface.

3.2.5.1.1 Performance of SpinTek

The cross flow velocity is not only directly controlled, its magnitude is significantly greater. A conventional cross flow system may have a velocity of 8 ft/sec. The SpinTek II high shear membrane typically operates at 55 ft/sec. Concentration polarization is dramatically decreased, performance is enhanced and most important, selectivity is determined by the membrane rather than the layer formed on the membrane.

SpinTek can concentrate the waste stream to approximately 60% solids and 40% water. One of the membranes that are available is the 0.07 μm, which will give 100% removal efficiency of particles 0.1 μm and larger. For washing the solids, SpinTek lends itself to continuous diafiltration, or the removal of the microsolute. According to SpinTek literature, a general rule is a 3X sample volume turnover will effect a 95% washout and a 5X sample turnover will effect a 99% washout. These approximations apply only to microsolutes that demonstrate zero rejection characteristics.

3.2.5.1.2 Experience in the Nuclear Arena

SpinTek has five high shear rotary filters located at Savannah River Site, Los Alamos National Laboratory and two at General Atomics. The DOE site filters are used to treat radioactive wastewater by concentrating the radioactive solids from the liquid stream. The two units at General Atomics are use for advanced metals removal for reactor effluent.

3.2.5.2 Pall Sep (Figure 3.2.5.2-1)

The Pall Sep system is a vibratory membrane that is designed (like all high shear membrane systems) to minimize concentration polarization and maximize flux throughout the membrane. To achieve the mechanical action, a membrane filter stack is connected to a seismic unit. An AC motor is used to produce the excitation for the system. The motor spins an eccentric mass mounted near the edge of the seismic mass which causes a torque to be applied to the seismic mass. As the rotational speed of the eccentric mass is increased, the filter stack begins oscillating in response to the seismic mass with a 180° phase lag. The energy of the movement of the seismic mass is translated through the torsion spring to the membrane filter assembly. As the eccentric speed approaches the natural frequency of the system, the amplitude of the membrane filter stack reaches a useful maximum for permate flux.

Figure 3.2.5.2-1 Pall Sep Filter

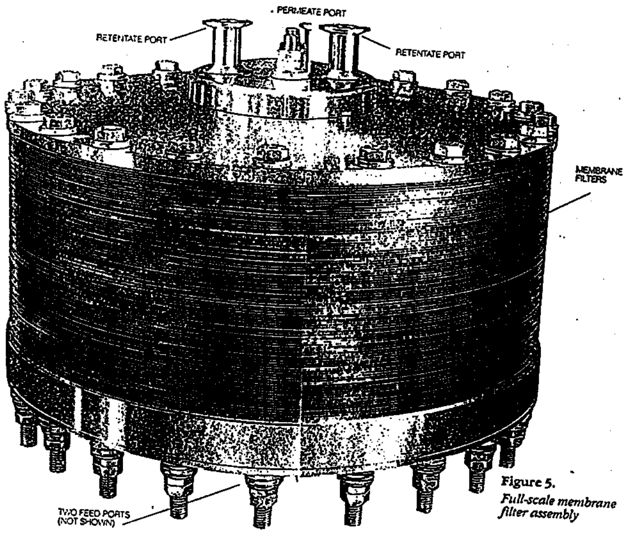
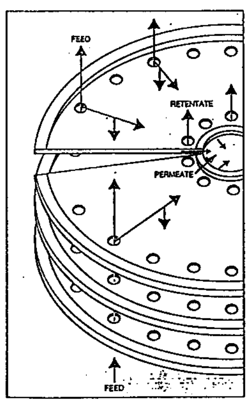


Figure 5.
Full-scale membrane filter assembly



Flow path of a membrane disc stack.

The Pall Sep system effectively employs vibrational energy for improved flux and capacity as compared to static filtration systems. The Pall Sep uses an oscillating disc filter stack which vibrates at approximately 50 - 60 Hz about a vertical axis. From this, shear rates on the order of 100,000 to 150,000 sec^{-1} are generated at the membrane surface. This focused energy is the essential feature that allows long term, stable flux operation. The membrane filter stack is designed for high installed area, as much as 400 square feet, which allows for low flow rates, if needed.

The compact design assures holdup volume is kept to a minimum. Due to the unique principle of operation, the high shear is accomplished with low energy input.

The membranes are bonded to both sides of stainless steel discs and the discs are then assembled into standard size filter stacks. Current systems employ polyethersulfone (PES) 0.45 and 1 μm nominal, and polytetrafluoroethylene (PTFE) 0.03 and 0.2 μm nominal microfiltration membranes. Of these polymers the PES would be the more radiation stable.

3.2.5.2.1 Performance of Pall Sep

According to the Pall Corporation, the high shear dynamic filtration provides complete containment and effluent clarity unachievable in separation of sub-micron particles by centrifugation. The high shear minimizes concentration polarization and the buildup of a gel layer which leads to rapidly decreasing permeate flux as occurs with conventional cross flow filters. Also, high concontraction of retained species are achievable in a single pass operation.

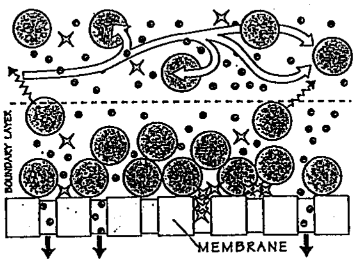
3.2.5.2.2 Experience in the Nuclear Arena

At this time, the Pall Sep has not been deployed for any nuclear customers.

3.2.5.3 Vibratory Shear Enhanced Process Filter (V-SEP) (Figure 3.2.5.3-1)

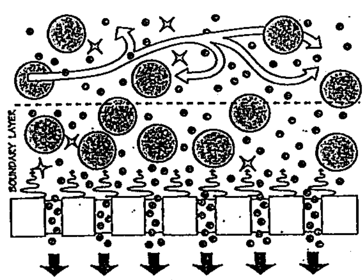
This filter unit consists of a unique stack membrane unit which vibrates rapidly to minimize fouling. It consists of multiple horizontally oriented disks which support flat sheet membrane material. The disks are sealed in a stack which vibrates at or near 60 Hz. The vibration induces intense shear at the membrane surface which prevents concentration polarization. The design allows for maximum throughput with minimal membrane surface and provides crystal clear permeate.

Figure 3.2.5.3-1 V-Sep Filter



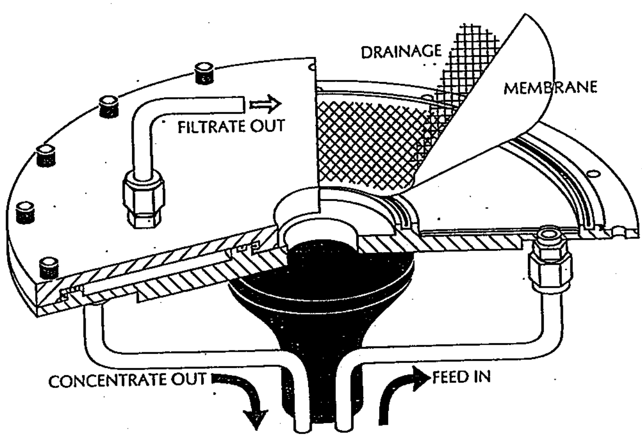
CROSSFLOW FILTRATION

Traditional crossflow membranes plug and foul because the majority of shear created by the turbulent flow is away from the boundary layer and cannot efficiently remove retained particles. This inefficient use of shear accounts for the eventual loss of flux experienced in traditional systems over time.



V✧SEP

V✧SEP's vibrational energy focuses shear waves at the membrane surface repelling solids and foulants within the boundary layer. This patented method allows for high concentrations while maintaining long term sustained rates up to ten times higher than conventional filtration systems.



3.2.5.3.1 Performance of the V-SEP

According to the manufacturer, the solids discharge will be in the 35 to 55% wt range. The efficiency for particles greater than 0.1 micron will be 100% and radioactivity will not degrade the membrane. If the V-SEP is used in conjunction with a plate and frame type filter, then 5 to 10% of interstitial fluids will remain with the filer cake. This would, of course, mean an extra unit operation following the V-SEP.

In cross flow designs, it is not economic to create shear forces measuring more than 10 - 15K sec^{-1}. This limits the use of cross flow to low-viscosity (watery) fluids, further restricting the use of conventional membrane separations systems. In the Vibratory Shear Enhanced Processing (V-SEP), the feed slurry remains nearly stationary, moving in a leisurely meandering flow between parallel membrane leaf elements. The leaf elements move in a vigorous vibratory motion tangent to the face of the membranes. The shear waves produced by the membrane's vibrations cause solids and foulants to be repelled and liquid to flow to the membrane pores unhindered.

3.2.5.3.2 Applications of V-SEP

Currently there are no DOE applications of this technology. However, the V-SEP is used in the pulp and paper industry, paint and pigment, oil production, mining and chemical processing industry. In all applications it is dedicated to removal and dewatering of sludge type material (viscous).

The disc stack is spun in a torsional oscillation like the agitator of a washing machine, producing a shear rate of approximately 150K sec^{-1} at 60 Hz, literally tens times greater than that obtainable in cross flow systems.

The final product is essentially extruded between the vibrating disc elements and out of the machine. The V-SEP machine can be operated in a single pass configuration because shear originates at the membrane surface and not in the process fluid.

3.2.5.3.3 Experience in the Nuclear Arena

Like the Pall Sep, the V-SEP has not been deployed with any customers in the nuclear arena.

3.2.5.3.4 Advantages and Disadvantages

3.2.5.3.4.1 Advantages

The high shear filtration allows for a very high efficiency on solid separations. For the K Basin flowsheet, it is almost a total separation efficiency. The application of high shear to the membrane surface has overcome many fouling problems that have plagued the filtration industry. Also, there is no need of a high flowrate in the recirculation loop, which allows for some simplicity in the system. The throughput that these technologies exhibit is adequate for the flowsheet. Finally the filter systems are fairly compact, small footprint.

3.2.5.3.4.2 Disadvantages

As with normal cross flow, there is a need to implement a recirculation loop. That lends an increase in complexity of piping, valving, and controls. Also, there remains the problem of the concentration of solids. A concentration of 30% is expected with K Basin sludge and no more. This is not enough for the flowsheet application as it would leave too much contamination in the solids and require more washings. As mentioned above, non of the vendors have qualified their system to a HLW stream. Development of the equipment is certainly feasible, but not practicable under this project.

3.3 Settling

3.3.1 Description of Technology

Particles heavier than the suspending fluid may be removed from a liquid in a large settling tank, in which the fluid velocity is low and the particles have ample time to settle out. These devices are of limited usefulness because of the incompleteness of the separation and the requirements to remove the settled solids from the floor of the vessel.

Industrial separators nearly all provide for the continuous removal of settled solids. The separation may be partial of very nearly complete. A settler that removes virtually all the particles from a liquid is known as a clarifier, where a device that separates the solids into two fractions is called a classifier. The same principles of sedimentation apply to both kinds of equipment.

If the solids in a suspension are mainly individual particles, only a few micrometers in diameter, the gravity settling rate would be very low and perhaps too low for practical operation (see Appendix B). In many fine suspensions, the particles form agglomerates of clusters of particles that will settle at reasonable rates. Agglomeration is promoted by adding flocculating agents, including strong electrolytes, which reduce repulsive forces (zeta potential) between the charged particles. Also, the introduction of polymeric flocculants that may be cationic, anionic, or nonionic will aid in the formation of larger particles for rapid settling. Flocculation may also be carried out by adding inexpensive materials such as lime, alumina, or sodium silicate which will form loose agglomerates that carry fine particles down with them as they settle.

Flocculated particles have different settling characteristics from suspensions of dispersed dense solids. The aggregates have a high porosity and retain a considerable amount of interstitial liquid that accompanies the flocs when they settle. The aggregates are also loosely bonded, and the sludge at the bottom of the settler compresses under the weight of additional solids. Because the size, shape and effective density of the flocs are not readily definable, it is not possible to predict the settling rate of the sludge density from theories or general correlations. The thickener design is based on measurements of the settling rates obtained from batch tests in the laboratory (McCabe, et. al, 1993).

3.3.2 Experience With Settling

Settling is mainly limited to water and industrial waste water treatment. The settling is exacerbated by the addition of trivalent cations and polymeric flocculants.

3.3.3 Application to K Basin Sludge Treatment

The applicability of a settling tank to the treatment of the sludge from the K Basin is somewhat limited. According to preliminary calculations, based on particle size distribution data from sludge characterization work (HNF-SP-1201, WHC-SP-1182, and HNF-1728), there is an indication that only 18% of the particles will settle within a 24 hour period (Appendix B, Table B.2). This is based on quiescent conditions and ignores any currents due to thermal or mechanical induction. Since processing will in most probably be batch, the solids retrieval from the acid digester will need to be expedited with minimal time dedicated to settling. This will shorten the processing time per batch which in turn minimizes floor space and equipment budget.

3.3.4 Discussion

Although settling is a rather inexpensive technology to implement, there are definite drawbacks. For example, real estate settling tanks are designed to eliminate the smallest particle of interest. This means that the smaller the particle of interest, the longer the tank has to allow the particle to impact the tank wall or floor rather than exit over a weir.

Since settling is not an option for the K Basin sludge treatment train, it will no longer be considered.

4.0 COMPARISON OF TECHNOLOGIES

Of the technologies that have been reviewed in this report, there are some that may be eliminated quickly. Those include: the sedimentation tank due to the time required for particle settling, some of the filtration technologies such as cross flow filtration due to the complexity of the unit operation in its configuration for processing solids, and the reduction in flux due to fouling considerations, both surface and subsurface. Most of the technologies, with the exception of some of the centrifugation types, have not been engineered for process in a nuclear environment. Table 4.0-1 is a compendium of data from the engineering study.

Table 4.0-1

Technology	Efficiency	Nuclear Application	Complexity
Gravity Settling	18% (inefficient)	Yes	No
Centrifugation (Robatel DPC 900)	95% plus	Yes	Moderate
Metallurgical Filters	67% (inefficient)	Yes	No
Cartridge Filter (3M)	99%	Yes	No
Cross Flow	99%	Yes	Yes[1]
High Shear Rotary Spin Tek Pall Sep V-Sep	99 to 100%	No	Moderate

Although the three high shear rotary filters are capable of performing outside a nuclear arena, they have not been adapted for the production of HLW. The K Basin sludge treatment effort does not have the time nor the budget to nuclearized these technologies. Therefore, based upon the complexity and off-the-shelf availability and adaptability, the following recommendation is made:

Centrifugation (Robatel DPC 900) followed by a nuclearized 3M™ polypropylene polishing filter. The choice of two technologies is predicated upon the probability of small (submicron sized) particles being in the feed stream to and not being efficiency captured by the centrifuge. The 3M filter has a track record in the nuclear industry to capture submicron particles.

Although the metallurgical filters are rated No for complexity, they along with cross flow filters will experience flux degradation over time due to surface and subsurface fouling. Restoring flux, and hencing production requires down time for chemical cleaning, washing, and bringing the unit back on line.

5.0 RECOMMENDATIONS

After considering the previous evaluation, the following solution is recommended and has been chosen to prepare the PFDs and material balances for the K Basin Sludge project.

The liquid separation will be split into two unit operations:

First, separation by centrifugation that will allow a majority of the solids to be separated from the liquid stream with an efficiency of 95%. More specifically a Robatel DPC 900 model (Appendix C).

Second, a polishing filter composed of a filter cartridge to ensure that the capture of those smaller particles that may escape the centrifuge will occur and not be allowed into the stream to TWRS. Also, the choice of a filter medium such as a polypropylene may enhance the capture of dissolved PCBs, as shown by the experiments performed by the Pacific Northwest National Laboratory (PNNL) with PVDF membranes.

This last separation would create waste under the form of a filter loaded with solids. For most of the filters containing low amounts of TRU, it is proposed to grout them in a 55 gallon drum for final disposal at the ERDF.

For those few filters that are associated with the treatment of some particular sludge and result in high TRU content, the filter cartridge will be disposed of in 55 gallon drums and sent to WIPP for final disposal (pending acceptance from WIPP).

Drawbacks associated with high shear cross flow filtration have been mentioned. Although this precludes in the present the retention of these technologies, the promise of performance offered by them would allow the solids/liquids separation in one unit operation only. It is estimated that it is too soon to completely abandon this approach. Contact will be initiated with the vendors to monitor their interest and progress in the nuclearization of their product. Depending upon their progress and the K Basin sludge time line, their technologies will be revisited for incorporation into the flowsheet.

As for the process that has been selected, additional testing needs to be carried out to:
- better understanding the particle size distribution of solids from the acid digester;
- better understanding the behavior of gel in the dissolution solution;
- determine the efficiency of a centrifuge with this waste form and water content of the solids;
- evaluate improvement of solids capture efficiency with flocculant addition;
- optimize the polypropylene filter configuration for the final polishing filtration operation, and
- washing of the cartridge filter cake to remove interstitial liquids.

6.0 REFERENCES

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List of Terms

KE1	Refers to K-East Basin sludge stream 1
KW2	Refers to K-West Basin sludge stream 2
ERDF	Environmental Restoration Disposal Facility
TWRS	Tank Waste Retrieval System
PCB	Polychlorinated Biphenyls
PUREX	Plutomium Uranium Extraction
DOE	Department of Energy
TRUEX	Transuranic Extraction (Process)
NCAW	Neutralized Current Acid Waste
REDOX	Reduction Oxidation
HLW	High Level Waste
WIPP	Waste Isolation Pilot Plant

Appendix A

Composition of KE1, KE2, KW1, KW2, and KW3 Streams at the Inlet of the Solids/Liquids Separation Step.

COMPOSITION OF THE DISSOLUTION SOLUTION (STREAM # ST-205)

	COMPOSITION OF A DAILY BATCH FOR					COMPOSITION OF TOTAL STREAMS
	KE1	KE2	KW1	KW2	KW3	
# OF BATCHES	146.1	24.4	11.2	10.2	22.4	
Volume	*2.377 m3*	*2.447 m3*	*2.221 m3*	*2.440 m3*	*2.438 m3*	*511.6 m3*
Density	*1.253*	*1.247*	*1.250*	*1.245*	*1.246*	*1.251*
Total Mass	**2,978.585 kg**	**3,050.529 kg**	**2,776.907 kg**	**3,037.309 kg**	**3,037.718 kg**	**639,933.9 kg**
LIQUID						
Volume	*2.355 m3*	*2.444 m3*	*2.172 m3*	*2.437 m3*	*2.435 m3*	*507.6 m3*
Density	*1.244*	*1.244*	*1.229*	*1.241*	*1.245*	*1.243*
Total Mass Liquid + Gaz	**2,930.219 kg**	**3,038.974 kg**	**2,669.212 kg**	**3,024.406 kg**	**3,032.093 kg**	**631,124.5 kg**
H2O	1,791.219 kg	1,860.557 kg	1,697.853 kg	1,864.443 kg	1,849.028 kg	386,669.0 kg
HNO3	899.000 kg	925.000 kg	840.000 kg	922.000 kg	921.000 kg	193,418.2 kg
H2C2O4						
HF						
NaOH						
Al(NO3)3	51.655 kg	37.626 kg	34.790 kg		48.792 kg	9,950.1 kg
AlF3						
Fe(NO3)3	146.499 kg	23.795 kg	78.124 kg		40.353 kg	23,766.6 kg
CaO	1.739 kg	0.117 kg	1.549 kg		0.074 kg	275.9 kg
NaNO2						
NaNO3						
Miscellaneous	10.559 kg	1.343 kg	3.983 kg	0.811 kg	10.275 kg	1,858.9 kg
UO2(NO3)2	29.548 kg	190.535 kg	12.914 kg	237.152 kg	162.571 kg	15,185.8 kg
Pu	*2.973 Ci*	*20.273 Ci*	*1.842 Ci*	*24.264 Ci*	*23.145 Ci*	*1,717.1 Ci*
Am	*3.873 Ci*	*23.598 Ci*	*1.750 Ci*	*19.820 Ci*	*18.324 Ci*	*1,775.5 Ci*
Cs	*48.258 Ci*	*218.785 Ci*	*15.382 Ci*	*777.125 Ci*	*260.731 Ci*	*26,356.5 Ci*
Sr	*45.400 Ci*	*246.011 Ci*	*9.997 Ci*	*606.594 Ci*	*360.717 Ci*	*27,042.8 Ci*
PCB	*0.035 g*	*0.036 g*			*0.037 g*	*6.848 g*
SOLIDS + RESINS						
Volume	*0.022 m3*	*0.003 m3*	*0.049 m3*	*0.002 m3*	*0.002 m3*	*3.9 m3*
Density	*2.185*	*3.835*	*2.211*	*5.448*	*2.305*	*2.292*
Total Mass Solids + Resins	**48.366 kg**	**11.555 kg**	**107.695 kg**	**12.903 kg**	**5.625 kg**	**8,809.4 kg**
Wt% solids	*1.62 wt%*	*0.38 wt%*	*3.88 wt%*	*0.42 wt%*	*0.19 wt%*	*1.38 wt%*
Al(NO3)3						
Al(OH)3	0.018 kg	0.139 kg			0.180 kg	10.1 kg
Al2O3	0.590 kg		0.438 kg			91.1 kg
Fe(NO3)3						
FeOOH	0.544 kg	0.088 kg	0.290 kg		0.150 kg	88.2 kg
C	0.185 kg	0.188 kg	0.081 kg		0.131 kg	35.5 kg
CaO	0.193 kg	0.013 kg	0.172 kg		0.008 kg	30.7 kg
Na2C2O4						
CO2						
H2O						
SiO2	43.775 kg	6.766 kg	106.669 kg		4.996 kg	7,864.1 kg
Grout						
Miscellaneous	0.107 kg	0.014 kg	0.040 kg	0.008 kg	0.104 kg	18.8 kg
Zircaloy		4.215 kg		10.101 kg		206.2 kg
Grafoil				2.723 kg		27.8 kg
HNO3						
H2C2O4						
Na2U2O7						
U	0.000 kg	0.031 kg	0.000 kg	0.072 kg	0.001 kg	1.5 kg
U3O7	0.004 kg	0.010 kg	0.002 kg		0.015 kg	1.2 kg
UH3	0.000 kg	0.002 kg			0.003 kg	0.2 kg
UO2	0.006 kg	0.019 kg	0.002 kg		0.035 kg	2.1 kg
UO2(NO3)2						
UO4-4H2O	0.000 kg				0.000 kg	0.0 kg
Pu	*0.009 Ci*	*0.061 Ci*	*0.006 Ci*	*0.073 Ci*	*0.070 Ci*	*5.2 Ci*
Am	*0.004 Ci*	*0.024 Ci*	*0.002 Ci*	*0.020 Ci*	*0.018 Ci*	*1.8 Ci*
Cs	*0.145 Ci*	*0.658 Ci*	*0.046 Ci*	*2.338 Ci*	*0.785 Ci*	*79.3 Ci*
Sr	*0.023 Ci*	*0.123 Ci*	*0.005 Ci*	*0.303 Ci*	*0.180 Ci*	*13.5 Ci*
PCB	*8.564 g*	*0.018 g*			*0.190 g*	*1,256.227 g*
RESINS						
Zeolite	2.527 kg					369.4 kg
OIER	0.417 kg	0.070 kg				62.6 kg
Pu	*0.019 Ci*	*0.021 Ci*				*3.279 Ci*
Am	*0.002 Ci*	*0.002 Ci*	*0.000 Ci*			*0.320 Ci*
Cs	*0.006 Ci*	*0.001 Ci*				*0.902 Ci*
TOTAL ACTIVITIES						
Total U	17.858 kg	115.152 kg	7.805 kg	143.326 kg	98.252 kg	9,177.8 kg
Total Pu	3.001 Ci	20.354 Ci	1.847 Ci	24.337 Ci	23.214 Ci	1,725.6 Ci
Total Am	3.879 Ci	23.623 Ci	1.752 Ci	19.840 Ci	18.342 Ci	1,777.6 Ci
TRU	**6.879 Ci**	**43.978 Ci**	**3.599 Ci**	**44.177 Ci**	**41.557 Ci**	**3,503.2 Ci**
Total Cs	48.410 Ci	219.444 Ci	15.428 Ci	779.464 Ci	261.516 Ci	26,436.7 Ci
Total Sr	45.423 Ci	246.134 Ci	10.002 Ci	606.897 Ci	360.898 Ci	27,056.3 Ci
Beta Gamma	**93.832 Ci**	**465.578 Ci**	**25.431 Ci**	**1 386.361 Ci**	**622.413 Ci**	**53,493.0 Ci**
CONCENTRATION						
PCB in liquid	12.00 ppb	12.00 ppb			12.06 ppb	10.85 ppb
PCB in solids	177.068 ppm	1.545 ppm			33.721 ppm	142.600 ppm
Solids	20.34 g/l	4.72 g/l	48.49 g/l	5.29 g/l	2.31 g/l	17.22 g/l
U	0.008 g/cm3	0.047 g/cm3	0.004 g/cm3	0.059 g/cm3	0.040 g/cm3	0.018 g/cm3
Pu total	**1.262 Ci/m3**	**8.319 Ci/m3**	**0.832 Ci/m3**	**9.976 Ci/m3**	**9.523 Ci/m3**	**3.373 Ci/m3**
238 Pu	0.252 Ci/m3	1.664 Ci/m3	0.166 Ci/m3	1.995 Ci/m3	1.905 Ci/m3	0.675 Ci/m3
239 Pu	0.505 Ci/m3	3.328 Ci/m3	0.333 Ci/m3	3.990 Ci/m3	3.809 Ci/m3	1.349 Ci/m3
240 Pu	0.505 Ci/m3	3.328 Ci/m3	0.333 Ci/m3	3.990 Ci/m3	3.809 Ci/m3	1.349 Ci/m3
Am	1.632 Ci/m3	9.655 Ci/m3	0.789 Ci/m3	8.133 Ci/m3	7.524 Ci/m3	3.475 Ci/m3
TRU	2.894 Ci/m3	17.974 Ci/m3	1.620 Ci/m3	18.108 Ci/m3	17.047 Ci/m3	6.848 Ci/m3
TRU	**2 310 nCi/g**	**14 416 nCi/g**	**1 296 nCi/g**	**14 545 nCi/g**	**13 680 nCi/g**	**5 474 nCi/g**
Beta Gamma	**39.469 Ci/m3**	**190.281 Ci/m3**	**11.449 Ci/m3**	**568.269 Ci/m3**	**255.325 Ci/m3**	**104.568 Ci/m3**

COMPOSITION OF THE SOLID LEACHING SOLUTION

	COMPOSITION OF A DAILY BATCH FOR					COMPOSITION OF TOTAL STREAMS
	KE1	KE2	KW1	KW2	KW3	
# OF BATCHES	146.1	24.4	11.2	10.2	22.4	
Volume	*0.914 m3*	*0.218 m3*	*2.036 m3*	*0.244 m3*	*0.106 m3*	*166.6 m3*
Density	*1.181*	*1.191*	*1.181*	*1.195*	*1.182*	*1.182*
Total Mass	1,080.038 kg	260.100 kg	2,405.157 kg	291.491 kg	125.659 kg	196,809.5 kg
LIQUID						
Volume	*0.894 m3*	*0.216 m3*	*1.990 m3*	*0.242 m3*	*0.104 m3*	*162.8 m3*
Density	*1.158*	*1.156*	*1.158*	*1.156*	*1.158*	*1.158*
Total Mass Liquid + Gaz	1,034.328 kg	249.226 kg	2,303.362 kg	279.350 kg	120.385 kg	188,486.3 kg
H2O	753.000 kg	182.000 kg	1,677.000 kg	204.200 kg	87.600 kg	137,242.5 kg
HNO3	276.500 kg	66.000 kg	616.000 kg	73.800 kg	32.150 kg	50,364.7 kg
H2C2O4						
HF	4.400 kg	1.050 kg	9.800 kg	1.150 kg	0.520 kg	801.4 kg
NaOH						
Al(NO3)3	0.090 kg	0.015 kg	0.148 kg		0.010 kg	15.3 kg
AlF3						
Fe(NO3)3	0.254 kg	0.010 kg	0.331 kg		0.008 kg	41.2 kg
CaO	0.003 kg	0.000 kg	0.007 kg		0.000 kg	0.5 kg
NaNO2						
NaNO3						
Miscellaneous	0.018 kg	0.001 kg	0.017 kg	0.000 kg	0.002 kg	2.9 kg
UO2(NO3)2	0.063 kg	0.151 kg	0.060 kg	0.199 kg	0.096 kg	17.7 kg
Pu	*0.028 Ci*	*0.076 Ci*	*0.012 Ci*	*0.072 Ci*	*0.063 Ci*	*8.3 Ci*
Am	*0.011 Ci*	*0.032 Ci*	*0.009 Ci*	*0.027 Ci*	*0.020 Ci*	*3.3 Ci*
Cs	*0.180 Ci*	*0.511 Ci*	*0.095 Ci*	*1.852 Ci*	*0.555 Ci*	*71.2 Ci*
Sr	*0.097 Ci*	*0.195 Ci*	*0.046 Ci*	*0.510 Ci*	*0.212 Ci*	*29.4 Ci*
PCB	*0.000 g*	*0.000 g*			*0.000 g*	*0.009 g*
SOLIDS + RESINS						
Volume	*0.021 m3*	*0.003 m3*	*0.046 m3*	*0.002 m3*	*0.002 m3*	*3.7 m3*
Density	*2.183*	*3.787*	*2.211*	*5.386*	*2.236*	*2.287*
Total Mass Solids + Resins	**45.710 kg**	**10.874 kg**	**101.795 kg**	**12.141 kg**	**5.274 kg**	**8,323.2 kg**
Wt% solids	*4.23 wt%*	*4.18 wt%*	*4.23 wt%*	*4.17 wt%*	*4.20 wt%*	*4.23 wt%*
Al(NO3)3						
Al(OH)3	0.017 kg	0.132 kg			0.171 kg	9.5 kg
Al2O3	0.557 kg		0.414 kg			86.1 kg
Fe(NO3)3						
FeOOH	0.514 kg	0.083 kg	0.274 kg		0.142 kg	83.4 kg
C	0.175 kg	0.178 kg	0.077 kg		0.124 kg	33.6 kg
CaO	0.183 kg	0.012 kg	0.163 kg		0.008 kg	29.0 kg
Na2C2O4						
CO2						
H2O						
SiO2	41.378 kg	6.396 kg	100.828 kg		4.723 kg	7,433.5 kg
Grout						
Miscellaneous	0.101 kg	0.013 kg	0.038 kg	0.008 kg	0.098 kg	17.7 kg
Zircaloy		3.985 kg		9.548 kg		194.9 kg
Grafoil				2.573 kg		26.3 kg
HNO3						
H2C2O4						
Na2U2O7						
U	0.000 kg	0.005 kg	0.000 kg	0.012 kg	0.000 kg	0.2 kg
U3O7	0.001 kg	0.002 kg	0.000 kg		0.002 kg	0.2 kg
UH3	0.000 kg	0.000 kg			0.001 kg	0.0 kg
UO2	0.001 kg	0.003 kg	0.000 kg		0.006 kg	0.3 kg
UO2(NO3)2						
UO4-4H2O	0.000 kg				0.000 kg	0.0 kg
Pu	*0.001 Ci*	*0.006 Ci*	*0.001 Ci*	*0.008 Ci*	*0.007 Ci*	*0.5 Ci*
Am	*0.000 Ci*	*0.001 Ci*	*0.000 Ci*	*0.001 Ci*	*0.001 Ci*	*0.1 Ci*
Cs	*0.044 Ci*	*0.199 Ci*	*0.014 Ci*	*0.707 Ci*	*0.237 Ci*	*24.0 Ci*
Sr	*0.004 Ci*	*0.020 Ci*	*0.001 Ci*	*0.049 Ci*	*0.029 Ci*	*2.2 Ci*
PCB	*8.095 g*	*0.017 g*			*0.179 g*	*1,187.449 g*
RESINS						
Zeolite	2.389 kg					349.1 kg
OIER	0.394 kg	0.066 kg				59.2 kg
Pu	*0.003 Ci*	*0.003 Ci*				*0.434 Ci*
Am	*0.001 Ci*	*0.001 Ci*	*0.000 Ci*			*0.109 Ci*
Cs	*0.003 Ci*	*0.000 Ci*				*0.392 Ci*
TOTAL ACTIVITIES						
Total U	0.039 kg	0.100 kg	0.037 kg	0.132 kg	0.066 kg	11.4 kg
Total Pu	0.032 Ci	0.085 Ci	0.013 Ci	0.080 Ci	0.070 Ci	9.2 Ci
Total Am	0.012 Ci	0.033 Ci	0.009 Ci	0.028 Ci	0.021 Ci	3.4 Ci
TRU	**0.044 Ci**	**0.119 Ci**	**0.022 Ci**	**0.108 Ci**	**0.091 Ci**	**12.7 Ci**
Total Cs	0.227 Ci	0.711 Ci	0.109 Ci	2.559 Ci	0.792 Ci	95.6 Ci
Total Sr	0.100 Ci	0.215 Ci	0.047 Ci	0.559 Ci	0.241 Ci	31.5 Ci
Beta Gamma	**0.327 Ci**	**0.925 Ci**	**0.156 Ci**	**3.118 Ci**	**1.033 Ci**	**127.1 Ci**
CONCENTRATION						
PCB in liquid	0.06 ppb	0.06 ppb			0.06 ppb	0.05 ppb
PCB in solids	177.099 ppm	1.551 ppm			33.999 ppm	142.667 ppm
Solids	49.99 g/l	49.79 g/l	50.00 g/l	49.77 g/l	49.59 g/l	49.97 g/l
U	0.000 g/cm3	0.000 g/cm3	0.000 g/cm3	0.001 g/cm3	0.001 g/cm3	0.000 g/cm3
Pu total	**0.035 Ci/m3**	**0.391 Ci/m3**	**0.006 Ci/m3**	**0.328 Ci/m3**	**0.662 Ci/m3**	**0.055 Ci/m3**
238 Pu	0.007 Ci/m3	0.078 Ci/m3	0.001 Ci/m3	0.066 Ci/m3	0.132 Ci/m3	0.011 Ci/m3
239 Pu	0.014 Ci/m3	0.156 Ci/m3	0.003 Ci/m3	0.131 Ci/m3	0.265 Ci/m3	0.022 Ci/m3
240 Pu	0.014 Ci/m3	0.156 Ci/m3	0.003 Ci/m3	0.131 Ci/m3	0.265 Ci/m3	0.022 Ci/m3
Am	0.013 Ci/m3	0.153 Ci/m3	0.004 Ci/m3	0.113 Ci/m3	0.197 Ci/m3	0.021 Ci/m3
TRU	0.048 Ci/m3	0.544 Ci/m3	0.011 Ci/m3	0.441 Ci/m3	0.858 Ci/m3	0.076 Ci/m3
TRU	**41 nCi/g**	**457 nCi/g**	**9 nCi/g**	**369 nCi/g**	**726 nCi/g**	**64 nCi/g**
Beta Gamma	**0.357 Ci/m3**	**4.237 Ci/m3**	**0.077 Ci/m3**	**12.781 Ci/m3**	**9.718 Ci/m3**	**0.763 Ci/m3**

COMPOSITION OF THE RESIN LEACHING SOLUTION

	COMPOSITION OF A DAILY BATCH FOR					COMPOSITION OF TOTAL STREAMS
	KE1	KE2	KW1	KW2	KW3	
# OF BATCHES	146.1	24.4	11.2	10.2	22.4	
Volume	***0.161 m3***	***0.025 m3***	***0.005 m3***	***0.045 m3***	***0.005 m3***	***24.8 m3***
Density	***1.084***	***1.095***	***1.120***	***1.091***	***1.122***	***1.085***
Total Mass	**174.699 kg**	**26.990 kg**	**5.376 kg**	**49.616 kg**	**5.385 kg**	**26,877.5 kg**
LIQUID						
Volume	***0.153 m3***	***0.024 m3***	***0.005 m3***	***0.043 m3***	***0.005 m3***	***23.5 m3***
Density	***1.074***	***1.082***	***1.095***	***1.078***	***1.116***	***1.075***
Total Mass Liquid + Gaz	**164.142 kg**	**25.618 kg**	**5.151 kg**	**46.851 kg**	**5.350 kg**	**25,269.6 kg**
H2O	141.900 kg	21.800 kg	4.254 kg	40.230 kg	4.212 kg	21,822.8 kg
HNO3	20.300 kg	3.100 kg	0.605 kg	5.720 kg	0.605 kg	3,121.1 kg
H2C2O4	1.500 kg	0.250 kg	0.050 kg	0.460 kg	0.050 kg	231.7 kg
HF						
NaOH						
Al(NO3)3	0.098 kg	0.069 kg	0.066 kg		0.089 kg	18.7 kg
AlF3						
Fe(NO3)3	0.267 kg	0.043 kg	0.142 kg		0.074 kg	43.3 kg
CaO	0.003 kg	0.000 kg	0.003 kg		0.000 kg	0.5 kg
NaNO2						
NaNO3						
Miscellaneous	0.019 kg	0.002 kg	0.007 kg	0.001 kg	0.019 kg	3.4 kg
UO2(NO3)2	0.055 kg	0.353 kg	0.024 kg	0.440 kg	0.302 kg	28.2 kg
Pu	*0.009 Ci*	*0.041 Ci*	*0.004 Ci*	*0.048 Ci*	*0.046 Ci*	*3.9 Ci*
Am	*0.008 Ci*	*0.039 Ci*	*0.003 Ci*	*0.033 Ci*	*0.030 Ci*	*3.2 Ci*
Cs	*0.668 Ci*	*0.337 Ci*	*0.016 Ci*	*0.833 Ci*	*0.279 Ci*	*120.8 Ci*
Sr	*0.084 Ci*	*0.456 Ci*	*0.019 Ci*	*1.125 Ci*	*0.669 Ci*	*50.2 Ci*
PCB						
SOLIDS + RESINS						
Volume	***0.008 m3***	***0.001 m3***	***0.000 m3***	***0.002 m3***	***0.000 m3***	***1.3 m3***
Density	***1.262***	***1.429***	***2.284***	***1.378***	***6.220***	***1.271***
Total Mass Solids + Resins	**10.557 kg**	**1.372 kg**	**0.224 kg**	**2.764 kg**	**0.036 kg**	**1,607.9 kg**
Wt% solids	***6.04 wt%***	***5.08 wt%***	***4.17 wt%***	***5.57 wt%***	***0.66 wt%***	***5.98 wt%***
Al(NO3)3						
Al(OH)3	0.000 kg	0.003 kg			0.004 kg	0.2 kg
Al2O3	0.002 kg		0.002 kg			0.4 kg
Fe(NO3)3						
FeOOH	0.011 kg	0.002 kg	0.006 kg		0.003 kg	1.8 kg
C	0.000 kg	0.000 kg	0.000 kg		0.000 kg	0.1 kg
CaO	0.001 kg	0.000 kg	0.001 kg		0.000 kg	0.1 kg
Na2C2O4						
CO2						
H2O						
SiO2	0.088 kg	0.014 kg	0.214 kg		0.010 kg	15.8 kg
Grout						
Miscellaneous	0.002 kg	0.000 kg	0.001 kg	0.000 kg	0.002 kg	0.4 kg
Zircaloy		0.008 kg		0.020 kg		0.4 kg
Grafoil				2.723 kg		27.8 kg
HNO3						
H2C2O4						
Na2U2O7						
U	0.000 kg	0.009 kg	0.000 kg	0.022 kg	0.000 kg	0.5 kg
U3O7	0.001 kg	0.003 kg	0.001 kg		0.005 kg	0.4 kg
UH3	0.000 kg	0.001 kg			0.001 kg	0.0 kg
UO2	0.002 kg	0.006 kg	0.001 kg		0.010 kg	0.6 kg
UO2(NO3)2						
UO4-4H2O	0.000 kg				0.000 kg	0.0 kg
Pu	*0.000 Ci*	*0.001 Ci*	*0.000 Ci*	*0.001 Ci*	*0.001 Ci*	*0.1 Ci*
Am	*0.001 Ci*	*0.008 Ci*	*0.001 Ci*	*0.007 Ci*	*0.006 Ci*	*0.6 Ci*
Cs	*0.045 Ci*	*0.205 Ci*	*0.014 Ci*	*0.729 Ci*	*0.245 Ci*	*24.7 Ci*
Sr	*0.007 Ci*	*0.037 Ci*	*0.002 Ci*	*0.091 Ci*	*0.054 Ci*	*4.1 Ci*
PCB	*2.057 g*	*0.001 g*			*0.001 g*	*300.694 g*
RESINS						
Zeolite	2.527 kg					369.4 kg
OIER	7.922 kg	1.326 kg				1,190.2 kg
Pu	*0.001 Ci*	*0.000 Ci*				*0.077 Ci*
Am	*0.001 Ci*	*0.000 Ci*				*0.159 Ci*
Cs	*0.525 Ci*	*0.088 Ci*				*78.836 Ci*
TOTAL ACTIVITIES						
Total U	0.036 kg	0.231 kg	0.016 kg	0.287 kg	0.197 kg	18.4 kg
Total Pu	0.010 Ci	0.041 Ci	0.004 Ci	0.049 Ci	0.047 Ci	4.0 Ci
Total Am	0.011 Ci	0.048 Ci	0.004 Ci	0.040 Ci	0.037 Ci	4.0 Ci
TRU	**0.020 Ci**	**0.089 Ci**	**0.007 Ci**	**0.089 Ci**	**0.083 Ci**	**8.0 Ci**
Total Cs	1.238 Ci	0.631 Ci	0.031 Ci	1.562 Ci	0.524 Ci	224.3 Ci
Total Sr	0.091 Ci	0.493 Ci	0.020 Ci	1.216 Ci	0.723 Ci	54.2 Ci
Beta Gamma	**1.329 Ci**	**1.124 Ci**	**0.051 Ci**	**2.778 Ci**	**1.247 Ci**	**278.6 Ci**
CONCENTRATION						
PCB in liquid						
PCB in solids	194.860 ppm	0.726 ppm			37.566 ppm	187.008 ppm
Solids	65.51 g/l	55.66 g/l	46.72 g/l	60.77 g/l	7.43 g/l	64.89 g/l
U	0.000 g/cm3	0.009 g/cm3	0.003 g/cm3	0.008 g/cm3	0.041 g/cm3	0.001 g/cm3
Pu total	**0.060 Ci/m3**	**1.680 Ci/m3**	**0.771 Ci/m3**	**1.072 Ci/m3**	**9.694 Ci/m3**	**0.162 Ci/m3**
238 Pu	0.012 Ci/m3	0.336 Ci/m3	0.154 Ci/m3	0.214 Ci/m3	1.939 Ci/m3	0.032 Ci/m3
239 Pu	0.024 Ci/m3	0.672 Ci/m3	0.308 Ci/m3	0.429 Ci/m3	3.877 Ci/m3	0.065 Ci/m3
240 Pu	0.024 Ci/m3	0.672 Ci/m3	0.308 Ci/m3	0.429 Ci/m3	3.877 Ci/m3	0.065 Ci/m3
Am	0.066 Ci/m3	1.941 Ci/m3	0.731 Ci/m3	0.874 Ci/m3	7.659 Ci/m3	0.162 Ci/m3
TRU	0.127 Ci/m3	3.621 Ci/m3	1.502 Ci/m3	1.946 Ci/m3	17.353 Ci/m3	0.323 Ci/m3
TRU	**117 nCi/g**	**3 306 nCi/g**	**1 342 nCi/g**	**1 784 nCi/g**	**15 464 nCi/g**	**298 nCi/g**
Beta Gamma	**8.245 Ci/m3**	**45.608 Ci/m3**	**10.614 Ci/m3**	**61.078 Ci/m3**	**259.900 Ci/m3**	**11.242 Ci/m3**

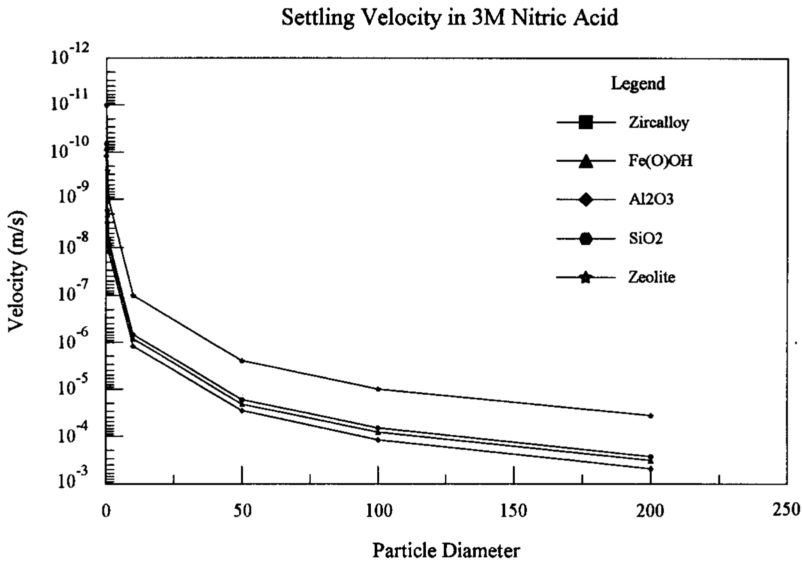
Appendix B

Settling

Table B-1 gives Stoke's settling velocities for the primary compounds that are assumed not to undergo dissolution in the acid digester. In calculating the Stoke's velocities, a shape factor of 0.85 was assumed due to the probability of surface modification by the nitric acid from any present sphericity. Figure B-1 is a graphical representation of Table B-1.

Table B-1 Stoke's Settling Velocities (m/s)

Particle Diameter (μm)	Zircalloy ρ=6511 Kg/m^3	Fe(O)OH ρ=3000 Kg/m^3	Al_2O_3 ρ=3970 Kg/m^3	SiO_2 ρ=2640 Kg/m^3	Zeolite ρ=1400 Kg/m^3
0.1	2.4E-10	8.3E-11	1.2E-10	6.7E-11	1E-11
0.5	6.1E-09	2.1E-09	3E-09	1.7E-09	2.5E-10
1.0	2.4E-08	8.3E-09	1.2E-08	6.7E-09	1E-09
10.0	2.4E-06	8.3E-07	1.2E-06	6.7E-07	1E-07
50.0	6.1E-05	2.1E-05	2.9E-05	1.7E-05	2.5E-06
100.0	2.4E-04	8.3E-05	1.2E-04	6.7E-05	1.0E-05
200.0	9.7E-04	3.3E-04	4.8E-04	2.7E-04	3.7E-05



Settling Velocity in 3M Nitric Acid
Legend
Zircalloy
Fe(O)OH
Al2O3
SiO2
Zeolite
Velocity (m/s)
10-12
10-11
10-10
10-9
10-8
10-7
10-6
10-5
10-4
10-3
0
50
100
150
200
250
Particle Diameter

Figure B-1

Table B-2
Settling Time (Hours) versus 0.1 m depths

Depth (m) from Bottom	Particle Size 0.1	0.5	1.0	10	50	100	200
0.1	7.75E+05	3.09E+04	7.75E+03	7.75E+01	3.10E+00	7.75E-01	2.05E-01
0.2	1.55E+06	6.18E+04	1.55E+04	1.55E+02	6.19E+00	1.55E+00	4.10E-01
0.3	2.32E+06	9.27E+04	2.32E+04	2.32E+02	9.29E+00	2.32E+00	6.15E-01
0.4	3.10E+06	1.24E+05	3.10E+04	3.10E+02	1.24E+01	3.10E+00	8.19E-01
0.5	3.87E+06	1.54E+05	3.87E+04	3.87E+02	1.55E+01	3.87E+00	1.02E+00
0.6	4.65E+06	1.85E+05	4.65E+04	4.65E+02	1.86E+01	4.65E+00	1.23E+00
0.7	5.42E+06	2.16E+05	5.42E+04	5.42E+02	2.17E+01	5.42E+00	1.43E+00
0.8	6.20E+06	2.47E+05	6.20E+04	6.20E+02	2.48E+01	6.20E+00	1.64E+00
0.9	6.97E+06	2.78E+05	6.97E+04	6.97E+02	2.79E+01	6.97E+00	1.84E+00
1.0	7.75E+06	3.09E+05	7.75E+04	7.75E+02	3.10E+01	7.75E+00	2.05E+00

Appendix C

Robatel Centrifuge Data

DPC 800

1) Process Description

The suspension to be clarified is fed in the centrifuge rotary bowel at a high speed. The solid particles are then literally thrown against the bowl wall by centrifugal force and the clarified liquid is discharged by overflow.

Once a certain quantity is reached in the bowl, the solids are discharged by a liquid fed under high pressure. The solids are evacuated through holes at the bottom of the bowl.

2) DPC 800 Description

Figure DPC800 is a schematic cutaway of a DPC800. The DPC 800 can be divided into three main parts:

- the active zone in which the radioactive liquids are processed,
- the support slab ensuring the shielding,
- the mechanical zone where the motor, bearing, sensors and switches are located.

2.1) Active Zone

The active zone comprises the following main components (refer to **Figure DPC800**).

1: the static vessel mounted on the slab.

2: the rotating bowel.

3: the liquid inlet.

4: the liquid feeding vessel.

5: the liquid feeding tube.

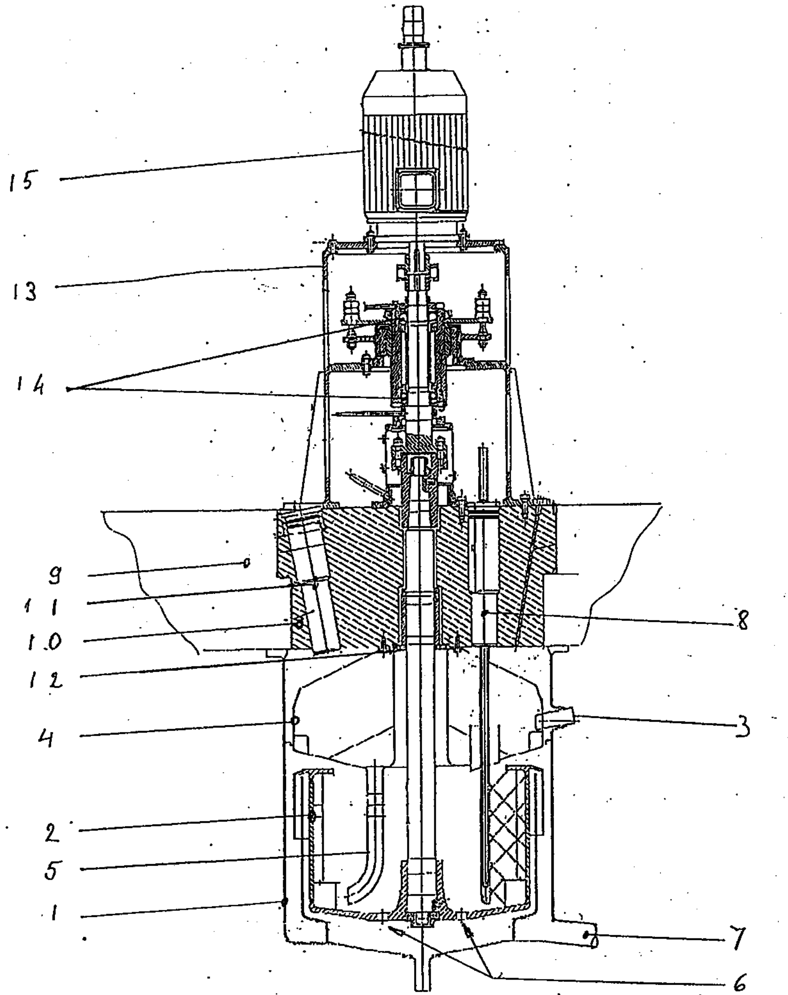
6: the cake evacuation hole.

7: the clarified liquid outlet.

8: high pressure tube for the solid cake discharge.

2.2) Support Slab

Figure C-1 DPC 800



9: the slab insuring the shielding protection.

10: the removable plug on which are mounted all the parts subjected to maintenance.

11: two plugs allowing the introduction of maintenance devices (camera, deplugging device, etc..)

12: seal

2.3) Mechanical Zone

The mechanical zone is protected from the active zone by the support shielding slab. The operators have a direct access for maintenance on the mechanical parts.

13: the frame mounted on the slab plug.

14: the bearings.

15: the motor.

DPC 900

1) Process Description

The DPC 900 clarification process is the same as for the DPC 800. The improvement is the solid cake discharge system: Once a certain mass is reached in the bowel, the solids are discharged at the bottom of the bowel by a liquid fed under high pressure. As the bowel is rotating at a low speed, an auger homogenizes the solid in order to avoid the agglomeration of particles which can plug the pipes. The solids are evacuated by means of a siphon.

2) DPC 900 Description

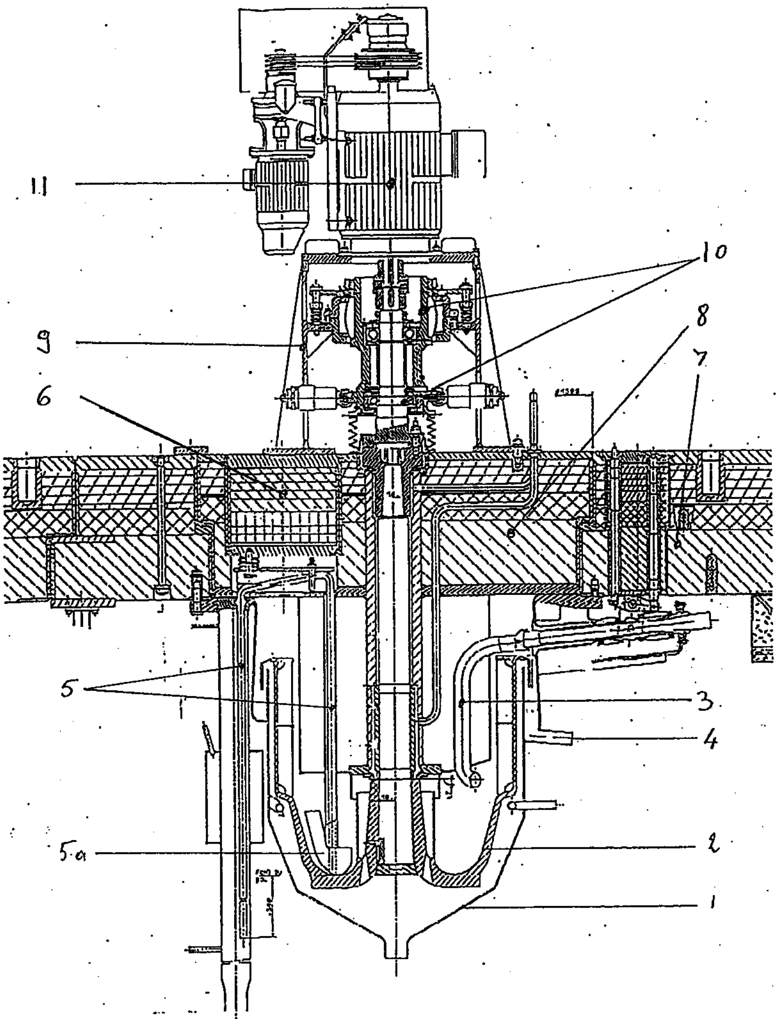
Refer to **FIGURE DPC900**. In order to simplify the maintenance, the DPC 900 can be divided into three main parts (identical to the DPC 800 design):

- The active zone.
- The support/shielding slab.
- The mechanical zone.

2.1) Active Zone (Refer to **FIGURE DPC900)**

1: the static vessel mounted on the slab

Figure C-2 DPC 900



2: the rotating bowel

3: liquid inlet

4: clarified liquid outlet

5: two siphons (only one is shown)
two high pressure tubes (not shown)

5a: auger mounted on the siphon

2.2) Support Slab

6: four plugs each equipped with a siphon or a tube

7: the slab insuring the shielding protection

8: the removable plug on which are mounted all the parts subject to maintenance

2.3) Mechanical Zone:

9: the frame mounted on the plug

10: the bearings

11: the motor

Specifications for DPC 800 and DPC 900

	DPC 800	DPC 900
Separation	Batch	Batch
G effect	1790	2010
Theoretical Equivalent Surface	1785 m^2	2460 m^2
Bowl volume	83 L	83 L
Stay time @ 1000 L/h	300 seconds	300 seconds
Height of the liquid ring	75 mm	62.5 mm
Cake weight by Cycle	34 Kg	34 Kg
Feed Time @ 1000 L/h with 100 g/L of solids	20 sec	20 sec
Accelerating Time	1 sec	1 sec
Decelerating Time	1 sec	1 sec
Cycle Time	1 sec	1 sec
Flow (average)	870 L/h	870 L/h

Robatel Centrifuge Efficiency

For all the 3 types of centrifuge the efficiency for particle size above 5 µm is 100%. Some tests with SiO_2 particulates (similar to the K Basin sludge) were performed in France on the DPC 900. The results for the nominal flow (650 L/h) are:

Particle Size	Efficiency
1.3 to 1.6 µm	82 to 91 %
1.6 to 2 µm	93 to 97%
2 to 10 µm	> 99%

For a flow at 1000 L/h, the efficiency for the particle size between 1.3 and 2 µm decreases significantly. Nevertheless, for the particle size above 2 µm, the efficiency remains above 99%.

Equipment in Nuclear Facilities

France:

La Hague, UP2-400	1 DPC 800 (no bowel replacement or mechanical problems for 20 years)
La Hague, UP3	2 DPC 900 (the DPC 900 models have been in operation for 8 plus years without mechanical problems)
La Hague, UP2-800	2 DPC 900
Marcoule	1 DPC 900

Japan:

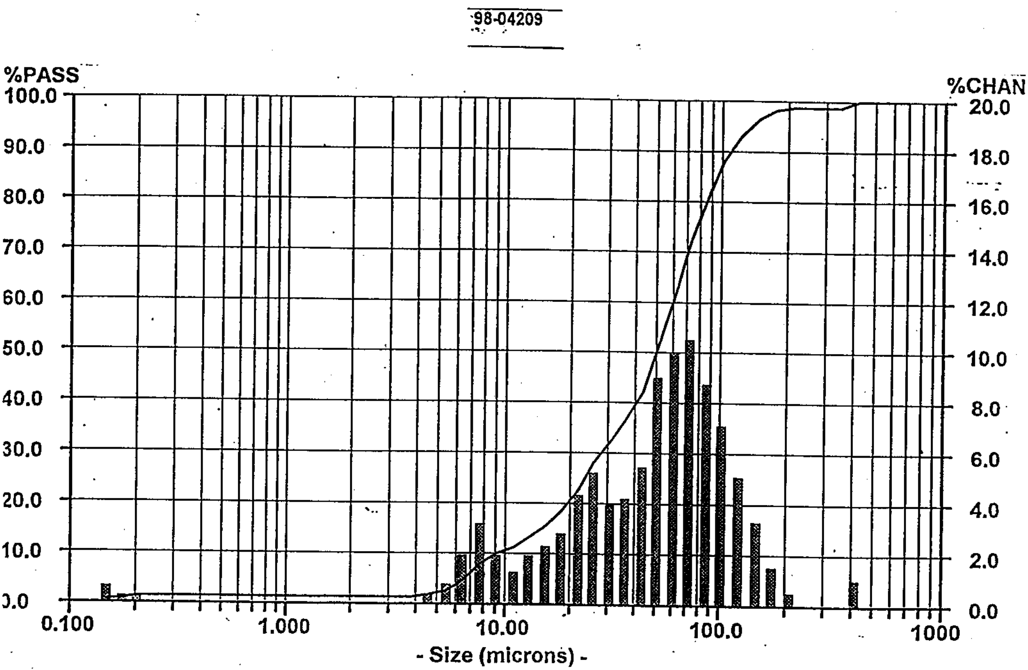
Rokkasho-Mura	2 DPC 900

England:

Thorp	3 DPC 800

Appendix D

Particle Size Distribution After the Acid Digester



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