Remediation of low-level mixed waste: cellulose-based materials and plutonium

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Abstract

Low-level mixed radioactive wastes containing cellulose-based materials and plutonium have been generated during various nuclear processing activities. Biological digestion of the organic- or cellulose- based material was examined as an environmentally acceptable and effective method of treatment for these and other similar wastes. Cellulase enzyme was used to initiate biodegradation prior to 90% destruction of the cellulose material by a sewage sludge consortium. Plutonium did not significantly effect the biodegradation. Bench-scale experimental data were used to design a batch treatment system. A cost and sensitivity analysis was performed to determine the optimal reactor size, materials of construction and media type. The sensitivity analysis indicated that while a 12-month treatment scenario using a carbon steel ball mill, sludge digester and vacuum thickener was the least expensive scenario evaluated on a levelized cost basis ($800 per ton of waste degraded per month), the 12-month scenario using stainless steel construction and the alternative dewatering system offered the most cost-effective treatment alternative and better corrosion resistance (levelized cost of $1130 per ton per month). The dewatering system consisting of a disk centrifuge and sludge dryer is capable of doubling the sludge solids content and produce an overall waste reduction of 67%. The proposed waste treatment system offers a cost savings of up to 31% compared to conventional disposal practices.

Keywords: Radioactive waste; Biodegradation; Cheese cloth; Remediation cost analysis; Plutonium; Cellulose-based material

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1. Introduction

The Department of Energy complex including the Rocky Flats Plant, Hanford, Savannah River, Pantex, Argonne National Laboratory, Los Alamos National Laboratory, and Idaho National Engineering Laboratory have generated large quantities of mixed hazardous wastes during nuclear materials processing, and research and development activities. These wastes, which contain both hazardous and radioactive constituents, are commonly referred to as legacy wastes. One specific legacy waste includes cheesecloth rags and tissue paper wipes, contaminated with trace quantities of radioactive metals and acidic cleaning solutions, that were used to clean glove boxes and decontaminate equipment. These wastes are classified as low-level mixed wastes (LLMW) as they contain less than 100 nCi of radioactive materials per gram of waste. Contaminated laboratory coats and aprons are also disposed of as low-level, mixed hazardous wastes. LLMW are currently stored in 55 gal drums at each facility awaiting disposal.

Incineration technologies were previously utilized to reduce the volume of LLMW at each site. However, this practice is generally no longer accepted by the public. Other common treatment/disposal methods include laundering and chemical oxidation. Unfortunately these processes produce large volumes of radioactive liquid wastes requiring treatment. Biodegradation has been identified as an environmentally benign, publicly acceptable solution that is capable of destroying the cellulose-based material and minimizing the final solid waste stream, while generating a liquid waste that can be either recycled to the process or used in other closed-loop systems. The entire process is accomplished without significant risk of releasing radioactive contaminants into the environment.

While biodegradation of cellulose and other bulky fibrous materials has been studied for many years, no research has been performed on the degradation of mixed hazardous wastes or the effect of plutonium on the biological degradation process. Early studies, conducted in the 1950s, focused on understanding the degradation of military tents and clothing by fungi. Work then continued during the 1970s when cellulose was examined as a potential replacement for petroleum fuel products [1]. In particular, anaerobic biodegradation of cheesecloth to produce methane has been evaluated. An isolate belonging to the *Bacteroidaceae* species was shown to solubilize 65% of a 5 g l^{-1} cheesecloth suspension in 6 days [2]. Further work in this area showed that *Bacteroides cellulosolvens* can solubilize 73% of a 5 g l^{-1} cheesecloth suspension in 2 days [3].

In addition to microbial degradation processes, scientists have studied the cheesecloth degradation pathways via enzymatic hydrolysis. The enzymatic hydrolysis of cellulose is a complex process involving four synergistic enzymes, endo-1,4-β-D-glucanases, exocellubiohydrolases, b-D-glucosidases, and *exo*-1,4β-D-glucosidases. The kinetics of cellulose degradation and the types of cellulase enzymes have been recently reviewed [4]. One of the primary cellulase enzymes, *endo*-1,4-[1,3:1,4]β-D-glucan-4-glucano-hydrolase, is isolated from *Penicillium funiculosum*. This enzyme hydrolyzes cellulose chains at random and liberates glucose from cellulose. Most metal ions inhibit cell-free extract enzyme activity. For example, 50 mM concentrations of copper and manganese ions

have been shown to inhibit cellulase activity [5]. However, little or no research has been conducted to evaluate the effect of radioactive metals including plutonium on cellulose hydrolysis. Thus, this research examined the effects of plutonium on cellulose hydrolysis to determine whether biodegradation in the presence of plutonium is a realistic remediation option.

2. Objectives

The goal of this paper is to evaluate the economic feasibility of degrading large quantities of low-level mixed wastes consisting of cellulose-based materials contaminated with trace quantities of plutonium in a biodegradation system, and to design a process based on the bench-scale experimental results. The components of the full-scale process are waste-feed processing, a degradation reactor, and sludge dewatering. Alternative media sources, materials of construction, and dewatering systems were also assessed. All costs were evaluated on a levelized monthly cost and present worth basis to determine the most economical process scenario. The optimal system design should be capable of significantly reducing the total waste volume requiring disposal at a treatment cost less than the cost of disposing the original wastes. Ideally, the degradation system should be capable of treating a wide variety of waste streams without producing additional legacy wastes requiring treatment or disposal.

3. Bench scale experiments

3.1. Materials and methods

3.1.1. Microorganisms

Two known cellulose-degrading bacterial strains (ATCC 33331, *Streptomyces flavogriseus*; and ATCC 35603, *Bacteriodes cellulosolvens*) and microorganisms from sewage sludge obtained from the Los Alamos waste treatment facility were tested for their ability to degrade cheesecloth. The sewage sludge microorganisms were obtained by placing 2 g of activated sewage sludge in 200 ml of AM-1 minimal salts medium (0.2 g of $(NH_4)_2SO_4$, 1.6 g of NH_4Cl, 3.0 g of Na_2HPO_4, 2.72 g of KH_2PO_4, 98 mg of $MgSO_4$, 70 mg of $CuSO_4$, 35 mg of $MnSO_4 \cdot H_2O$, 24 mg of $ZnCl_2$, 1 mg of $CaCl_2$, 18 mg of $CoCl_2$, 7 mg of H_3BO_4, 60 mg of $(NH_4)_6Mo_7O_{24}$, 6 mg of $FeSO_4$, and 600 mg of citric acid in 1 l of distilled water) containing 0.5% yeast extract. Glycerol freezer stocks were made from a culture grown aerobically overnight. No further purification or manipulation of the culture was attempted. One freezer stock was used as inoculum for all experiments performed with sewage sludge microorganisms.

3.1.2. Degradation of cheesecloth with cellulase

Flasks containing 200 ml of AM-1 medium, 1 g of cheesecloth and 0.1 g of cellulase (Sigma Chemical Company) were used for these experiments. The cheesecloth was cut

into 1 in squares. Solutions were maintained at a constant pH of 5.0 using NaOH. Samples were taken from the flasks every 30 min for the first 3 h and then every 24 h for the remaining test period, using aseptic techniques. A phenol/H_2SO_4 reduced sugar assay was performed using the method of Khan et al. [2]. Briefly, 50 μl of an 80% phenol solution was added to a 2 ml liquid sample. A 5 ml portion of concentrated H_2SO_4 was then added rapidly. The mixture was shaken and allowed to react at room temperature for 10 min. The absorbance of the solution was measured at 480 nm on a Hewlett Packard spectrophotometer. The amount of reduced sugars produced by hydrolysis was then determined by comparing the adsorbance measurements to glucose standards in AM-1 medium with cellulase.

3.1.3. Degradation of cheesecloth with cellulase and microorganisms

AM-1 medium (200 ml), 10 g of cheesecloth, and 0.1 g of cellulase were added to 1 l flasks. The cheesecloth was cut into 1 in squares. Bacteria were added after 24 h. Three cultures were evaluated independently for their ability to degrade cheesecloth. ATCC 33331 and the sewage sludge consortium were grown aerobically, while ATCC 35603 was grown microaerophilically. To obtain microaerophilic conditions, flasks were flushed with nitrogen gas for 2 min and closed with a stopper. The culture was maintained at a pH of 7.0 and room temperature. The amount of cheesecloth degraded was determined by the filtration of cells and culture fluids through a 2 μm Whatman filter. Undegraded cellulose remained bound to the filter. The majority of the cells were in the filtrate. Control experiments without cellulase or microorganisms were also performed.

3.1.4. Cheesecloth degradation in the presence of plutonium

Two batch plutonium experiments were performed in a glove box to determine the effect of radioactivity on cheesecloth degradation. In the first experiment, 3 l of AM-1 medium, 10 g of cellulase, and approximately 600 g of cheesecloth rags contaminated with 42 g of plutonium were added to a 5 l flask. Approximately 1100 g of cheesecloth containing 66 g of plutonium were used in the second experiment. Both flasks were placed on magnetic stir plates and continuously mixed. After 2 weeks, the flasks were inoculated with mixed bacterial cultures obtained from activated sewage sludge. The pH was monitored and maintained at 7.0. After 1.5 months, the slurry was filtered through 2 μm Whatman filters to determine the amount of cheesecloth degradation and to determine the fate of the plutonium, for example whether the plutonium was present in the liquid phase, adsorbed to cells, or present as a solid.

3.2. Experimental results

Experiments were first performed to determine the most effective microorganisms for degrading cheesecloth. These screening tests were conducted without radioactive metals present. The microorganisms that demonstrated the highest degradation rates were then used in cheesecloth/plutonium experiments to evaluate what effect (if any) radioactive isotopes had on cellulose degradation. The results for both sets of experiments are discussed below.

Table 1
Cheesecloth degradation with micro-organisms

Bacteria inoculum	Percent degradation after 1 week	Percent degradation after 3 weeks
ATCC 33331	0	0
ATCC 35603	0	1
Sewage sludge	0	10

3.2.1. Cheesecloth degradation

Three separate cultures, two ATCC strains previously isolated for their high cellulase production and a consortium from activated sewage sludge, were evaluated individually for their ability to utilize cheesecloth as the sole carbon source. The results are shown in Table 1. Significant cheesecloth degradation was not observed for the ATCC strains after 3 weeks of incubation, and only a small amount of degradation was observed using the sewage sludge consortium. Because of these poor biodegradation activities, we attempted to accelerate the process by supplementing with cellulase enzyme. Cellulase hydrolyzes cellulose or cheesecloth first to cellobiose and then to glucose. Quantification of the cellulase to initiate the destruction is shown in Fig. 1. The extent of reaction is measured by the amount of reduced sugar, primarily glucose, that formed. Since the substrate (cheesecloth) concentration is high, the enzymatic reaction can be approximated by a zero-order reaction, $C = kt$, for short time periods (less than 10 h). Least squares analysis of the data resulted in a rate constant, k, of 0.0082 ± 0.0002 g 1^{-1} h^{-1}). The rate constant is reported with its 95% confidence interval. Because the cellulase enzyme is relatively expensive, only enough cellulase was added to initiate degradation.
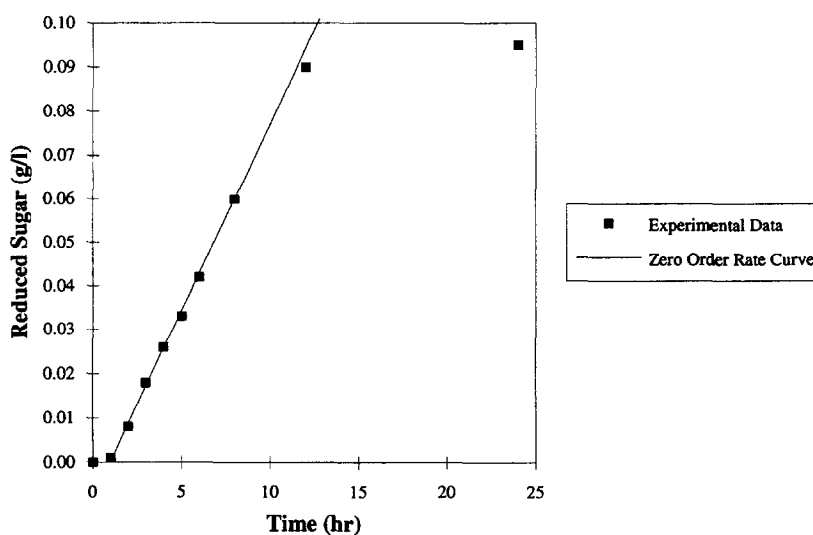

Fig. 1. Formation of reduced sugar from cheesecloth using cellulase enzyme.

The microbial portion of the process was developed to degrade 90% of the cellulose-based materials in the stream. Thus, microorganisms from each of the three sources were tested on the cellulase- pretreated material (Fig. 2). Rapid biodegradation was observed when the sewage sludge microorganisms were used while slower rates were accomplished with the pure cultures. Substrate degradation for the sewage sludge consortium can be estimated by the first-order equation

$$S = S_0 e^{-kt} \tag{1}$$

where S_0 and S are the initial and final substrate concentrations. The rate constant, k, was found to be 0.16 ± 0.07 days^{-1} at the 95% confidence level.

Based on these experimental results, the biodegradation experiments in the presence of plutonium were carried out using cellulase to initiate degradation followed by biodegradation with the sewage sludge consortium. From Eq. (1), the estimated time for 99% degradation of the cheese cloth is 28 days. However, the effects of plutonium on the degradation rate were unknown; thus the mixed waste experiment was monitored until solid chunks of cheesecloth were no longer visible. The sludge solution was then filtered and analyzed to determine the quantity of remaining cheesecloth and the fate of the plutonium.

3.3. Degradation of cheesecloth contaminated with plutonium

The biodegradation experiments from which these data are drawn were conducted to explore the potential of biodigestion to liquefy a portion of a solid plutonium process waste stream (Table 2). An additional goal of this work was to explore recovery of the
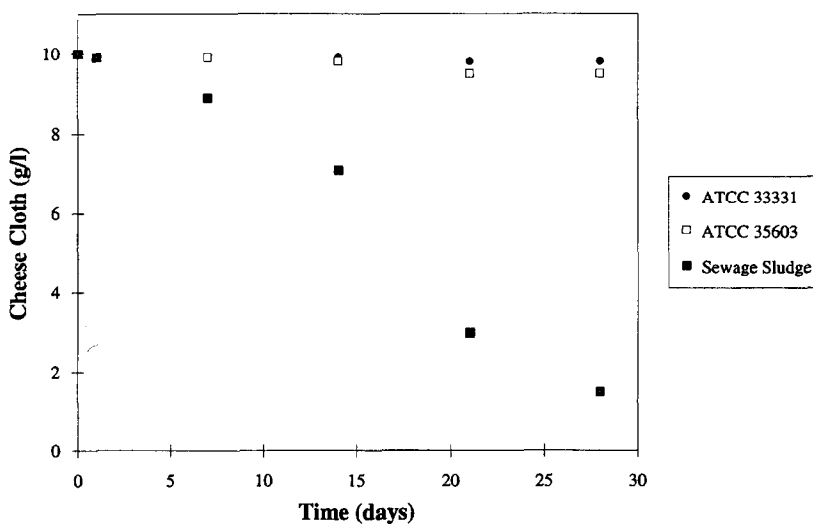

Fig. 2. Biodegradation of cheesecloth pretreated with cellulase enzyme. Comparison between two ATCC strains and a sewage sludge consortium.

Table 2
Cheesecloth biodegradation with plutonium

	Solid phase		Liquid phase	
	Cheesecloth	Pu	Water	Pu
Initial				
Batch 1	0.6 kg	42 g	2.5 kg	0
Batch 2	1.1 kg	66 g	2.5 kg	0
Final				
Batch 1	0.045 kg	41 g	2.2 kg	0.21 g
Batch 2	0.055 kg	65 g	2.2 kg	0.27 g

plutonium. The concentration of plutonium in the process waste material ranged from 6 to 7% by weight. This concentration of plutonium is several orders of magnitude greater than the quantity of radioactive materials allowed in low-level mixed wastes (0.0002 wt.%), and thus provided more stringent test conditions than would be encountered in actual LLMW.

It was not possible to take intermediate samples during the experiment because of facility procedural regulations. Thus, only the initial and final concentrations were analyzed. The results are presented in Table 2. The destruction of the cheesecloth ranged from 92 to 95% in the two experiments. The total quantity of solid waste (plutonium and cheesecloth) was reduced by approximately 88%. The majority of the plutonium was collected on the filter, comprising about half of the solid material collected. It may be possible to recycle this plutonium. Approximately 0.4–0.5% of the plutonium passed through the filter into the filtrate; thus use of a finer filter may retain these smaller plutonium particles, minimizing the need for additional water treatment processes.

Effective biodegradation of cheesecloth was achieved in the presence of plutonium (Table 2). The plutonium utilized in this experiment was weapons-grade plutonium at levels much higher than expected in a typical LLMW waste. However, even these large levels of plutonium did not appear to impact cellulose biodegradation (Fig. 2 and Table 2).

4. Process design and economics

The process design must consider the composition and properties of an actual waste. Because plutonium and uranium are present in the waste, the issue of criticality must be addressed. The composition of an actual LLMW stream is presented in Table 3 [6]. As shown, the mean activity of cellulose-based low-level mixed wastes is several orders of magnitude lower than the 100 nCi g^{-1} limit. Due to the low level of activities present in the mixed wastes, transuranic isotope monitoring and laboratory health and safety guidelines, waste degradation will not result in the accumulation of sufficient fissionable material to reach criticality, thereby eliminating the need for a geometrically favorable reactor design [7].

Table 3
Low-level radioactive waste characterization [a,b]

Isotope	Specific activity (nCi g^{-1})		
	Low	Mean	High
^{239}Pu	2.5×10^{-4}	0.25	99.9
^{241}Am [c]	5×10^{-4}	0.25	99.9
^{238}U [c]	1.6×10^{-3}	0.63	45
^{235}U	8×10^{-5}	9.8×10^{-5}	1.2

[a] Waste description: moist or damp combustible material such as paper towels, wipes and cloth generated from operations performed from either inside or outside of gloveboxes.

[b] Radioactive characteristics: the estimated surface radiation levels for drums are (mean) 0.23 mrem h^{-1} and (range) 0.0–7.2 mrem h^{-1}; and the estimated surface radiation levels for boxes are (mean) 0.34 mrem h^{-1} and (range) 0.0–2.0 mrem h^{-1}. Minor amounts of carbon dioxide may be released due to biological decomposition.

[c] Not fissionable.

4.1. Process design

Bench-scale experimental data were used to size and develop budgetary costs for a full-scale biological reactor to degrade large quantities of cellulose-based materials contaminated with plutonium. The full-scale process comprised a waste-feed preparation system, reaction vessel and activated sludge dewatering system (Fig. 3). Key design
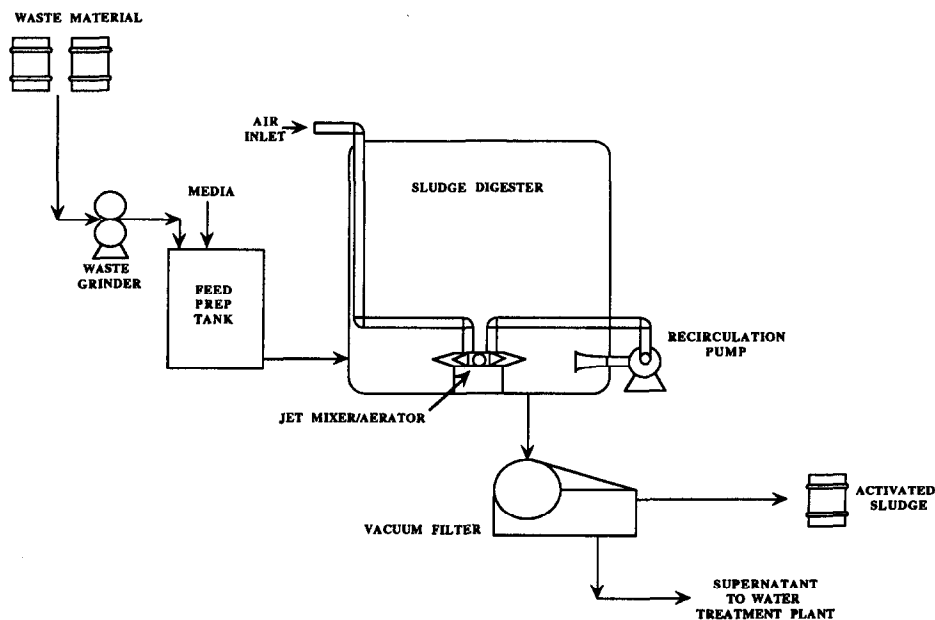

Fig. 3. Schematic of the full-scale cellulose sludge digestor system. Major process components are a grinder to shred wastes, a sludge digestor, and a vacuum filter to dewater wastes.

Table 4
Design inputs

Variable	Value
Waste volume	1300 m^3
Waste specific gravity (S.G.)	1.0
Media	
BOD/N	20:1
BOD/P	100:1
BOD/Fe	200:1
Standard medium	Urea/monoammonium phosphate
Alternative medium	Fish meal
Media S.G.	1.0
Feed solution S.G.	1.0
Feed concentration	11.5 wt.%
Process times	6, 9, 12 months
Reactor hold-up time	30 days
Reactor operation	Batch
Batch processing time	40 h
Waste conversion to CO_2/H_2O	80%
Conversion to cell mass	20%
Oxidation rate	1.3 lb O_2 per 1 lb waste
Waste sludge concentration	30%
Alternative waste sludge concentration	60%
Tank diameter/height ratio	1:1
Excess tankage	10%
Material of construction	Stainless steel
Filter size	6.144 lb per $Ft^2 h$

parameters, including waste volume, reactor retention time and waste conversion to CO_2, are presented in Table 4[8–10]. Economic criteria including media, power and labor costs, and interest rates are presented in Table 5. These criteria were used to develop capital equipment and operating costs for several processing scenarios.

Fig. 3 shows a schematic of the process. First, the fibrous mixed wastes are shredded in a grinder or ball mill to increase the surface area accessible to the microorganisms.

Table 5
Economic inputs

Variable	Value
Power cost	50 mill kWh^{-1}
Media cost	–
Standard	$11.15 per 1000 gal
Fish meal	$92.25 per 1000 gal
Cellulase	$0.1 lb^{-1}
Water	$0.64 per 1000 gal
Labor rate	$25 h^{-1}
Annual interest rate	5%
Salvage value	50% of capital

The waste and microbial nutrients are combined and pumped to the sludge digester. Next, cellulase is added to the digester to pretreat the cellulose followed by inoculation with activated sludge cultures to degrade the bulk of the cellulose. Following the digestion period, the activated sludge slurry is dewatered to produce a dry filter cake. The aqueous phase can be recycled in this process or used in another closed system at the facility.

To treat a volume of approximately 1300 m^3 of low-level mixed waste, a process was designed which would operate for either 6, 9, or 12 months. The waste volume, feed concentration, and processing times were used to calculate reactor volumes of 500 000 gallons, 333 000 gallons, and 250 000 gallons, respectively. Equipment sizing for each scenario is presented in Table 6. To provide the oxygen required by the microorganisms, the digesters were equipped with a unique jet mixer/aerator designed to produce fine gas bubbles and enhance gas–liquid diffusion by pumping high-pressure water through a series of double jet nozzles. The pressure drop across the jets entrains low-pressure air into the water stream to produce bubbles as small as 1 μm. The water jets and rising air bubbles mix the slurry and minimize solids settling. The mixer/aerator consists of a variable speed liquid recirculation pump, low-pressure air blower and jet mixer located in the reaction vessel. The aerator is sized to provide 1.3 lb of air per 1 lb of waste feed.

Table 6
Equipment design

Equipment	Processing scenarios		
	6 Months	9 Months	12 Months
Reaction vessel			
Volume (gal)	500 000	333 000	250 000
Height (ft)	46	40	36
Diameter (ft)	46	40	36
Agitator h.p.	40	20	12
Mixer / aerator			
SCFM	827	552	414
ACFM	995	663	497
Unit h.p.	40	40	40
Vacuum filter dewatering system (to 30% solids)			
Filter area (ft^2)	389	259	194
Unit size (ft^2)	8 × 16	8 × 12	6 × 12
Total h.p.	83	67	460
Alternative dewatering system — disc centrifuge (to 60% solids)			
Disc centrifuge			
Capacity	–	–	2000 gph
Bowl size	–	–	513
H.p.	–	–	40
Dry – Air dryer			
Size	–	–	15 kW

Two potential dewatering systems were considered. Initially, a vacuum filter was selected to dewater the activated sludge slurry from the digester to produce 30% solids in the base-case design scenarios. An alternative dewatering system designed to increase the solids content of the activated sludge to 60% solids was also evaluated for the 12-month processing scenario. The alternative system, a disk centrifuge and a novel Dry-Air sludge dryer, is capable of reducing the total mass of the final product by a factor of two compared to vacuum filtration.

The major equipment components included in the cost estimate are the digester, agitation and aeration equipment, and activated sludge dewatering system. The remaining equipment components (pumps, feed grinder, media tank and associated piping and controls) were estimated as 30% of the larger equipment costs. Equipment costs are presented for both stainless steel and carbon steel construction. Operating costs are given for two different culture media.

4.2. Process economics

The base-case design consists of a sludge digester and vacuum filtration dewatering system constructed from stainless steel; the base-case medium consisted of urea and phosphate. The capital costs for the base-case designs range from $1.3 million to $1.8 million for the 12 month and 6 month scenarios as shown in Table 7. The capital costs were derived from vendor-supplied estimates. Freight and installation costs were estimated at 20% and 2 times the delivered costs, respectively. Miscellaneous equipment and control costs were estimated as 30% of the capital equipment. Engineering and contingency costs were estimated at 20% of the capital equipment. These costs are

Table 7
Cost estimate

Equipment [a]	Processing scenario		
	6 Months	9 Months	12 Months
Reaction vessel [b]	$555 000	$451 000	$396 000
Vacuum filter	$573 000	$532 000	$437 000
Miscellaneous	$339 000	$295 000	$250 000
Foundations	$54 000	$43 000	$37 000
Capital cost	$1 521 000	$1 322 000	$1 120 000
Eng./contin.	$304 000	$264 000	$224 000
Total capital cost	$1 825 000	$1 586 000	$1 344 000
Operating costs (per month)			
Media	$4900	$3270	$2450
Power	$2270	$1710	$1470
Cellulase	$480	$320	$240
Labor	$2000	$2000	$2000
Total	$9650	$7300	$6160

[a] Equipment costs include erection, coatings and freight.
[b] Includes tank, agitation/aeration system.

intended to cover engineering and design costs associated with a more detailed design and to quantify the uncertainty in the design and cost of commercial scale equipment.

Operating costs for the three base-case processing scenarios are also presented in Table 7. Operating costs include media, cellulase, power and labor, which is based on 10 man-hours per week for routine operations and 40 h for batch processing for a total of 80 man-hours per month. As shown in Table 7, media and power costs represent approximately 64–74% of the total operating costs. The monthly operating costs decrease with increasing processing time due to smaller reactor volumes and correspondingly smaller motors.

A levelized cost analysis was performed to determine the equivalent monthly costs for capital and operating expenses. Levelized cost analyses are useful for comparing alternatives with different economic lives. The levelized costs for the three scenarios are presented in Table 8 on a dollars per month and dollars per ton of waste degraded per month basis. As shown in Table 8, the 12 month scenario has the lowest levelized cost of approximately $121 000 per month ($1020 per ton degraded per month). The levelized costs for the shorter processing scenarios were much higher due to the higher capital and operating costs associated with the larger reaction vessels.

The capital and operating costs were also analyzed on a present worth basis. The present worth represents the initial capital required to fund the entire project including all equipment and operating expenses. The present worth of each scenario is also presented in Table 8 with and without a salvage credit (estimated at 50% due to the very short processing times). Including equipment salvage value reduces the present worth by approximately 50%.

The cost estimates presented in Tables 7 and 8 indicate that the 12 month processing scenario is the most cost effective alternative. This is due to the large cost savings (both capital and operating) of operating a smaller reaction vessel. Longer processing times (greater than 1 year) were considered excessive, and therefore not evaluated.

The impacts of utilizing carbon steel materials and a high-protein fish meal media on the levelized and present worth cost estimates were evaluated in a sensitivity analysis. As shown in Table 9, switching to the fish meal media (730% cost increase) results in an

Table 8
Levelized cost estimate

| | Processing scenarios | | |
	6 Months	9 Months	12 Months
Monthly operating costs ($)	9700	7300	6200
Levelized capital costs ($)	308 500	179 800	115 000
Total ($ per month)	318 200	187 100	121 100
Total ($ ton^{-1} per month)	1330	1180	1020
Present worth			
Without salvage [a]	1 882 000	1 650 000	1 416 000
With salvage	992 000	886 000	776 000

[a] Salvage value based on 50% of initial equipment cost.

Table 9
Sensitivity analysis

	Processing scenarios		
	6 Months	9 Months	12 Months
Option #1 [a]			
Monthly cost ($)	353800	210900	139000
Cost ($) per ton per month	1500	1300	1200
Option #2 [b]			
Monthly cost ($)	249700	147500	97500
Cost ($) per ton per month	1000	900	800
Option #3 [c]			
Monthly cost ($)	285400	171300	115300
Cost ($) per ton per month	1200	1100	1000
Option #4 [d]			
Monthly cost ($)	318200	187100	121100
Cost ($) per ton per month	1300	1200	1000

[a] Stainless steel construction, fish meal medium.
[b] Carbon steel construction, standard medium.
[c] Carbon steel construction, fish meal medium.
[d] Base-case stainless steel construction, standard medium.
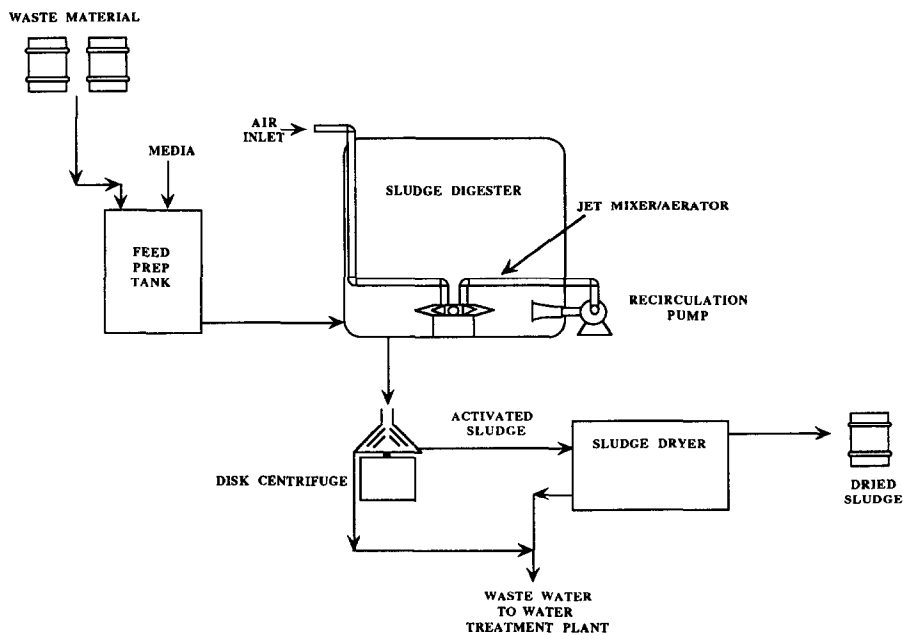

Fig. 4. Schematic of the full-scale cellulose sludge digestor system with the alternative dewatering system.

11–15% increase in the levelized costs while carbon steel construction (20% decrease) reduces the levelized costs by approximately 20%. Increasing the media costs and decreasing the equipment costs still results in a total levelized cost reduction because capital equipment represents such a large percentage of the total levelized costs.

Due to the low solids content in the final activated sludge produced by the vacuum filter (30%), an alternative dewatering system was evaluated for the 12 month processing scenario. The alternative dewatering system consisted of a disk centrifuge and Dry-Air sludge dryer designed to increase the solids content in the waste product to 60%. A process flow diagram for the alternative dewatering system is presented in Fig. 4. Decreasing the moisture content to 40% by weight effectively doubles the overall mass and volume reduction of the treatment process. The capital, operating and levelized costs for the alternative dewatering scenario are compared to the base-case scenario in Table 10. Although the alternative dewatering system increased the total capital and levelized costs by approximately 10%, the alternative design decreased the total waste volume by a factor of two compared to the vacuum filter design and achieved an overall reduction of 67%.

Before selecting the optimal waste treatment process, one must compare the costs associated with treatment to current disposal practices. At the present time, low-level

Table 10
Alternative dewatering system analysis

	Base-case [a]	Alternative [b]
Equipment costs ($)		
Reaction vessel [b]	396 000	396 000
Dewatering system	437 000	522 000
Miscellaneous	250 000	275 000
Foundations	37 000	37 000
Capital cost	1 120 000	1 230 111
Eng./Contin.	224 000	246 000
Total capital cost	1 344 000	1 476 000
Operating costs ($ per month)		
Media	2450	2450
Power	1470	2030
Cellulase	240	240
Labor	2000	3590
Total	6160	8300
Levelized costs ($)		
Monthly cost	121 000	135 000
Per ton per month	1020	1130
W/salvage, per ton per month	560	620
Waste product		
Dried sludge, amount (lb) per month	160 000	80 000

[a] Base-case dewatering system consists of vacuum filter designed to dry activated sludge to 30% solids.
[b] Alternative dewatering system includes disk centrifuge and Dry-Air sludge dryer. These components are designed to produce activated sludge product at 60% solids.

mixed wastes like those described in this paper (referred to as low-level mixed waste combustibles at Rocky Flats) are disposed of in shallow trenches at the Nevada test site at a rate of $15 per cubic foot (including transportation from Colorado to Nevada) [6]. Based on this rate, disposal of the original waste volume of 1300 m^3 would cost approximately $690 000.

While it may appear that it is cheaper to dispose of the waste without treatment (the capital cost for the alternative dewatering system is approximately $1.5 million, and operating costs are approximately $95 000 per year) it is important to remember that the equipment can be used to treat additional wastes. The treatment process reduces the waste volume by 67%, reducing the cost for disposing of the dried sludge at the Nevada test site to approximately $230 000. Assuming an operating life of 15 years and that equipment decontamination/disposal costs are 50% of the initial capital cost, the straight-line depreciation equipment cost is approximately $148 000 per year. This results in a total cost for treating 1300 m^3 of low-level mixed waste (including equipment, operating and waste disposal costs) of approximately $474 000. This represents a 31% saving compared to current disposal practices.

5. Conclusions

The system of choice to remediate low-level mixed waste consists of a ball mill, sludge digestor and a disk centrifuge/sludge dryer dewatering system. A stainless steel construction is necessary to ensure low corrosion rates. A low-cost urea and phosphate medium is suitable for biodegradation. Cellulase is required to initiate the degradation process. Using this system, a total solid waste volume reduction of 67% is accomplished. The bioprocess is extremely robust, reducing the quantity of cellulose by approximately 90% even in the presence of high levels of plutonium. All aqueous process streams can be recycled or reused. Operating the process for 12 months allows the waste to be treated for approximately $1130 per ton per month, and if the equipment is salvaged, for approximately $620 per ton per month. Continued operation of the facility to process other biodegradable wastes stored or generated at DOE facilities allows the capital cost to be depreciated over a longer process life. This results in reduced annual processing costs that can represent up to a 31% savings when compared to current disposal practices. Biodegradable LLMW often found at DOE facilities include used oils, fuels, and solvents. Decontamination and decommissioning of these facilities can be expected to generate additional wastes appropriate for this treatment.

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