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Sludge characterization, removal, and dewatering*

J. Gregory Mott and Stephen Romanow
CH2M Hill, P.O. Box 440, Reston, Virginia 22090 (USA)

Abstract

In April 1988, E.I. du Pont de Nemours and Company retained the services of CH2M HILL to perform a sludge characterization study, treatability study, remedial design, and to provide construction management services during the remedial action for a slip containing wastewater sludge situated on the Baltimore Harbor. The slip contained an estimated 18,500 cubic yards of sludge that averaged 20 percent solids by weight. Organic compounds were the primary constituents in the sludge, with highest concentrations represented by benzene, ethylbenzene, toluene, and xylenes. During 1989 and 1990, the sludge was removed by a floating dredge, crane, and an air conveyance boom pumping system. A steel sheet pile wall was constructed around the slip to prevent the slip banks from collapsing during removal of the sludge. The sludge was treated using a cationic polymer of high molecular weight during flocculation, and a membrane filter press for dewatering. The sludge cake averaged 52 percent solids by weight. All sludge cake was disposed of offsite in a RCRA-permitted landfill.

1. Introduction

CH2M HILL conducted a sludge characterization and treatability study, prepared a remedial design and specifications, and provided construction management services for E.I. du Pont de Nemours and Company from 1988 to 1990. The sludge was located in a slip in Baltimore Harbor, Baltimore, Maryland, at a facility previously owned by Du Pont. The slip served as a wastewater collection basin from 1970 to 1983 and has functioned as a surface water collection basin from 1983 until today. In 1987, the property owner obtained a modification to a National Pollutant Discharge Elimination System (NPDES) permit that allows for the elimination of the existing outfall at the slip dike. The permit modification also required that the slip be filled in to prevent runoff from accumulating. Final closure is expected to occur at a later date. In the interim, the objectives are to characterize, remove, and dewater the sludge.

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2. Sludge characterization and treatability study

The objectives of the field work conducted at the slip were to determine the thickness of the sludge layer and to collect samples for raw sludge characterization, treated sludge characterization, and treatability testing. To achieve the objectives of the sampling and chemical analysis programs, several important factors were considered.

First, based on the toxicity characteristic leachate procedure (TCLP) analysis previously provided by the property owner, it was determined that the most probable contaminants in the sludge were volatile organic compounds (VOCs). Because of the physical and chemical nature of these compounds, the samples were handled carefully to prevent unnecessary agitation and possible loss of contaminants.

Second, sampling techniques were developed for both relatively liquid sludge (12 to 15% solids) and relatively solid sludge (more than 15% solids). Because the sludge in this case was fairly thick, the solid-sampling technique was used. This technique is described further on in this paper.

Third, health and safety issues were constantly evaluated during sampling. High concentrations of benzene and other VOCs were suspected, in which case respiratory protection would be required. Also, because the sludge had not been adequately characterized before this study, it was not known if other hazardous compounds, such as cyanides, would be present.

3. Sampling locations

The Request for Proposal indicated that 12 samples obtained on a wide space grid would provide for adequate characterization of the sludge. The sampling program was developed under the assumption that 12 samples would be sufficient.

The slip, roughly 150 feet by 405 feet, was fitted into a 45-block grid; each block measured 30 feet by 45 feet. To characterize the sludge throughout the entire slip, six sample locations in the center of six blocks distributed across the slip were identified. Both discrete depth and composite sludge sample locations were chosen. Also at these locations, sludge samples were collected for treatability testing. The property owner was consulted about the sample locations before field work began. Sample locations are shown in Fig. 1. The grid system was also used to determine where to take depth measurements.

Several samples were obtained at each location for raw sludge characterization. Composite (full-depth) sludge samples were collected at locations 2, 4 and 6 (see Fig. 2). Discrete depth samples were collected at locations 1, 3 and 5, providing for a total of 10 samples. Two duplicate samples also were collected. The following depth intervals were observed:
Location 1—0–3 ft, 3–5 ft; Location 3—0–4 ft, 4–8 ft; Location 5—0–4 ft, 4–8

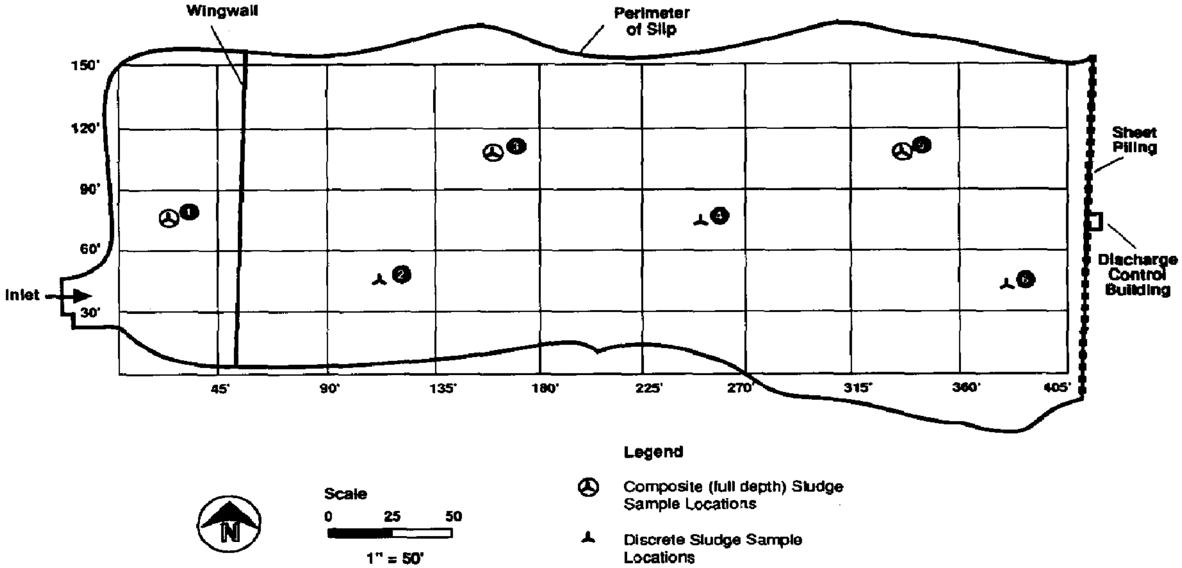

Fig. 1. Sludge sample locations.

ft, and 8–12 ft. In addition to the individual samples collected at each location for raw sludge characterization, one composite sample from locations 1, 2 and 3 and one from locations 4, 5 and 6 were also submitted for a more comprehensive analysis of raw sludge organic compounds.

Five gallons of sludge was also collected at each of the six locations to provide enough material for the treatability studies identified by the property owner. A composite was made of all the 5-gallon samples and then submitted to four vendors and to Du Pont. Table 1 is a list of the vendors and the volume of sludge each received. The volume sent to each vendor (Table 1) was determined by the amount each vendor required for the test.

Soil samples were collected at Locations 4 and 6 to determine if the soil under the sludge has been contaminated. Soil was collected from an interval of 1 to 1.5 feet below the sludge layer at each of the locations. An attempt to collect a soil sample at Location 1 failed, apparently because a gravel bottom prevented the auger from obtaining a sample.

TABLE 1

Vendors and volume of sludge received

Vendor	Volume of sludge received (gallons)
Mittelhauser Corporation (SRC) (Laguna Hills, California)	2
ENRECO, Inc., Laboratories (Amarillo, Texas)	2
Interim Dewatering Services (Kennett Square, Pennsylvania)	10
CF Systems Corporation (Woburn, Massachusetts)	2

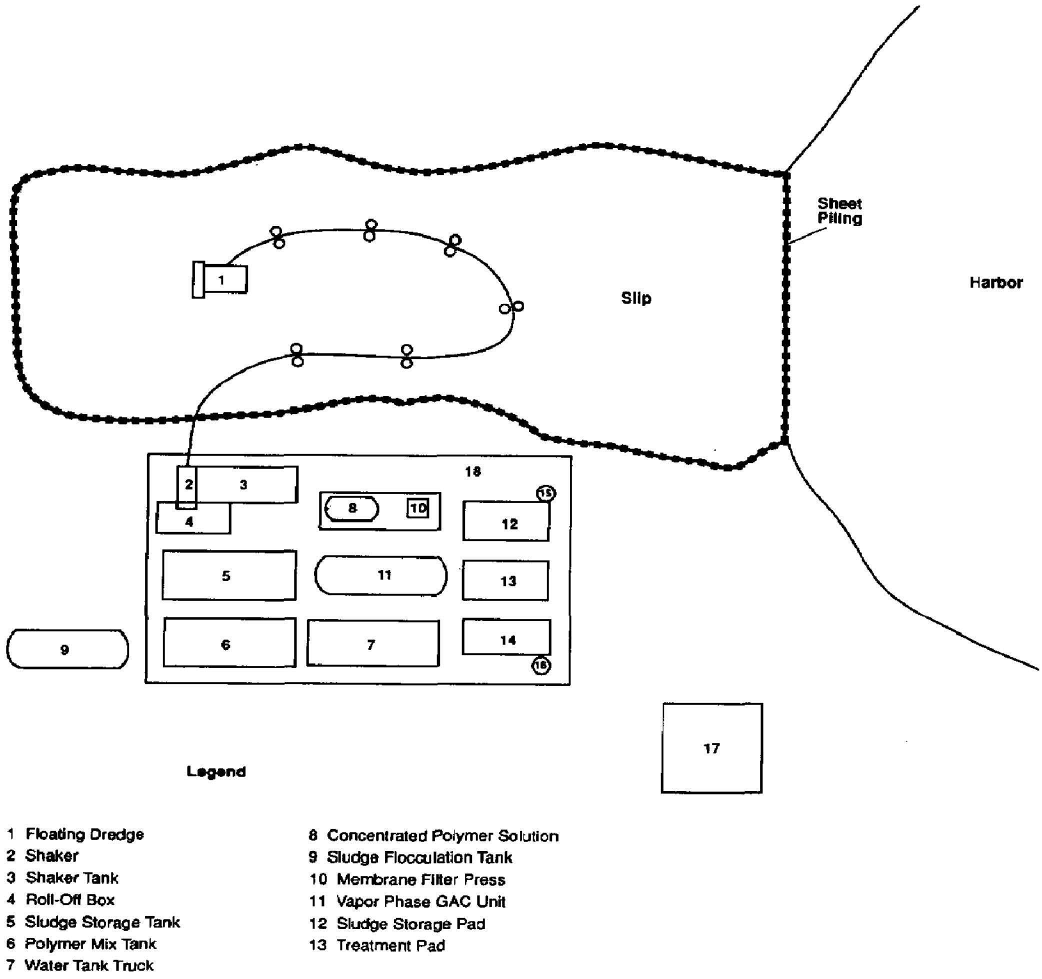

Fig. 2. Treatment system components.

4. Sample collection

Before collecting any samples, both the length and width of the slip were measured and staked to identify sample locations. A heavy-duty nylon rope was then stretched across the short dimension of the slip where a sample would be taken. The sampling platform — two flat-bottomed boats fixed together — was then pulled into location by the two sampling team members.

Before collecting the sludge, sample depth measurements across the slip were taken. A 15-foot pole marked off in 1-foot intervals was used to probe the surface water and sludge and estimate their combined depth. Then the depth of the surface water was estimated using a string attached to a flat weight. (Resistance could be felt when the flat weight came in contact with the sludge.) To obtain an estimate of the thickness of the sludge, the depth of surface water was subtracted from the combined depth of water and sludge. These measurements were taken at about the middle of each block along each cross section containing one of the six sample locations.

Composite sludge samples were collected by pushing a 2-inch stainless steel tube to the bottom of the sludge layer. The tube was then removed, and the surface water at the top of the tube was poured out. The sludge sample was extruded into a 5-gallon bucket. A variation to this technique was used when discrete depth samples were obtained. This technique used a neoprene plug positioned at the bottom of the 2-inch stainless steel tube and attached to a $\frac{1}{2}$-inch rod running up through the tube. This plug was also attached by a $\frac{1}{2}$-inch rod to another neoprene plug. The other plug hung outside the 2-inch tube before sampling. As the tube was pushed downward from the top of the desired sampling interval the $\frac{1}{2}$-inch rod was held in position. The tube was then pushed down and would seat on the bottom plug as the bottom of the sample interval was reached. The tube was then taken out of the slip, and the sludge sample was extruded from the tube by pushing the $\frac{1}{2}$-inch rod connected to the top neoprene plug.

The soils encountered below the sludge were too firm to be sampled using the sludge-sampling technique. Therefore, a 3-inch PVC pipe was lowered to the interface of the sludge and soil and seated firmly. The sludge in the interior of the PVC pipe was bailed out using the sludge-sampling method. A soil auger was then used to obtain a 1 to 1.5 foot composite soil sample.

When sampling was complete at a given location, all equipment that came in contact with the sludge was decontaminated by pressure-steam cleaning before moving to the next location. The liquids generated during decontamination were drained back into the slip.

4.1 Raw sludge characterization — chemical analyses results

CH2M HILL analyzed all sludge samples for oil and grease, total solids, chemical oxygen demand, and organics using EPA method 602. The three composite sludge samples were analyzed for Extraction Procedure Toxicity (EP Toxicity) metals and nickel, priority pollutant metals, cyanide, and organics using EPA methods 624 and 625. In addition, EA Laboratories (Sparks, Maryland) analyzed the composite samples using the Toxicity Characteristic Leaching Procedure (TCLP) described in Appendix 1 of 40 CFR Part 268. The subsequent leachate was analyzed for halogenated hydrocarbon pesticides, phenoxy acid herbicides, arsenic, barium, cadmium, total chromium, lead, mercury, selenium, silver, total cyanide, and sulfide. EA Laboratories also performed ignitability, corrosivity, and reactivity testing on the raw sludge.

Organic compounds of highest concentration in the raw sludge were benzene, ethylbenzene, toluene, and xylenes. Table 2 shows the concentration ranges and average concentration detected for these four compounds. As shown in Table 3, only benzene exceeded RCRA subtitle C Toxicity Characteristic Rule (TC Rule) regulatory level for TCLP-extracted raw sludge. Both ethyl-

TABLE 2

Organic compounds from raw sludge with highest detected concentrations

Compound	Concentration range (mg/kg)	Average concentration (mg/kg)
Benzene	52–600	271
Toluene	11–130	71
Ethylbenzene	19–340	140
Xylenes	66–1,000	474

TABLE 3

Raw sludge TCLP results compared to TC Rule regulatory levels

Parameter	Units	Sample number		TC Rule regulatory levels[a]
		C1, 2, 3 (EA #1839)	C4, 5, 6 (EA #1840)	
Volatiles extracted				
Trichloroethene	μg/l	110	33	500
Benzene	μg/l	690	680	500
Tetrachloroethene	μg/l	3	3	700
Chlorobenzene	μg/l	200	130	100,000
Semivolatiles extracted				
1,4-Dichlorobenzene	μg/l	3	3	7,500
1,2-Dichlorobenzene	μg/l	4	13	500

[a]Levels as discussed in the March 29, 1990, Federal Register, p. 11798 (40 CFR 261.24).

benzene and total xylenes are not included as contaminants in the proposed TC Rule and therefore do not have related regulatory limits. Trichloroethene also exceeded the proposed regulatory level in one of two samples.

According to EA Laboratories, the raw sludge exhibited characteristics of hazardous waste in the ignitability and reactivity categories. However, upon additional inquiry, the laboratory staff indicated that only one of two samples exhibited the ignitability hazardous waste characteristic. Therefore, additional sludge samples were collected and analyzed for ignitability. These additional samples did not exhibit hazardous waste characteristics in terms of ignitability.

The reactivity hazardous waste characteristic reported by EA Laboratories is not accurate because the total cyanide and sulfide concentrations are below the current EPA action levels. The action levels for total releasable cyanide and sulfide are 250 mg HCN/kg waste and 500 mg H_2S/kg waste, respectively, as presented in the manual 'Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (EPA SW-846)'.

Heavy metals also were detected in the sludge samples. In highest concentrations were chromium, copper, lead, and zinc. Concentrations ranged from 186 mg/kg to 1,038 mg/kg. Leachate obtained from the sludge using the EP toxicity and TCLP analyses did not contain metals in concentrations exceeding the regulatory levels.

The soil immediately beneath the sludge layer was found to be contaminated also. The same four organic compounds detected in the sludge — benzene, ethylbenzene, toluene, and xylenes — were detected in the soil as well. The concentrations in the soil, however, were lower by one to two orders of magnitude. The specified scope of the sampling effort did not allow the vertical extent of soil contamination to be determined.

4.2 Sludge treatability — Chemical analyses results

The type of analyses performed by CH2M HILL laboratories on the vendor-treated sludge samples and other treatment residuals is presented in Table 4. Table 5 summarizes the TCLP analysis performed by ENSECO (Cambridge, Massachusetts) on the vendor-treated sludge. Samples are identified by descriptive titles. CF Systems used a critical fluids extraction procedure that yielded residual water, organic, and solid phases. ENRECO tested two stabi-

TABLE 4

Summary of treated sludge and residue characterization chemical analyses performed by CH2M HILL laboratories

Vendor	Sample description	Analyses
CF Systems	Residual water phase	BOD, pH, TOC, TSS, COD, GC624
	Residual solid phase	GC624
	Residual organic phase	TOC, COD
	Raw feed sludge	GC602
ENRECO, Inc.	Treatment system 1 solid	GC602
	Treatment system 4 solid	GC602
	Raw feed sludge	GC602
Mittelhauser Corp.	Treatment system centrifuged solid	GC602
	Treatment system no centrifuged solid	GC602
	Raw feed sludge	GC602
Interim Dewatering Services	Dewatered solid-No Profix	GC602
	Filtrate-No Profix	VOA, BOD, TSS, pH, COD, TOC, O&G
	Dewatered solid-Profix Q	GC602
	Filtrate-Profix Q	VOA, O&G
	Dewatered solid-Profix P	GC602
	Filtrate-Profix P	VOA, O&G
	Raw feed sludge	GC602

TABLE 5

Summary of treated sludge characterization TCLP chemical analyses performed by ENSECO Laboratories

Vendor	Sample description	Analyses
CF System	Residual solid phase	HSL Volatile organics[a] Additional volatile organics[b] Solvents[c]
ENRECO, Inc.	Treatment system 1 solid	As above
	Treatment system 4 solid	As above
Mittelhauser Corp.	Treatment system centrifuged solid	As above
	Treatment system no centrifuged solid	As above
Interim Dewatering Services	Dewatered sludge–No Profix	As above
	Dewatered sludge–Profix Q	As above
	Dewatered sludge–Profix P	As above

[a]By EPA method 624/HSL.
[b]BY EPA method GC624/8240.
[c]By direct aqueous injection.

lization techniques (System 1 and System 4), each of which yielded a stabilized sludge. Mittelhauser Corporation also tested two stabilization techniques (referred to as 'Centrifuged' and 'No Centrifuged') yielding a stabilized sludge. Interim Dewatering Systems (IDS) used three dewatering/stabilization processes referred to as 'No Profix', 'Profix P' and 'Profix Q', each of which yielded a dried, stabilized solid and a filtrate.

Only CF Systems and Mittelhauser treatment processes were able to lower the sludge concentrations of all volatiles found in the raw feed sludge. Residual solids from the CF process appear to contain more volatiles than the raw feed sludge. This may be attributed to the fact that the treated solid volatiles were analyzed by a much more sensitive analytical technique than the raw feed sludge.

Regarding the treated sludges, Table 6 compares the levels of volatile organics found in the TCLP extract and TC-Rule regulatory levels. Only the benzene level is exceeded. Mittelhauser was the only vendor able to lower the benzene levels in the extract below the regulatory level. Interim Dewatering Services (IDS) conducted TCLP analysis on the treated sludge and submitted results to Du Pont separately. Results from IDS showed a lower concentration of benzene than the ENSECO results, yet the TC-Rule benzene levels were still exceeded.

The CF Systems and IDS water residual phase contained organic compounds when tested. Any of these phases would have to be disposed of properly, which means additional treatment would be necessary.

TABLE 6

Treated sludge TCLP results compared to TC Rule regulatory levels

Parameter ($\mu g/l$)	CF Systems residual solid	ENRECO 1 solid	ENRECO 4 solid	Mittelhauser centrifuged solid	Mittelhauser no centrifuged solid	IDS No Profix solid	IDS Profix P solid	IDS Profix Q solid	Regulatory level
Benzene	230	470	540	BMDL[a]	BMDL	3,400	3,400	5,800	500
Chlorobenzene	BMDL	BMDL	BMDL	BMDL	BMDL	110	120	150	100,000

[a]BMDL = Below Method Detection Limit.

4.3 Sludge volume estimate

Measurements of sludge thickness ranged from 4.7 ft to 10.6 ft, with an average thickness of 7.6 ft for the 30 measurements. An in-place sludge volume of 18,500 cubic yards was calculated based on these measurements. This volume does not include the 1.5 ft to 2.5 ft of standing water above the sludge.

5. Sludge removal and dewatering

Analytical results of the sludge characterization and treatability study were key factors in the determination that removal and dewatering would be the most appropriate and economical means of remediation. The sludge characterization study revealed that neither the raw sludge nor the treated sludge needed to be classified as hazardous waste. Consequently, handling and disposal were not regulated under the Resource Conservation and Recovery Act (RCRA), and offsite disposal became an attractive alternative for remediation because many regulatory requirements associated with RCRA – requirements such as permitting that often increase costs and lengthen schedules – would not be required. Although the raw sludge did fail the TCLP analysis because of a high concentration of benzene in the leachate, the TC Rule was only a proposed rule during remediation of the site. The TC Rule remained unenforceable until September 25, 1990.

The decision to employ dewatering as the treatment method was based primarily on economics. Of the four treatability studies performed, two examined stabilization and two examined dewatering. The stabilization methods called for adding a stabilizing agent to the raw sludge, creating a stabilized sludge as the final product but also increasing the volume and weight — and thus, the disposal costs — of the sludge. On the other hand, dewatering techniques separate the liquid phase from the solid phase. The volume of dewatered sludge is lower than the volume of raw sludge, and disposal costs are reduced. But there are some drawbacks: dewatering also generates a filtrate, or liquid by-product, that often requires treatment, disposal, or a discharge permit. Costs associated with handling the liquid by-product can be considerable.

In this case, however, the filtrate generated at the site did not require treatment or disposal, and associated costs were avoided. The filtrate was simply discharged back into the slip to keep the groundwater in the vicinity from infiltrating into the slip and probably becoming contaminated. Because the slip is close to the harbor, groundwater at the site occurs approximately at mean sea level (MSL), or 3 to 4 ft below grade. The water in the slip will be remediated later, after all sludge is removed.

6. Removal and dewatering process

The system for removing and dewatering sludge was implemented in two phases. During the first phase — site preparation — a steel sheetpile wall, treatment pad, storage pad, and decontamination pad were constructed. During the second phase, the treatment system was mobilized and operated.

6.1 Site preparation

A steel sheetpile wall was constructed around the perimeter of the slip and tied into the existing steel sheetpile wall at the east end which separated the slip from the harbor. The objective of the wall was to prevent the slip's banks from collapsing during removal of the sludge. Because the removal technique required a floating dredge, a 100-pound-per-square-foot surcharge loading on the slip was an important design parameter in the sheetpile wall design. Soil borings drilled near the slip indicated some variability of the soils in the upper 25 ft of the site. Consequently, a safety factor of 1.3 was used for the sheeting. The specifications required a lightweight (PLZ-23), Grade 50, 30-foot-long steel sheetpile. The tip of the sheetpile was driven 23 ft below MSL using a vibratory hammer.

Before sludge removal began, three pads were constructed to prevent spillage and contamination of the ground during sludge treatment and handling. The treatment pad contained the entire treatment system and was 155 ft long and 55 ft wide. The decontamination pad served as an area in which heavy equipment and trucks were decontaminated and was 30 ft long and 20 ft wide. Both the treatment pad and decontamination pad were lined with a 30-mm hypalon liner with a 6-ounce nonwoven geotextile placed above and below the liner. Six inches of underdrain aggregate was placed above the geotextile. The sludge storage pad was constructed of reinforced concrete with a 240-cubic-yard storage capacity. The 30-foot-wide, 50-foot-long storage pad included a 3-foot reinforced concrete wall on one side with an earthen wall behind it. All three pads were surrounded by lined or concrete (storage pad) berms and equipped with a sump and sump pump that directed all liquid from the pads into the slip.

7. Treatment system components

The components that made up the treatment system are listed below and shown in Fig. 2.

- Floating dredge
- Shaker
- Shaker tank
- Roll-off box
- Sludge storage tanks (3)
- Polymer mix tank
- Water tank truck
- Concentrated polymer solution
- Sludge flocculation tank
- Membrane filter presses (3)
- Vapor phase GAC units (2)
- Sludge storage pad
- Treatment pad

7.1 Treatment process flow

A hydraulically driven floating dredge moved along the surface of the slip while removing the sludge from the bottom. The dredge used an impeller auger to bring sludge from the bottom of the slip to the treatment system. The sludge was transported to the treatment system in slurry form via a 10-inch flexible HDPE pipe supported by buoys.

The sludge slurry entered the treatment system through the shaker. The vibrating shaker consisted of four 2-foot by 4-foot vibrating screens, backed by a 10- or 12-mesh screen. The shaker removed rocks and debris from the sludge slurry. The shaker was completely enclosed in a steel box to minimize vapor emissions. The rocks and debris fell off the shaker into the roll-off box and were disposed of in a permitted RCRA landfill. The refined sludge slurry then entered the 10,000-gallon shaker tank.

The refined sludge slurry was directed either to the storage tanks or to the sludge flocculation tank. The three sludge storage tanks each held 15,000 gallons of sludge slurry. These tanks, combined with the shaker tank, provided 55,000 gallons of storage capacity. This volume of storage capacity was necessary to support operation of the treatment system 24 hours a day; the dredge operated only during daylight hours for health and safety reasons. The system was designed with maximum flexibility so that the refined sludge slurry could directly enter the sludge flocculation tank from any of the storage tanks or shaker tank.

The polymer mix tank supplied the polymer solution to the sludge flocculation tank. The polymer mix tank combined water from the water tank truck with concentrated polymer solution. The polymer used was a high molecular weight cationic polymer. The polymer mix tank diluted the concentrated polymer solution at a 1:100 ratio of concentrated-polymer-to-water, thus producing a 1% polymer solution.

The polymer solution was mixed with the refined sludge slurry in the sludge flocculation tank. Approximately 200 gallons of 1% polymer solution was mixed with 12,000 gallons of refined sludge slurry. The flocculation tank was closed and equipped with three flocculators. On average, one-half hour of flocculation was required before the floc was ready to enter the membrane filter press.

Three 92-cubic-foot membrane filter presses were included in the treatment system. The presses ran in parallel batches. Press cycle times averaged 75 minutes and ranged from 60 to 150 minutes. The amount of filter cake produced during each press cycle ranged from 1.5 to 2 tons. Press cycle times increased gradually as the project progressed. This was accompanied by a gradual decrease in the amount of filter cake produced during each press cycle. The increase in cycle times and decrease in resulting filter cake were caused by a falling percentage of solids in the sludge slurry. The decrease in percentage of solids was attributed to the disturbance or mixing action of the dredge during the course of the project. The sludge cake averaged 52% solids by weight, ranging from 34 to 77% solids.

Each membrane filter press was equipped with a vapor phase, granular activated carbon (GAC) unit. All tanks and vents were piped through a common manifold to the filter press. Here, vapor emissions were captured and directed through the vapor phase GAC units. The volume of vented air was metered in order to determine breakthrough.

Other sludge removal techniques were employed as necessary when the regular dredge system could not be used. For instance, the dredge required a minimum of 18 inches of water, and could not operate in the shallow areas at the periphery of the slip. Other portions of the slip contained large pieces of debris that could have damaged the dredge. For these reasons, a backhoe and clamshell were used to remove sludge in these troublesome areas. The excavated sludge was stabilized with kiln dust and disposed of in an RCRA-permitted landfill. As the removal approached completion, the dredge became less effective because the consistency of the sludge became thinner. This resulted in part from the low specific gravity of the sludge (1.1) and the continued disturbance caused by the dredge's impellers. Consequently, an air conveyance boom pumping system (ACBPS) was used to remove sludge during the final stages of the project. The ACBPS functioned as a giant vacuum cleaner, sucking up the remaining sludge, creating minimal disturbance, and directing the sludge slurry to the treatment system.

8. Summary and conclusions

The sludge characterization and treatability study revealed that the sludge did not have to be classified as a hazardous waste and that dewatering was the most appropriate treatment method. Sludge was removed for the most part by a floating dredge and, to a lesser degree, by an ACBPS, or excavated. The ACBPS was used because of the consistency of the sludge during later stages of the project. Sludge in shallow portions of the slip and sludge containing large pieces of debris was excavated by backhoe or clamshell and stabilized with kiln dust. All stabilized sludge and dewatered sludge was disposed of in a RCRA-permitted landfill.

The treatment system used a high molecular weight cationic polymer as a flocculent and three membrane filter presses for dewatering. Press cycle times averaged 75 minutes and ranged from 60 to 150 minutes per cycle. The amount of filter cake produced ranged from 1.5 to 2 tons each press cycle. As the project progressed, a trend of increasing press cycle times and decreasing filter cake amounts was observed. This trend was attributed to a reduction from 10 to 2 in the percentage of solids by weight in the sludge slurry entering the system. This reduction in solids probably was caused by the disturbance or mixing action of the dredge's impellers, coupled with the low specific gravity of the sludge.

The dewatered sludge filter cake averaged 52% solids by weight, ranging from 34 to 77% solids by weight. Analyses of the filtrate returned to the slip indicate that it averaged 8.7 ppm total suspended solids (TSS), ranging from less than 1 to 31 ppm TSS. A total of roughly 30,000 tons of sludge has been removed from the slip. The work was completed by September, 1990.