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PCB Sediment Decontamination Processes—Selection for Test and Evaluation

Project Summary

by
Ben H. Carpenter
Research Triangle Institute
Research Triangle Park, NC 27709

Contract No. 68-02-3992
RTI Project No. 471U-3065-65

Project Officers: Donald L. Wilson, T. David Ferguson
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ABSTRACT

Eight alternative treatments for PCB-contaminated sediments have been assessed as candidates for immediate thorough test and evaluation. The processes are: Basic Extraction Sludge Treatment (B.E.S.T), UV/Ozone or Hydrogen/Ultrasonics Technology, Bio-Clean Naturally-Adapted Microbe, Potassium Polyethylene Glycolate (KPEG), Low Energy Extraction, MODAR Supercritical Water Oxidation, Critical Fluid Systems (CFS) Propane Extraction, and Battelle In Situ Vitrification.

The processes were evaluated using five criteria: the probability of cleaning sediments to 2 ppm or less; the availability of a test system; the test and evaluation effort required; the time required for future availability of a commercial treatment process; and the probable cost of treatment using [illegible] process. These criteria were addressed by engineering analysis of available data and site visits to developers' facilities.

The processes were ranked comparatively as to the overall desirability of thorough test and evaluation using all five criteria collectively. Two rating methods were applied: a multiplicative model using a Desirability Function and a linear model, d-SSYS, using weighted utility functions. Both methods converted the process characteristics to ratings on a scale from 0 to 1 (worst to best). The Desirability approach normalized the characteristic using the difference between acceptable and borderline values; d-SSYS normalized the characteristic using the difference between the maximum and minimum values. In calculating the overall score, the factors were weighted equally in the Desirability Function. Probable cost of treatment and test and evaluation effort were assigned weights 4 to 5 times those of the other three characteristics in the d-SSYS ranking. These independent approaches gave final overall desirability scores as follows:

Process	Desirability score	d-SSYS score
[illegible]sic Extraction Sludge Treatment, Resources Conservation Company	0.623	0.8127
UV/Ozone or Hydrogen/Ultrasonics Treatment, Ozonic Technology, Inc.	0.621	0.8010
Naturally-Adapted Microbes Process, Bio-Clean, Inc.	0.617	0.7583
Potassium Polyethylene Glycolate (KPEG), Galson Research, Corp.	0.615	0.7434
Low Energy Extraction, New York University	0.614	0.4529
Supercritical Water Oxidation, MODAR, Inc.	0.600	0.4738
Propane Extraction Process, Critical Fluid Systems	0.590	0.6214
In Situ Vitrification, Battelle	0.460	0.2299

While all the processes except In Situ Vitrification appear to merit further development for this application, those three with the highest comparative ratings are recommended for immediate EPA-supported thorough test and evaluation. These are the Basic Extraction Sludge Treatment, UV/Ozone or Hydrogen/Ultrasonics Technology, and Bio-Clean Naturally-Adapted Microbe processes.

This recommendation does not mean that the other processes merit no fur[illegible]r T and E. The Potassium Polyethylene Glycolate (Galson), Low Energy Extraction (New York University), MODAR Supercritical Water Oxidation, and Critical Fluid Systems Propane Extraction processes rank very close to the top three. Thus these seven processes merit consideration for testing at least through the preliminary phases to confirm their performances.

This project summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

INTRODUCTION

The PCB-contaminated sediment problems in New Bedford, Massachusetts (EPA Region I) in New York State (EPA Region II) and in Waukegan, Illinois (EPA Region V) are reported to be the worst in the nation in terms of PCB concentration and the total quantity of PCBs present. In addition, there are numerous industrial lagoons with large quantities of PCB contaminated sediments. PCB contamination poses threats to both drinking water and the fishing [illegible]stry.

The only available proven treatment technology is dredging and expensive incineration. Land disposal of the sediments untreated has legal restrictions. The Environmental Protection Agency (EPA) has initiated a three-phase research program to identify, validate, and demonstrate effective and economical chemical/biological processes for the removal/destruction of PCBs in sediments. The Phase 1 study screened 64 emerging process technologies and selected eleven for evaluation: Potassium Polyethylene Glycolate with Dimethyl Sulfoxide (Galson Research Corporation); O.H.M. Methanol Extraction; Advanced Electric Reactor (J.M Huber Corporation); Acurex Solvent Wash (Electric Power Research Institute); Bio-Clean Naturally-Adapted Microbe (Bio-Clean, Inc.); Battelle In Situ Vitrification; Light Activated Reduction of Chemicals ((LARC), Atlantic Research Corporation); MODAR Supercritical Water Oxidation; Soilex Solvent Extraction; Sybron Bi-Chem 1006B; and Composting (as studied by the Atlantic Research Corporation) (Carpenter, 1987). The evaluation showed the first eight of these to have potential for reduction of PCB concentrations to the desired background levels or less, with minimal environmental impacts and low to moderate cost. All of the eight except the Advanced Electric Reactor required further development and testing.

This Phase 2 study was undertaken to establish suitable factors for further assessment of candidate processes, to identify additional data needs, and provide a basis for selection of three processes for a defensible, thorough technical assessment, including laboratory experiemnts and field evaluation. The study involved consultations with treatment process developers, technical assessment of the processes, and the selection of the three highest ranking processes for immediate test and evaluation.

SCREENING OF CANDIDATE PROCESSES

The seven candidate processes that required further development and testing were screened at the start of this Phase 2 (Validation) study for availability of a continuing developer and a treatment system for use in test and evaluation of the process. The results of this screening are given in Table 1. Three processes were eliminated from further consideration. The Solvent Wash process is not available for assessment because its sponsor, the Electric Power Research Institute, is seeking a firm to undertake the further needed development of the process before it is ready for further consideration. The

TABLE 1. INITIAL SCREENING OF TREATMENT PROCESSES

Process	Contact	Continuing Developer	Test System(s) Available
KPEG	Dr. Robert L. Peterson Galson Research Corporation 6601 Kirkville Road East Syracuse, NY 13057	Yes	Yes
OHM Extraction	Sue Mason OH Materials 16406 U.S. Rt. 224 E. Findlay, OH 45839-0551 (419) 423-3526	No	No
EPRI Solvent Wash[a]	Ms. Mary McLearn Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94304	No	No
Battelle Vitrification	Craig Timmerman Battelle Pacific Northwest Laboratory P. O. Box 999 Richland, WA 99352	Yes	Yes
Bio-Clean, Inc.	Dr. Lance B. Crombie, Director of Labs 201 W. Burnsville Prkwy., Suite 130G Burnsville, MN 55337 (612) 890-1118	Yes	Yes
MODAR Supercritical Water	Ralph A. Morgan Modar, Inc. 3200 Wilcrest, Suite 220 Houston, TX 77042 (713) 785-5615	Yes	Yes

(Continued)

TABLE 1 Continued)

Process	Contact	Continuing Developer	Test System(s) Available
LARC	George Anspach Atlantic Research Corporation 5390 Cherokee Avenue Alexandria, VA 22312	No	No
Basic Extraction Sludge Treatment	Mark Tose Resources Conservation Co. 3101 N.E. Northup Way Belleview, WA 98004 (206) 828-2376	Yes	Yes
CF Systems Propane Extraction	Thomas J. Cody, Jr. CF Systems Corporation 25 Acorn Park Cambridge MA 02140 (617) 492-1631	Yes	Yes
Ultrasonics/UV Technology	Edward A. Pedzy Ozonic Technology, Inc. 90 Herbert Avenue P. O. Box 320 Closter, NJ 07624 (201) 767-1225	Yes	Yes
Low Energy Extraction Process	Walter Brenner/Barry Rugg New York University Dept. of Applied Science 26-36 Stuyvesant Street New York, NY 10003 (212) 598-2471	Yes	Planned

[a] This process was identified as the Acurex process in the Phase 1 study.

developer of the OHM Extraction process has chosen not to invest in this process. The developer of the LARC process has not identified sufficient markets and the process is not available from them.

Meanwhile, four technologies not assessed in the Phase 1 study have become available: the Basic Extraction Sludge Treatment (B.E.S.T.) process (Resources Conservation Company); the Critical Fluids Systems Propane Extraction process; the UV/Ozone or Hydrogen/Ultrasonics process (Ozonic Technology, Inc.); and the Low Energy Extraction process (New York University). These have all been assessed as candidates for thorough test and evaluation. The UV/Ozone or Hydrogen/Ultrasonics Technology provides continuity for the radiant-energy approach previously represented by the LARC process. The other three processes provide improved approaches to the extraction technology. The results of initial screening of these processes are also given in Table 1.

DESCRIPTIONS OF TREATMENT PROCESSES

The Basic Extraction Sludge Treatment process pretreats the feed (sediment, sludge, oily contaminants, water) with an alkaline composition, then admixes with triethylamine (TEA) while cooling below the critical solution temperature (U.S. Patents 3899419, 3925201, 4002562, 4056466). A single liquid phase is formed from which the solid matter is separated. The liquid is then heated to above the critical solution temperature to form an amine-rich phase and a water-rich phase, after which the water phase is decanted. The amine phase contains all of the oil contaminants. It is processed to recover the oil and contaminants, and the TEA is recycled for the processing of additional material.

The UV/Ozone or Hydrogen/Ultrasonics Technology involves three factors, all of which have been shown to be effective. The UV/Ozone technology has been demonstrated for destroying PCBs in industrial waste waters (Arisman et al., 1981). PCBs have been extracted from soils using Tween 80 surfactant (Scholz and Milanowski, 1984). They have been removed from metallic surfaces using surfactants and ultrasonics (Smith and Sitabkhan, 1986). UV/Hydrogen has been shown to destroy PCBs in non-aqueous solvents (Kitchens et al., 1979, 1984). Ozonics Technology, Inc. is equipped to apply all three factors in a comparative evaluation of ozone vs hydrogen.

The Bio-Clean process utilizes selected naturally adapted microbes to destroy PCBs under aerobic conditions. Contaminated sediment is charged as a water slurry to a digester. The charge is adjusted to optimum pH and heated to extract the PCBs. Surfactants may be added to promote extraction. After extraction, the slurry is cooled, neutralized, and inoculated. The PCBs are degraded in from 48 to 72 hours depending on the process conditions and the microbes employed (Bio-Clean, Inc., 1985) (Crombie, 1986, 1987) (Unterman, 1985).

The Potassium Polyethylene Glycolate process degrades PCBs by nucleophilic substitution. An equal volume of contaminated sediment and reagent are blended in a reactor, and heated to remove excess water and promote the reaction. The Galson version of the process promotes extraction of PCBs with dimethyl sulfoxide (Peterson, 1986). The treated sediment is settled, the reagent removed by decantation, and the solids are washed with water (Research Demonstration Permit Application, 1987).

The Low Energy Extraction process involves separation of water from the sediments, a solvent leaching with a hydrophylic solvent (e.g. acetone) usually carried out in countercurrent stages, and transfer of the leached organic contaminants to a hydrophobic solvent (e.g. kerosene) in which it is concentrated for final destructive treatment. The final treatment is a separate process. Residual contaminants in the water stream are adsorbed onto [illegible]ontaminated sediments. The system recycles all solvents and returns only decontaminated sediments and water to the environment (Brenner et al., 1986).

The MODAR Supercritical Water Oxidation process feeds a water slurry of contaminated sediments together with liquid oxygen to a pipe reactor where, at 400-600 °C and 22-25 MPa, the contaminants dissolve and react rapidly with the oxygen. The reactor effluent is cooled by heat exchange with fresh feed. Pressure let down and separation of sediments, liquid, and gases is carried out in multiple stages to minimize erosion of valves and optimize equilibria (Staszak et al., 1987).

The Critical Fluid System Propane Extraction process uses propane at ambient temperature and 1.8 MPa (200 lb/in^2) to extract PCBs along with other oily organics from a water slurry of the sediment. The batch extraction is repeated as required to achieve specified reductions in contaminants. The treated slurry is discharged after separation from the liquid propane which contains the dissolved contaminants. The propane solution is fed to a separator where the solvent is removed by vaporization and recycled. The contaminants are drawn off for final treatment in a separate process.

The Battelle In Situ Vitrification process was developed to stabilize radionuclide-contaminated soils by melting into a durable glass and crystalline form (Buelt et al., 1987). Submerged sediments are dredged and relocated for treatment. Four electrodes are inserted into the sediments in a square array. A path for electric current is made by placing a mixture of graphite and glass frit between the electrodes. Dissipation of power through the starter materials creates temperatures high enough to melt a layer of sediments, which establishes a conductive path. The molten zone grows downward through the contaminated soil. At the high temperatures created (> 1700 °C) organic materials pyrolyze, diffuse to the surface, and combust. Off-gases are collected, monitored, and treated (Timmerman, 1986).

DEVELOPMENT OF EVALUATION CRITERIA

The following criteria were used to select treatment processes for thorough test and evaluation:

1. The likelihood that the process will acceptably clean up the PCB-contaminated sediments;
2. The probable cost of the application of the treatment after performance is proven;
3. The relative level of T and E effort to be supported by the Environmental Protection Agency;
4. The availability of a processing system to test; and
5. The likely future commercial availability of the process.

The standard selected for acceptable cleanup is a PCB concentration in treated sediments (or soils) of 2 ppm or less.

EPA has considered PCB requirements preparatory to their promulgation as an amendment to the PCB regulations (40 CFR, Part 761, April 2, 1987, pp. 10688-10710). The proposed standards require cleanup as follows.

1. Nonrestricted area -- $\leq$ 10 ppm plus 10" cap of soil $\leq$ 1 ppm.
2. Restricted area -- 25 ppm.
3. Outdoor electrical substation -- 25 ppm, or 50 if a warning sign is maintained.

These standards would apply to PCB spills occurring after promulgation. Spills occurring earlier, and spills which are apt to result in spread of

PCB's into other media (groundwater, surface waters, grazing lands, and vegetable gardens) are to be decontaminated to requirements established at the discretion of the EPA regional officer.

These levels (10 ppm, 25 ppm, and 50 ppm) are to be attained by removing all contaminated soil exceeding these levels. The removed soil is subject to disposal regulations: cleanup to <2 ppm. For this reason, permits issued for alternative destruction processes generally will require that all treated materials and by-product waste streams must have PCB concentrations of less than 2 ug/g resolvable chromatographic peak (2 ppm). If this condition is not met, the effluents containing 2 ppm or greater must be disposed as if they contained the PCB concentration of the original influent material. If the PCB feed material being treated by the process is over 50 ppm PCB, then the resulting effluents must be incinerated unless an analysis is conducted and indicates that the PCB concentration is below 2 ppm per PCB peak.

In accordance with these policy and treatments requirements, the cleanup target for alternative treatments has been set at $\leq$2 ppm PCB.

The probable cost of treatment is presented as the cost per cubic meter of sediment treated, based on a system sufficiently large to process 380,000 m^3 of Hudson River sediments in 2.5 years. By focusing on a specific site and size of cleanup task, each process could be assessed using available data from sampling and analyses to characterize the feed materials to the processes, and comparative cost estimates for a specific application could be obtained. The sediments from the Hudson River present a variety of sediment types for testing PCB-treatment processes.

The probable cost of treatment was obtained from the developers for those processes sufficiently supported by commercial firms, or was estimated using as major cost elements capital costs, and operation and maintenance costs. Treatment process requirements determined capital, energy, and maintenance costs. Labor rates, overhead, contingency, profit, and health and safety were costed using standard unit values for all the processes.

Since no full-scale systems exist for the processes under assessment, capital costs were estimated by designing a full-scale system, utilizing the data available as a basis. Equipment costs were then obtained as budget estimates from manufacturers or developers, or estimated using the method of exponents:

$$C_i = C_1 (Q_i/Q_1)^n$$

where: C_i = cost for ith capacity (size);
Q_i = ith capacity;
n = empirical constant;
C_1 = cost of reference capacity; and
Q_1 = reference capacity.

Values for the reference capital cost and the exponent, n, were obtained in part from the literature and in part from equipment manufacturers.

Labor hours were estimated based on an automated industrial chemical processing plant (Peters and Timmerhaus, 1980):

$$e_2 = e_1 (Q_2/Q_1)^n$$

where: e_1 = Operator hours per day and processing step of reference case;
e_2 = Operator hours per day and processing step of case 2;
Q_1 = Process capacity of reference case;
Q_2 = Process capacity of case 2; and
n = Empirical constant.

The values used in this evaluation are: e_1 = 18 h/d x step;
Q_1 = 9.07 mt/d
n = 0.22

The number of foremen and chemists are taken to be 15 percent of the number of operators. In addition to these workers, there is one site manager.

The hourly wages are assumed to be:

Operators:	15 $/hr
Foreman:	18 $/hr
Chemist:	25 $/hr
Manager:	60 $/hr

Maintenance was estimated at 10 to 15 percent of the capital cost, depending on the number of unit operations involved and engineering practices for the operation. The allowance for safety equipment was generally \$0.30/m^3 of sediment treated (\$114,000 for the cleanup of 380,000 m^3 of sediment).

The treatment system cost estimate was capitalized (recovered) over the [illegible]5 years of operation taken as the base period. Some developers provided treatment costs that were correspondingly lower for subsequent applications.

The test and evaluation effort required was estimated based on a comparison of available process data with the requirements for thorough test and evaluation. The following information must be provided to qualify a process for a permit to test:

1. Waste characteristics;
2. Process engineering description;
3. Sampling and monitoring plan;
4. Accident and spill prevention and countermeasure; and
5. Demonstration test plan.

For these assessments, Hudson River sediments were selected as the characterized wastes.

Hudson River sediment samples have been classified according to their content of clay, silt, muck, muck and wood chips, sand, sand and wood chips, coarse sand, and coarse sand and wood chips (Tofflemire and Quinn, 1979). Sediments have been shown to range from clay to cobbles, with the largest mass fraction being in the sand sizes.

The highest PCB concentration was in the muck with wood chips class, which typically had over 30 percent silt and clay, high volatile solids and some small but visible wood chips. The size lowest in PCB was medium sized sand or gravel without wood chips.

The coarse fraction (>0.42 mm) of the sediments typically contained wood chips, sawdust, shale chips, cinders, and coal fragments. The fine size fractions contained some fragments of the above, plus sand (containing quartz and feldspar), silt, clay, and organic material.

Process engineering descriptions were developed for each process assessed. These varied in completeness because the processes varied in stage of development from conceptual to field tested. While unit operations were identified and described for all processes, the descriptions were based only on performance requirements. Detailed equipment specifications have not been made, except where necessary to obtain cost estimates (e.g., high pressure compressors and slurry pumps).

The descriptions included process flow diagrams and identified all product and waste streams. Additional process information included summaries of bench tests, pilot tests, and field tests, if available.

Sampling and monitoring plans were then developed, based on the scale of process tests required, the purposes of the tests, and the extent of data needed to characterize the process performance and scaleup the system to full-scale. Some of the processes, when the developers' prior experience justifies it, can be scaled-up from bench-scale tests. Thus, the size of system indicated for test and evaluation (T and E) is the size the developer feels can be scaled-up with confidence. For the needed tests, the extent of sampling and analyses was indicated. Methods of analysis were specified. From the information developed, T and E costs were estimated.

For most of the processes assessed, test systems are available from the developer. Most developers would need financial support of the testing time and effort. The availability of a suitable test system and any conditions/restrictions on its use were considered for each process.

Accident and spill prevention and counter-measures needs have been identified. Part of the estimated treatment cost is allocated to these factors.

The processes vary as to the strength and extent of their sponsorship. Some developers are commercial firms in the waste treatment business with resources committed to further commercialization of their process. Some developers have a need for financial support to achieve commercialization. In all cases, the short-term (2.5 years) effort projected in this evaluation, and the uncertainties of further markets make the construction of a full-scale treatment system contingent upon completion of the T and E (with attendant EPA approval of the process) followed by a contract for the cleanup work itself. Under these necessary conditions, all the processes assessed would be commercially available. The estimated time required to make them available varies from process to process, however, and this has been taken into consideration in this evaluation.

PROCESS EVALUATION

All the processes assessed have merit. In selecting among them, a ranking system has been employed for comparative simultaneous evaluation of all five criteria characteristics (Harrington, 1965). For each process, the desirability of immediate thorough test and evaluation was expressed by a [illegible]irability value, D_j:

$$D_j = (d_{1j} d_{2j} d_{3j} d_{4j} d_{5j})^{1/5} \tag{1}$$

where: d_{ij} = the rating of process j for criteria i for i from 1 to 5, $0.0 \leq d \leq 1.0$.

This function is a multiplicative decision model, although it may be regarded as a linear model if it is utilized in its logarithmic form. The methodology does not in its original form provide for weighting of the factors involved. Instead, it applies equal weights to all factors. Each factor may be weighted, however, by the application of an appropriate exponent. This is shown as follows:

$$D_{j,\text{modified}} = (d_{1j}^{x_1} d_{2j}^{x_2} d_{3j}^{x_3} \dots d_{nj}^{x_n})^{1/n} \tag{2}$$

where: x_i = the weight of factor i.

The logarithmic form is:

$$D_{j,\text{modified}} = 1/n\,(x_1 \log d_{1j} + x_2 \log d_{2j} + x_3 \log d_{3j} + \dots + x_n \log d_{nj}). \tag{3}$$

$$0 < d < 1$$

The value found for each characteristic, y, was transformed to a value of d according to the following judgements:

Value of d	
1.0-0.99	Represents the ultimate level of the characteristic y. Improvement beyond this point would have no appreciable value.
0.99-0.80	Acceptable and excellent. Unusually good performance.
0.80-0.63	Acceptable and good.
0.63-0.40	Acceptable. Some improvement is desirable.
0.40-0.30	Borderline acceptability.
0.30-0.01	Unacceptable. This one characteristic could lead to rejection of the process.

The scale of d so developed is a dimensionless scale to which any characteristic may be transformed so that it may be interpreted in terms of its desirability for the intended application. In this evaluation, the most cost-effective final process was sought that could be available in the shortest reasonable time.

A characteristic assessed on a numerical scale was transformed to the scale of "d" by the basic equation:

$$d_i = e^{-e^{0.77941[(-y_i + y_{il})/(y_{ih} - y_{il})}} \qquad (4)$$

In this equation: y_i is a value of a treatment process characteristic i;
y_{ih} is the acceptable valuable of yi; and
y_{il} is the borderline value of y_i.

Table 2 shows the acceptable and borderline values of y_i for each characteristic rated.

TABLE 2. ACCEPTABLE AND BORDERLINE VALUES FOR PROCESS CHARACTERISTICS

Characteristic	Acceptable Value[a]	Borderline Value[b]
Probability of cleaning to ≤ 2 ppm	0.9	0.3
Probable cost of treatment, $/m^3	100	300
T and E effort, $/1000	300	900
Test system availability, rating	0.9	0.3
Time to provide commercial system, months	18	36

[a] d = 0.63 for these values.
[b] d = 0.37 for these values.

The probability of cleaning to ≤ 2 ppm was set at 0.9 if such performance had been demonstrated with soils of any type, 0.8 if such performance was projected from test data, and 0.3 if no data were available. The use of 0.9 and 0.8 distinguishes slightly between processes reaching the goal of ≤ 2 ppm on initial tests and those for which reaching this goal could be projected from initial tests.

The probable cost of treatment was considered acceptable if \$100/m^3, and borderline if \$300/m^3.

T and E effort was considered acceptable up to \$300,000. Values above \$900,000 were considered borderline, but could be justified if the process had potential for lowering the cost of treatment, or rated extremely well on other [illegible]ired characteristics.

Test system availability was rated 0.9 for an available company-provided system with experienced operating staff and resources to commercialize the process; 0.8 if further government purchases were required to provide a system; and 0.3 if a suitable test system were not available.

Time to provide a commercial system sized to effect cleanup of 152,000 m^3 of sediment per year was considered acceptable at 18 months, but borderline if 36 months were required.

Using the values of the characteristics shown in Table 2, Equation 4 was applied to calculate the individual ratings shown for each process in Table 3. This table also shows the overall desirability rating of the process, calculated using Equation 1.

All the processes show acceptable "D" values. The Basic Extraction Sludge Treatment, UV/Ozone or Hydrogen/Ultrasonics, and Bio-Clean Naturally-Adapted Microbe processes show the highest values, and are recommended for immediate test and evaluation.

This recommendation does not mean that the other processes merit no fur[illegible]r T and E. The Potassium Polyethylene Glycolate (Galson), Low Energy Extraction (New York University), MODAR Supercritical Water Oxidation, and Critical Fluid Systems Propane Extraction processes rank very close to the top three. Thus these seven processes merit consideration for testing at least through the preliminary phases to confirm their performances. The Potassium Polyethylene Glycolate process rates lower primarily because of the high estimated cost of treatment.

The Low Energy Extraction process has a low rating because of the relatively higher cost of development that may be necessary and the length of time to commercialization. Uncertainty about the possible commercial sponsorship led to the lower rating for availability of a test unit. The $827,000 Test & Evaluation cost includes the cost of a pilot unit, however. For the other processes, this cost was not included because it was contributed by the developer or had already been purchased by the government. The estimated cost of treatment using this process is lower, however, than any other process. If this estimated cost could be attained, the development cost for the process adds only \$2.17/m^3 of sediment treated:

TABLE 3. OVERALL DESIRABILITY OF IMMEDIATE T AND E OF THE EIGHT CANDIDATE PROCESSES

	KPEG, Galson	Modar Supercritical Water	Bio-Clean	UV/Ozone-Hydrogen/ Ultrasonics Technology	CFS Extraction	B.E.S.T.	Low-Energy Extraction	In Situ Vitrification
Probability of cleaning to ≤ 2 ppm	0.9	0.8	0.8	0.8	0.8	0.8	0.9	0.9
d rating	0.63	0.59	0.63	0.59	0.59	0.59	0.63	0.63
Probable cost of treatment, $/m^3	160-191	86-136	156	90-120	153-264	133	50-57	443-483
d rating	0.54[a]	0.62	0.57	0.63	0.50	0.59	0.68	0.16
T and E effort								
$1000	216	483	166	151	123	149	170-827[b]	400
d rating	0.66	0.56	0.68	0.69	0.69	0.69	0.64	0.59
Availability of a system for a test								
Future purchase by govern. required							0.8	0.8
future purchase by govern. not required	0.9	0.9	0.9	0.9	0.9	0.9		
d rating	0.63	0.63	0.63	0.63	0.63	0.63	0.59	0.59
Likely future availability of the process								
months	19.5	21.5	19	21-24	25	19	25	19-24
d rating	0.62	0.59	0.62	0.59-0.55	0.54	0.62	0.54	0.62-0.55
Overall desirability, D								
earliest future avail.	0.615	0.60	0.617	0.625	0.59	0.623	0.614	0.46
latest future avail.	0.615	0.60	0.617	0.616	0.59	0.623	0.614	0.45
average	0.615	0.60	0.617	0.621	0.59	0.623	0.614	0.46

[a] Average cost used for rating.

[b] Cost of $170,000 if developed by sponsoring firm. A cost of $280,000 was used in the evaluation to allow for the uncertainty.

$$\$827.000 + 380.000\ \mathrm{m}^3 = \$2.17.$$

This would have a small impact on the final treatment cost, if added to the estimated \$76-\$83/m^3. From this point of view, the major obstacle to a higher rating for this project is the 25-month development time required, and the lack of a firmly committed commercial sponsor for the test system.

The MODAR process has a high T and E cost, but a potential application to a broad range of contaminants besides PCBs.

The In Situ Vitrification process has the highest estimated cost of treatment, which derives in significant proportion from the cost of electricity and consumable electrodes used in the treatment. As previously mentioned, the advantages of in situ treatment could not be had in the treatment of submerged sediments. The fact that a solid mass is the product presents a problem in disposal. The process appears best suited for in-situ fixation of radioactive wastes.

APPLICATION OF ALTERNATIVE PROCESS SELECTION METHODOLOGY

While this project was under way, an alternative process selection methodology became available at HWERL. The methodology is available as a computer program entitled "d-SSYS, A Computer Model for the Evaluation of Competing Uncertainties," (Klee, 1987). This method was applied in addition to the Desirability Function approach.

The D-SSYS calculates weights for each evaluation factor using values of weight ratios assigned by the user. Weight ratios were assigned to emphasize the importance of the ranges of treatment cost and test-and-evaluation cost. The range of ratings for probability of cleaning to ≤ 2 ppm PCBs is only 0.1 (Table 3), indicating that all the processes might reasonably be expected to meet the requirement. The availability of a test system was not considered as important as the total test and evaluation cost. The time required to make a commercial process available showed a range of only six months, and was judged of lesser importance than the two major costs assessed. All ratios among the five factors that resulted from these assignments are shown below as a matrix. For example, the ratio (test system availability)/(T and E cost) is shown as the intersection of Row 4 and Column 3 as 0.2.

	Clean to 2 ppm	Cost	T & E Cost	Test System Availability	Early Commercial Availability
Clean to 2 ppm	1	0.2	0.2	1	0.8
Cost	5	1	1	5	4
T and E Cost	5	1	1	5	4
Test system availability	1	0.2	0.2	1	0.8
Early com. availability	1.25	0.25	0.25	1.25	1

From these ratios and the following tabular algorithm, the factor weights (W) were generated.

Factors	Ratios	w	Weights, W
Clean to 2 ppm	0.2000	0.20	0.0755
T and E Cost	4.000	1.00	0.3774
Future commercial proc.	1.25	0.25	0.0943
Test system availability	0.2000	0.20	0.0755
Cost	5.000	1	0.3774
		2.65	

The procedure for weight generation is as follows:

Construct an intermediate weighting scale (the w-column) by the following procedure. Opposite that last factor enter a "1". The remaining numbers in this column are formed by the product of its predecessor and Ratio value opposite it in a sort of zigzag route up the column. For example, the first w-value, 0.20 is the product of the second w-value (1.00) and the first Ratio-value (0.2000).

- Total the w-values. This total is 2.65. Construct a column of standardized weights by dividing each element of the w-column by this total to obtain the W-column. The elements in the W-column will, perforce, total one.

The program then scales the factor scores to obtain a linear utility function:

$$y' = b_0 + b_1 \text{ (factor score)} \qquad (5)$$

$$0 < y' \leq 1.$$

In applying the scaling procedure to the two factors "Probability of Cleaning to $\leq$ 2 ppm" and "Availability of a Test System," it is noted that these are positive factors (the higher the factor score, the better the proc-al and the 'y' values are obtained by:

$$y'_{ij} = \frac{\text{score}_{ij} - \text{minimum score}_{ij}}{\text{maximum score}_{ij} - \text{minimum score}_{ij}} \qquad (6)$$

The other three factors are noted to be negative (the higher the factor score, the worse the process) and the y' values are obtained by:

$$y'_{ij} = \frac{\text{maximum score}_{ij} - \text{score}_{ij}}{\text{maximum score}_{ij} - \text{minimum score}_{ij}} \qquad (7)$$

The y'_{ij} values for the five factors by which each of the eight processes were assessed are given in Table 4.

TABLE 4. SCALED RATINGS OF EIGHT TREATMENT PROCESSES

	Clean to 2 ppm	Probable Tr. Cost	T & E Cost	Test System Availability	Early Commercial Availability
KPEG (Galson)	1	0.59	0.75	1	0.92
MODAR	0	0.87	0.043	1	0.58
Bio-Clean	0	0.67	0.89	1	1
UV/OZ or H_2/Ultrasonics	0	0.89	0.93	1	0.42
CFS Propane Extraction	0	0.45	1	1	0
C.S.T.	0	0.77	0.93	1	1
Low Energy Extraction	1	1	0	0	0
In Situ Vitrification	1	0	0.26	0	0.58

Depending on the users degree of risk that he is willing to accept, d-SSYS fits a utility function to the y' values via the following function:

$$\text{utility} = y'^{f} . \qquad (8)$$

The exponent f is evaluated by presenting the user with a structured lottery.

d-SSYS requires a comparison between two simple lotteries for each factor rated.

Lottery 1 = | 50% chance of most undesirable rating.
| 50% chance of most desirable rating.

Lottery 2 = | X value of the rating for certain.

Using probable treatment cost as an example, RTI selected for Lottery 1:

50% chance of a treatment cost of $\$313/\text{m}^3$
50% change of a treatment cost of $\$80/\text{m}^3$

and an X value equal to the mathematical expectation of Lottery 1 for Lottery 2:

$$(0.5 \times \$313) + (0.5 \times 80) = \$196.50/\text{m}^3.$$

The value of $\$196.50/\text{m}^3$ on the y' scale is

$$y' = \frac{\$313 - \$196.5}{\$313 - \$80} = 0.5$$

The utility of Lottery 2 is easily determined, since it is equal to the utility of Lottery 1:

$$(0.5)(\text{utility of } \$313/\text{m}^3) + (0.5)(\text{utility of } \$80/\text{m}^3) = (0.5 \times 0.0) + (0.5 \times 1) = 0.5.$$

From Equation 8:

$$f = (\ln \text{utility})/\ln y' \qquad (9)$$

$$f = (\ln 0.5)/\ln 0.5 = 1$$

Note that if Lottery 2 had been set at a lower cost for certain, f would have been greater than 1 and the function would have been a risk-taking one, in that one would be willing to pay more for Lottery 1 in the hope of gaining a treatment cost of $\$80/\text{m}^3$.

The remaining utilities for each factor are then calculated using Equation 8 (Klee, 1987, p. 23).

Using the ratings scaled by Equation 8, the program computes an overall deterministic score for each treatment process as the sum of the scaled factor ratings times the scaled factor weights. Using the factor ratings of Table 44 (which equal the utility when f = 1) and the weights cited above, the following deterministic scores were obtained for the treatment processes (Table 5).

TABLE 5. DETERMINISTIC SCORES FOR TREATMENT PROCESSES

Process	Score
Basic Extraction Sludge Treatment	0.8127
UV/Ozone or Hydrogen/Ultrasonics	0.8010
Bio-Clean Naturally-Adapted Microbe	0.7583
Potassium Polyethylene Glycolate, Galson	0.7434
Critical Fluid Systems (CFS) Propane Extraction	0.6214
MODAR Supercritical Water Oxidation	0.4738
Low Energy Extraction, New York University	0.4529
In Situ Vitrification, Battelle	0.2299

The highest scores were attained by the Basic Extraction Sludge Treatment, UV/Ozone or Hydrogen/Ultrasonics Technology, and Bio-Clean Naturally-Adapted Microbe processes, the same processes that ranked highest using the Desirability Function ranking methodology. These are recommended for immediate test and evaluation.

In the application of this ranking, probable treatment cost and test and evaluation cost were assigned weights 4 to 5 times those of the other three factors. This increased emphasis on the costs involved did not change the top three processes. With different weights assigned, it would be possible to obtain a different ranking of the processes.

CONCLUSIONS

Eight emerging treatment processes for decontamination of PCB-contaminated sediments have been evaluated as candidates for thorough test and evaluation (T and E) using a test system judged of sufficient size by the developer to provide performance, cost, and scaleup data for a large commercial plant. The processes assessed include: Basic Extraction Sludge Treatment (B.E.S.T); Bio-Clean Naturally-Adapted Microbe; Critical Fluid Systems Propane Extraction; Potassium Polyethylene Glycolate, Galson; Low Energy Extraction, New York University; MODAR Supercritical Water Oxidation; UV/Oxone or Hydrogen/Ultrasonics Technology; and Battelle In Situ Vitrification.

The processes were evaluated using as criteria:

- The probability of cleaning sediments to ≤ 2 ppm PCBs;
- The probable cost of treatment;

- The relative level of Test and Evaluation effort to be supported by EPA;
- The availability of a processing system to test; and
- The likely future commercial availability of the process.

While all the processes except perhaps In Situ Vitrification merit further development for treatment of sediments, comparative simultaneous evaluation of their ratings on a scale of 0 to 1 gave the following results:

	Relative Desirability of Thorough Test and Evaluation	
Process	Desirability score	d-SSYS score
Basic Extraction Sludge Treatment, Resources Conservation Company	0.623	0.8127
UV/Ozone or Hydrogen/Ultrasonics Treatment, Ozonic Technology, Inc.	0.621	0.8010
Naturally-Adapted Microbes Process, Bio-Clean, Inc.	0.617	0.7583
Potassium Polyethylene Glycolate (KPEG), [illegible]lson Research, Corp.	0.615	0.7434
Low Energy Extraction, New York University	0.614	0.4529
Supercritical Water Oxidation, MODAR, Inc.	0.600	0.4738
Propane Extraction Process, Critical Fluid Systems	0.590	0.6214
In Situ Vitrification, Battelle	0.460	0.2299

The Basic Extraction Sludge Treatment Process (Resources Conservation Co.), UV/Ozone or Hydrogen/Ultrasonics Technology, and Bio-Clean Naturally-Adapted Microbe processes have the highest ratings, and are recommended for immediate thorough test and evaluation. This evaluation was confirmed using the d-SSYS Computer Model for the Evaluation of Competing Alternatives (Klee, 1987).

The Potassium Polyethylene Glycolate (Galson), Low Energy Extraction (New York University), MODAR Supercritical Water Oxidation, and Critical Fluid Systems Propane Extraction processes ranked very close to the top three. These processes have potential for treatment of a broad range of hazardous contaminants and are recommended for at least those preliminary phases of thorough test and evaluation which confirm performance and establish process [illegible]meters for pilot-scale tests.

References cited are identified fully in the full report.

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