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Leak Detection Systems for Uranium Mill Tailings Impoundments with Synthetic Liners

Prepared by D. A. Myers, S. W. Tyler, P. J. Gutknecht, D. H. Mitchell

Pacific Northwest Laboratory
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U.S. Nuclear Regulatory Commission
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ABSTRACT

This study evaluated the performance of existing and alternative leak detection systems for lined uranium mill tailings ponds. Existing systems for detecting leaks at uranium mill tailings ponds investigated in this study included groundwater monitoring wells, subliner drains, and lysimeters.

Three alternative systems which demonstrated the ability to locate leaks in bench-scale tests included moisture blocks, soil moisture probes, and a soil resistivity system. Several other systems in a developmental stage are described. For proper performance of leak detection systems (other than groundwater wells and lysimeters), a subgrade is required which assures lateral dispersion of a leak. Methods to enhance dispersion are discussed.

Cost estimates were prepared for groundwater monitoring wells, subliner drain systems, and the three experimental systems. Based on the results of this report, it is suggested that groundwater monitoring systems be used as the primary means of leak detection. However, if a more responsive system is required due to site characteristics and groundwater quality criteria, subliner drains are applicable for ponds with uncovered liners. Leak-locating systems for ponds with covered liners require further development. Other recommendations are discussed in the report.

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EXECUTIVE SUMMARY

The objective of this study was to evaluate the performance of existing and potential alternative systems for leak detection at uranium mill tailings ponds. Systems were evaluated with respect to their function, design requirements, and estimated capital and operating cost.

Existing systems examined were groundwater monitoring wells, lysimeters, and subliner drain systems. Three experimental systems examined in detail were a moisture block array, a soil moisture probe, and a soil resistivity system. Four other systems briefly addressed as potential methods for leak location were time domain reflectometry, acoustic emission, fiber optics, and tensiometers.

The study recommends that liner leaks be detected through groundwater monitoring wells. The well network is suggested to determine baseline groundwater quality and to indicate when contamination has reached the groundwater. Lysimeter wells is the only other system with this capability; however, there is no advantage in using lysimeters to sample the saturated zone. Groundwater wells are inexpensive to construct in relation to the impoundment cost. Maintenance and analytical costs are estimated to be \$8500/yr for a system of 10 wells.

Depending on site-specific characteristics, additional leak detection systems may be required at a mill; however, such systems are expensive. Leak detection requirements for each site will need to be determined based on the hydrogeology of the site, the pond design, and groundwater quality criteria.

A subliner drain system may be required at a site with a high water table for relieving water pressure on the underside of a liner. In this case, the drain system could also be a leak detection system. The subliner drain system is also recommended for lined evaporation ponds with neither soil cover nor tailings. In this situation a leak can be located by visual inspection after a pond is drained.

If site characteristics and groundwater quality criteria necessitate a system capable of pinpointing leaks, the soil resistivity system, consisting of electrodes buried in soil around the perimeter of a pond, is the most economically attractive of the three systems tested at PNL. It would increase the cost of a 16.2-ha impoundment by about 50%; however, it requires large-scale verification. The moisture block system is more expensive and the expected operating life of moisture blocks limits their applicability. The soil moisture probe has high manpower requirements, making the system operating cost unreasonable.

The three experimental leak-locating systems require a subgrade which laterally disperses moisture. The subliner drain system requires a saturated medium around the drain. Recommendations for subgrades for each system are discussed. A major cost element of the three experimental leak-locating systems is the special medium below the liner required to laterally disperse a

leak. Two promising systems which may not require special subgrade preparation are fiber optics and time domain reflectometry. These systems require further investigation to determine their practicality.

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If site characteristics and groundwater quality criteria necessitate a system capable of pinpointing leaks, the soil resistivity system, consisting of electrodes buried in soil around the perimeter of a pond, is the most economical. Fully attractive of the three systems tested at PML, it would increase the cost of a 10.5-in impoundment by about 50%; however, it requires large-scale verification. The moisture block system is more expensive and the expected operating life of moisture blocks limits their applicability. The soil moisture probe has high manpower requirements, making the system operating cost unreasonable.

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INTRODUCTION

Uranium milling operations generate large quantities of spent leachate and tailings which are stored in impoundments usually constructed with either clay or synthetic liners. Leachate is separated from the tailings at some mills and collected in evaporation ponds constructed only for liquids. Although present technology is capable of preventing waste liquid discharges to the environment through the use of synthetic pond liners, the long-term reliability and integrity of these liner systems has not been proved. Montague (1982) reports synthetic liner leakage rates of 200 to 400 liters per day due to geomembrane failure at several lined landfill sites in New Jersey. Leak detection systems currently used at uranium mills (subliner drains and wells) can detect leaks only after a significant volume of fluid has penetrated the liner. Since maintaining groundwater quality beneath a disposal area is the objective of lined tailings ponds, other systems were investigated that would enable liner repairs to be made prior to significant groundwater degradation.

Leak detection and control systems have been recommended by the U.S. Nuclear Regulatory Commission (NRC) for use beneath all uranium mill tailings ponds (Graves 1982; Scarano 1981). A summary of the recommendations is included below:

1. Leak detection systems should be able to detect leaks before groundwater degradation occurs.
2. A differentially permeable, layered subgrade with a drain system is recommended for small evaporation ponds.
3. Large tailings ponds require downgradient monitoring wells and appropriate remedial actions if it is determined that groundwater contamination has occurred.

The Pacific Northwest Laboratory (PNL)^(a) has evaluated various leak detection systems as part of a study on lined mill tailings impoundments for the NRC. The purpose of the study was to determine the capabilities and limitations of existing and potential leak detection systems for uranium mill tailings ponds.

Monitoring wells, lysimeters, and subliner drain systems are methods currently used to detect leaks at uranium tailings ponds. The functions of these three systems, as well as moisture blocks, tensiometers, soil moisture probes, resistivity, time domain reflectometry, acoustic emission, and fiber optics, are described in the section on leak detection systems. Also included are results from laboratory-scale demonstrations of the moisture block, soil moisture probe, and soil resistivity systems.

(a) Operated by Battelle Memorial Institute.

Each of the experimental systems requires lateral dispersion of a leak for either proper detection or improved economics. Methods to enhance lateral dispersion of a leak are described in the report.

Cost estimates for six leak detection systems have been included in order to determine which systems are most cost effective.

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(2) Operated by Battelle Memorial Institute.

CONCLUSIONS AND RECOMMENDATIONS

The requirements for leak detection systems at a uranium mill will depend on site characteristics, mill design, and groundwater quality criteria. Site characteristics which may affect detection system requirements include groundwater depth and gradient, aquifer use, hydraulic conductivities of substrates, and soil neutralization and ion exchange capacities. Mill design features affecting the decision are leachate composition, the quantity and location of tailings and evaporation ponds, and pond operating life. Important groundwater criteria include the allowable contaminant levels in groundwater, if any, in the event of a leak.

Based on the above data, minimum leak monitoring requirements will need to be established for each site. Additionally a plan must be prepared which dictates required actions by the mill operation when a leak is detected by a monitoring system. The options may include pond closure, drainage, and/or repair. Containing contaminated groundwater with a long-term pumping program is another alternative.

Groundwater monitoring wells discussed in this report are recommended at every site. These wells should be located to provide water samples to determine baseline water quality and also to determine if contamination of groundwater has occurred because of a leaking pond. At an installation with more than one impoundment, it is recommended that pond spacing and well placement be such that data from wells can determine which pond is leaking.

Quarterly sampling and analysis of groundwater is recommended. Because sulfate, calcium, sodium, iron, and selenium plumes are expected to precede plumes of other contaminants at a typical site (Rahn 1978), analysis for these components is highly recommended. Analysis for radionuclide contamination is needed for baseline characterization. Requirements for quarterly radionuclide analysis should depend on site-specific factors. The criterion recommended for determining that a leak has occurred when using groundwater wells is a significant increase in concentration of any component which may be attributed to a leaking pond.

Even though a groundwater monitoring well system will indicate that a leak has occurred, the interval between leak occurrence and detection may be as long as several years depending on hydrological conditions. The consequences of not detecting a leak more rapidly must be shown to justify the additional cost of installing a more responsive leak detection system. For example, if groundwater quality criteria require that no increase in groundwater contaminant levels is allowed, a more responsive leak-detection system may be required.

A properly designed drain network below a liner is a proven leak detection system with rapid response. The system is most applicable at lined evaporation ponds without tailings or soil cover because after a leak is detected, its location may be determined by visual inspection of the liner when the pond is drained. Subliner drains are also applicable at sites where a high water table

may damage the synthetic liner or interfere with other types of leak detection systems. The cost of a drain system can vary dramatically, depending on the native materials available at the site.

For ponds with the liner covered by tailings or soil the use of a leak-locating system may be required if technology exists to repair the liner once a leak is located. Of the experimental systems tested in this study, the peripheral soil resistance system is the most promising economically and technically although it still requires large-scale demonstration. The limited operating life of moisture blocks precludes their use, and the operating costs of the soil moisture probe system are prohibitive.

Detection systems designed to concentrate on sections of liners such as seams with higher potential for developing leaks are a possible alternative to broad-scale monitoring. Many systems described in this report can be adapted to monitoring a series of seams. Hybrid systems using finely spaced observation points in the vicinity of seams and broadly spaced detectors elsewhere could reduce detection system costs by as much as 60%. PNL recommends that NRC consider detection systems below seams as an alternative to monitoring entire ponds.

Lateral dispersion of moisture is recommended for the experimental leak-locating systems examined in this study. A fine-grained layer over a coarse gravel layer is required for proper performance of the soil resistivity system tested. Lateral dispersion of leaks increases the spacing interval for moisture blocks and soil moisture probe systems, thereby decreasing system costs.

Promising new developments such as high density/cost-effective surveillance tools for lined ponds should be pursued. These systems include time domain reflectometry and fiber optic methods.

LEAK DETECTION SYSTEMS

This section discusses the functions, advantages, disadvantages, and applications of different leak detection systems which may be used at lined uranium mill tailings ponds. Some of these systems, such as groundwater monitoring wells, subliner drains, and lysimeters (moisture extraction cups), have been employed at mills, while others have had very few or no applications as leak detectors. The latter group includes moisture blocks, tensiometers, soil moisture probes, soil resistivity systems, time domain reflectometry, acoustic emission and fiber optics. Waller and Davis (1982) listed experimental systems including some of the above which may be applicable for leak detection at uranium mill impoundments. They found that none of the systems had detected leaks prior to groundwater contamination at existing lined landfill sites.

There are three basic methods by which a leak in a synthetic lined pond can be detected. The first method is by detection of contamination of the groundwater. Groundwater monitoring wells and lysimeter wells fall into this category. A second method is by collecting the leaking fluid or a portion of it before it reaches the groundwater. Examples of this detection method are drains below a liner, drains between two liners, and lysimeters in unsaturated zones under the liner. The third method of leak detection measures some physical change created by a change in the soil moisture beneath the liner. Some examples of this method are soil moisture blocks, soil resistivity techniques, and soil moisture probes. There are many other techniques which fall into this category. Because of these different means of detection there are advantages and disadvantages to each system which are discussed in subsequent sections.

REQUIREMENTS FOR LEAK DETECTION SYSTEMS

The requirements for a leak detection system for a lined impoundment need to be determined on a site-specific basis. The factors which should affect the requirements for a leak detection system at a uranium tailings pond include 1) the hydrogeology of the site, 2) pond design, and 3) the groundwater quality requirements.

The hydrogeology of the site will affect the liquid discharge rate through a hole in a synthetic liner, thereby affecting the time required for contamination of groundwater and the extent of the contamination. Important factors which need to be addressed are the depth and gradient of the groundwater; hydraulic conductivities, porosities, and moisture content of the soils under the lined pond; and soil neutralization and ion exchange capacities.

The factors of the pond design which may affect the requirements for a leak detection system are 1) pond sizes, depth, and operating life; 2) leachate composition; and 3) presence of tailings or soil cover on the liner. The pond size, depth, and operating life tie in with the previous discussion of the behavior of a leak since these factors also affect the probability of a leak affecting the groundwater. Leachate composition is required to assess the potential contaminants' travel through the soil. The presence or absence of

soil or tailings on the liner will affect the requirement for leak detection systems because of differences in methods of locating and repairing leaks in covered and uncovered liners.

Groundwater quality regulations will affect leak detection system requirements. Proposed regulations (USEPA 1983) state that there will be no increase allowed over background levels of most hazardous chemicals in groundwater downgradient of a tailings pond. Enforcement of this proposed rule would suggest that more responsive leak detection systems will be required. If the groundwater quality criteria were based on the proximity of other aquifer users and the nature of the aquifer use, then leak detection requirements at some sites might be less stringent.

SYSTEMS USED AT URANIUM MILLS

Several leak-detection systems have been installed at operating uranium mills. Groundwater monitoring wells are the most common system; however, several sites use subliner drainage systems, and lysimeters are used to a lesser extent.

Monitoring Wells

A groundwater monitoring well system is one of two leak detection systems that can be used to determine whether the groundwater has been contaminated and if so, the severity of contamination. (Lysimeters can also detect groundwater contamination.)

The effectiveness of a monitoring system based solely on wells is determined by the degree to which the local hydrogeology has been defined. It can be expected that a series of wells will need to be drilled before the final, optimized monitoring network evolves.

Monitoring wells serve as an access point from which to obtain a sample for analysis, and therefore must be constructed in a manner to assure sampling from the desired horizon. In addition, they must be placed in the proper lateral direction and at the optimum distance in relation to the dispersion characteristics of the aquifer materials.

A monitoring well system is not able to pinpoint a leak in a pond. However, a network of wells can be used to determine which pond is leaking in a multiple pond system.

Monitoring wells cannot be considered a leak containment system. Larger wells are required to recover diluted contaminants in groundwater downgradient of a leaking pond.

One disadvantage of monitoring wells is that they are only able to detect leaks that have existed for some time (perhaps years). When a leak occurs at a typical uranium tailings pond, a relatively harmless contaminant plume is expected to reach the groundwater prior to the more toxic substances (Rahn and

Mabes 1978). Even though the initial contaminant plume may be relatively harmless, it still may be unacceptable. Another disadvantage of groundwater wells is that anomalous contaminant readings sometimes occur and therefore results of the sampling are sometimes inconclusive.

Pressure/Vacuum Lysimeters

A pressure/vacuum lysimeter, also known as a moisture extraction cup, consists of a porous ceramic cup and two tubes that lead from the cup to the surface. The lysimeter is set in a borehole surrounded by a pure silica powder which protects the cup from clogging by formation fines. A bentonite or grout seal is placed above the instrument to hydraulically isolate its position vertically. A vacuum is applied to the tubes, drawing soil water or groundwater into the cup. Pressure is then applied and the liquid sample is collected at the surface.

An advantage of a lysimeter is its ability to sample both saturated and unsaturated zones. Additionally, a series of lysimeters in a single well can provide a profile of contaminant concentration with depth. Disadvantages include a limited sampling radius, fragility, special installation procedures, and difficult maintenance. Due to the limited sampling radius, a large number of lysimeters are required for a pond leak detection system. For sampling in the saturated zone, lysimeters have no advantage over groundwater wells.

Lysimeters are used at the lined uranium tailings pond operated by Dawn Mining Company at Ford, Washington. The system consists of 15 lysimeters surrounding the pond in unsaturated soil at the level of the bottom of the impoundment. From discussions with the mill operator it was learned that all but one of the lysimeters have performed satisfactorily over a 1.5 year period.

Subliner Drain Systems

Subliner drain systems that consist of gravel (and perhaps perforated pipes) are designed for use in saturated media. Drains will not detect or collect liquids in unsaturated systems. Leaking fluid will actually flow around a leak collection system when the media is partially saturated. As reported by Johnson et al. (1981), the large pores of a gravel drain (or pipe) are the first to be drained during initial dewatering and the last to be filled upon rewetting. The water is held under increasing tension as water content decreases in the small pores of a partially saturated soil. Saturation of the soil beneath an impoundment is not required for downward movement of liquid from a liner leak toward the groundwater table. Thus, liquid in partially saturated soil will first move, both horizontally and vertically, through fine-grained materials whose smaller pores are more readily filled with water.

Small (1980) states that while subliner drains employed to monitor leakage could identify large fluid losses and possibly contain leachate from uranium mill tailings impoundments, their primary functions would be to provide drainage of groundwater and to vent gas or air trapped beneath a liner. The effectiveness of subliner drains in collecting leaks is also questioned in the cut-

and-fill reservoir industry (Kays 1977). It is understood that flow into drains will only occur if the resistance to flow in the gravel blanket (surrounding the pipe) is less than that of the underlying substrate (whether it be a second liner or a compacted clay layer).

The design of the tailings impoundment for the Cotter uranium-vanadium acid-leach mill near Canon City, Colorado includes drainage systems above and below a synthetic liner. The purpose of the drains below the liner is to prevent reverse hydrostatic pressure, which could cause liner damage (Lubina et al. 1979). A network of finger drains was planned to intercept topographic low areas where springs might occur or water could accumulate. Numerous drains were also placed in highly fractured areas and where an existing pond had created a groundwater mound. A trench was cut into the soft rock to hold a perforated pipe surrounded by clean gravel. The gravel was wrapped in filter fabric to prevent migration of fines into the drains. Blanket drains were required in some small areas. This system will probably only detect very large liner leaks (those causing saturated flow beneath the liner) and would locate the leaks only to the degree that the system is broken into portions that drain to separate sumps.

Other uranium mills with subliner drains include Sweetwater, operated by Minerals Exploration Corp.; Bison Basin, operated by Ogle Petroleum Inc.; and North Platte, operated by Uranium Resources Inc. The latter two sites use 2.5 cm polyvinyl chloride pipe (slotted 30° below the horizontal centerline) placed in trenches cut in a low-permeability (10^{-5} cm/s), compacted subgrade. According to test reports submitted to NRC, a simulated leak of 4 L/min was detected at the Bison Basin Project, although the detection time lagged initiation of the leak by 54 hours. Higher leak rates had more rapid detection times.

Several hazardous waste landfills in New Jersey employ a leachate collection system between two liners of compacted clay or synthetic membranes (Montague 1982). Typically, the system consists of perforated pipe placed in low spots below a sloping landfill bottom. Leachate is pumped to a waste-water treatment plant. In cases where flow has developed in the drains, no groundwater degradation has been seen in groundwater monitoring wells. The leachate collection systems therefore seem to perform their function of leak collection. It appears that the gravel or sand layer between the two impermeable liners (in which the pipes are placed) becomes saturated as long as the lower liner remains intact.

The primary advantage of a drain detection system is that a liquid is collected that can be analyzed to positively determine whether a leak has occurred. Other systems which rely on some physical phenomena such as soil resistivity might falsely indicate a leak, which can be very costly to a mill operator. A disadvantage is the inability of such a system to pinpoint a leak so that repair is possible.

Design considerations which are critical to proper performance of a drain system are 1) the sub-base must have a permeability two orders of magnitude

less than the material in which the drains are placed, 2) the drains should be designed to prevent clogging by fines, and 3) the drains must be installed in a uniform slope without any low points where collected liquid could leak out of the perforated pipe instead of draining to the sump.

EXPERIMENTAL SYSTEMS TESTED AT PNL

Experiments were initiated to test three potential leak detection systems, with few applications: moisture blocks, a soil moisture probe, and a soil resistivity system. Each of the experiments was carried out in a laboratory and thus was limited in area to 61 cm x 61 cm x 30 cm. In each case, the principal soil type used was Hanford Sand. An additional experiment with the resistivity and moisture block systems used Palouse Soil, a fine-grained eolian material. An analysis of grain size distribution of both materials is given in Table 1. In each of the experiments, the moisture content of the soil was allowed to reach equilibrium before beginning a test.

TABLE 1. Grain Size Distribution of Hanford Sand and Palouse Soil

Sieve Size	Sieve Opening, mm	% Retained	
		Hanford Sand	Palouse Soil
>20	0.841	5.8	--
20 x 40	0.42 - 0.841	50.0	--
40 x 70	0.21 - 0.42	23.0	--
70 x 100	0.149 - 0.21	7.3	--
100 x 200	0.074 - 0.149	9.1	2.8
200 x 325	0.044 - 0.074	4.7	6.5
<325	0.074	--	90.1

Moisture Blocks

A moisture block consists of two electrodes embedded in a porous block of gypsum. The use of moisture blocks to measure changes in soil moisture content has been a common practice for many years. The 6 cm³ blocks are responsive to changes in soil capillary pressure over a wide range. Response time is relatively short, with the blocks coming to equilibrium within hours after a rapid change. Moisture content is determined by reading the electrical resistance across each block, which must be calibrated in the soil in which it is to be used.

Moisture blocks have not yet been commonly applied as leak detection systems. To use them as leak detectors, an array of blocks would need to be placed below a liner and wired to a central readout position. The number of blocks necessary would depend upon the unsaturated flow characteristics of the underblanket and the desired level of accuracy in leak location. Blocks would require calibration for the type of material in which they are placed.

Moisture blocks would serve as leak detection and location devices, but would not, under most circumstances, measure leak severity. Furthermore, they would probably not be applicable in areas which could be influenced by the presence of a shallow water table. This limitation would become more severe if the water table fluctuated enough to reach the liner bottom. Also, great care would have to be taken during installation of the underblanket and liner to avoid damaging the detector array.

Another disadvantage of a moisture block system is that its effective life in the environment below a tailings pond is not known. In agricultural applications, manufacturers quote lifetimes of 2 to 8 years. The failure mode is either loss of calibration due to buildup of salts or dissolution of the gypsum. The blocks below a pond cannot be recalibrated or replaced.

If a leak were detected using these instruments, the liner repaired, and the pond returned to service without replacement of the base materials, a subsequent leak of the repaired section might not be detected unless the base materials had had sufficient time to dry.

An experiment was designed to test the potential of moisture blocks as a liner leak detection system. The experiment also helped determined the frequency at which moisture blocks must be spaced to detect moisture from an unknown location.

The basic experimental arrangement and devices used for the testing of soil moisture blocks as leak detection devices are shown in Figure 1. Leaks can be detected and recorded using this system.

Instead of measuring soil moisture directly with a soil moisture meter (a recalibrated resistivity meter) we applied a constant, regulated alternating current (ac) voltage across the blocks and measured the voltage drop across each block. Tap water with a conductivity of about 150 $\mu\text{mho/cm}$ was added to a randomly selected control location at a known rate. Readings were taken every 1 to 2 hours to determine an arrival or detection time.

As illustrated in Figure 2, with an average leak rate of 1 L/h, the moisture front moves rapidly downward in Hanford soil, affecting the first moisture block within 30 minutes. Lateral spread of the moisture front then comes into prominence as indicated by the adjacent blocks during subsequent periods. Nearly all the blocks detected the moisture front within 24 hours. This experiment is of particular significance because it duplicates a typical subgrade to be found beneath mill tailing impoundments. The container simulates a well-compacted base material with very limited vertical hydraulic conductivity; on the limited scale of the experiment, it also approximates the lateral flow created by a radical increase in hydraulic conductivity of an underlying component of the subgrade. Based on this, any one of the moisture blocks would have detected the simulated leak.

FIGURE 1. Arrangement of Moisture Blocks

FIGURE 2. Typical Arrival Sequence of Moisture Front in Hanford Sand Reaching Moisture Blocks (ET = Elapsed Time)

In summary, a moisture block network is a potential leak detection system; however, limitations are a limited operating life (not practical for 20 year applications) and the requirement for dry ambient soil.

The rapid response (within 24 hours) to the leak makes this system a technically viable, early-response detection system. A spacing of 1 meter between instruments would give reasonable assurance of early detection and location of leaks beneath a tailings pond.

Soil Moisture Probes

The use of moisture probes (neutron attenuation devices) is a long accepted means of measuring soil moisture in vertical profiles. The instrument uses a neutron source (commonly americium/beryllium), which emits neutrons through a thin-walled metal casing into the soil. The neutrons are slowed and reflected back to a detector in proportion to the number of hydrogen atoms in the soil (the most common source of hydrogen atoms is interstitial water). The instrument requires calibration for the particular soil type being monitored.

An advantage of a soil moisture probe as a leak detector is that it can be calibrated and serviced at any time as opposed to moisture blocks, which are inaccessible. A disadvantage is that a moisture probe system requires much more manpower to operate than any of the other systems examined in this report. Another drawback to these systems is the necessary use of a radioactive source. Great care must be exercised in the use of the tool to assure it is not lost beneath the ground. In the case of borehole logging tools, the strength of the source necessitates radiation protection procedures for the people handling the equipment.

In the most common mode of use, a small diameter hole is bored down into the ground and cased with thin-wall metal pipe; the annulus between the casing and the borehole is carefully filled and recompactd with native soil and allowed to come to equilibrium. Soil moisture is then monitored by lowering the instrument to a given level in the hole, actuating the instrument, and recording the resultant count after a fixed time interval (determined by the specific instrument). The system described above has been a proven method of determining soil moisture to $\pm 1\%$ when calibrated for the soil in question. Aligning the instrument in the horizontal mode makes no difference in its accuracy; however, if it is to be placed beneath a saturated source such as a tailings pond, it must be placed at sufficient depth so that it does not "see" the pond.

An experiment was designed to demonstrate use of a soil moisture probe as a potential leak detection system below a lined pond. The soil moisture probe test apparatus is illustrated in Figure 3. The instrument used in the experiment was a Campbell Pacific Nuclear Model 503 Hydroprobe with a 10/50 mCi Am/Be source. The casing used was polyvinyl chloride because it would be more corrosion-resistant than steel or aluminum below a uranium mill pond.

FIGURE 3. Layout of Experiment Using Soil Moisture Probe

A 4 liter leak was simulated over a period of 20 minutes. This would increase soil moisture content by 4 vol% if distributed evenly throughout the volume of soil. The moisture front first reached the center of the test grid, showing that the water was not evenly distributed, but rather behaved as an actual leak would (see Figure 4). Table 2 gives the change in relative moisture (increases in count rate) with time for this portion of the experiment.

The data in Table 2 show that a change in moisture content (count ratio increase) is detected less than 10 minutes following addition of water to the experimental apparatus. The maximum increase in count ratio is equal to an increase in soil moisture of less than 3 vol%. The concentration of increased soil moisture values in Figure 4 illustrates the ability of the soil probe to locate a leak. Most negative values are due to fluctuations of the instrument. The large count rate drop (-484) is probably an erroneous reading.

FIGURE 4. Changes in Count Ratio Indicating Distribution of Soil Moisture Following a Simulated Leak in Soil Moisture Probe System

TABLE 2. Count Ratio Increases with Time for Soil Moisture Probe Experiment

Time	Count Ratio	Time	Count Ratio
0	1.000	18'30"	1.032
3'	1.010	19'20"	1.023
3'50"	1.015	20'	1.413
4'30"	1.003	20'35"	1.016
5'15"	1.003	22'20"	1.035
5'50"	1.008	23'	1.051
6'30"	1.013	23'25"	1.036
7'7"	1.014	24'5"	1.047
7'40"	1.015	27'	1.107
8'15"	1.026	28'6"	1.095
9'	1.015	29'17"	1.126
10'	1.025	30'30"	1.143
		4 h 48'	1.185

Resistivity

Several methods utilizing earth resistivity for detection of leaks have been advanced in recent years. These methods range from the use of wires beneath a pond to an array of probes in a standard configuration such as a Wenner or Schlumberger system described by Kaufmann et al. (1981) and illustrated by Davis and DeWiest (1966) (Figure 5).

FIGURE 5. Wenner and Schlumberger Resistivity Arrays (Davis and DeWiest 1966; reprinted by permission of John Wiley & Sons, Inc.© 1966, all rights reserved)

Leak detection by geophysical techniques is made possible due to the nature of electrical transmission through the soil. Electrical properties of earth depend upon the ionic concentration in the shallow, unsaturated materials overlying the water table. Moisture in the interstices of the soil particles tends to mobilize ions normally held on the particle surface. In addition, the fine layer of moisture increases the area of contact between soil particles. An increase in soil moisture increases the conductivity of a given soil because of these two phenomena, thereby increasing the amount of current that can be passed between two electrodes. If the fluid entering the unsaturated zone is of high ionic strength, then it will further increase the apparent conductivity along a given path.

A drawback to the use of resistivity/conductivity measurements as a means of leak detection is that the depth of penetration is proportional to the separation of the probes (Kaufmann et al. 1981). This problem is accentuated using the standard Wenner or Schlumberger systems, which were designed for exploration at increased depths. However, techniques that utilize sets of wires with close, even spacing (as in Figure 6) would not be affected. The method may be

FIGURE 6. Resistivity Array Using Sets of Electrodes (after Kaufmann et al. 1981; reprinted by permission of Ground Water Monitoring Review® 1981, all rights reserved)

affected by electrode separation, but when it is combined with the multiple layer approach (see Lateral Flow Enhancement section), the method can be constrained to examining a limited depth profile.

Resistivity/conductivity methods using fixed arrays lend themselves to continuous monitoring. They have the potential to be fully automated using computer control, thereby reducing the chance of human error while making the system an "around-the-clock watchdog."

Electrodes Beneath the Liner

Kaufmann et al. (1981) describe an electrode detection system installed beneath the lower liner of two evaporation ponds of a waste-water treatment facility being constructed in Arizona shown in Figure 6. The in-situ resistivity array will measure the apparent resistivities of soils beneath the ponds and note changes due to leakage of conductive fluids through the liner. Electrodes 14 m apart in a grid pattern are connected to individually shielded conductor cables buried in sandfilled trenches covered with compacted soil. A resistivity meter connected to the junction box where all the cables terminate surveys all the possible Wenner arrays. Readings are taken prior to filling the pond to create a baseline map of resistivity. A leak would drastically lower the resistivity of a few node points at the onset of leakage. The main disadvantage of this system is the inability to repair electrodes under the liner.

Surface Potential System

Peters et al. (1982) describe an electrical resistivity technique being developed for locating liner leaks in waste disposal facilities. The method is based on the fact that an impervious plastic or rubber liner will act as an electrical insulator between the materials above and below the liner. A puncture or separation in the liner (which allows fluid to escape) will create an electrical current path from the contained fluid through the soil. Current flow between two electrodes located inside and outside the liner will be different when a path is created through the liner than when current can only flow over the buried edges of the liner. The surface potentials can be used to locate leaks because they are directly related to the current distribution in the vicinity of the search electrode. This system is being investigated for the U.S. Environmental Protection Agency (EPA).

Major drawbacks of this surface potential system are that it requires 1) a liquid surface across the entire impoundment, 2) computer modeling of the flow-paths to pinpoint leaks, and 3) large-scale verification.

Peripheral Electrode System

The soil resistivity system tested on a small scale at PNL uses electrodes around the perimeter of a test plot. The advantage of this system is that

repairs or modifications to the electrodes can be made without disrupting pond use. Components buried under a pond (i.e., electrodes or moisture blocks) cannot be repaired.

The purpose of the soil resistivity system tested at PNL was to demonstrate the concept of a peripheral electrode system. The resistivity experiment conducted for this project consisted of an array of electrodes around the perimeter of the area to be monitored (Figure 7). Leaks were simulated with low-conductivity water. Experiments were run with both Hanford Sand and Palouse Soil. In each set of experiments, the leak was detected within hours of its initiation.

These tests demonstrated that certain precautions must be taken to assure that measurements are valid representations of subsurface conditions: 1) each electrode must be thoroughly tamped into place to assure maximum contact with the surrounding soil matrix, and 2) initial moisture content of the subgrade must be high enough so that the conductivity between points can be measured. In most instances, soil moisture sufficient to permit good compaction of a subgrade is adequate. Seepage through a liner would likely be sufficient to maintain electrical conductivity, but this needs to be tested at an arid site.

Figure 8 shows a typical response of the test apparatus to a spot addition of water. Initial response is along the most direct electrode pathway. Resistivity drops along additional pathways indicate the moisture is spreading laterally due to soil tension. Response is rapid, affecting the majority of the test apparatus in less than 20 hours. The test apparatus, as in the soil moisture block experiment, approximates a mill pond subgrade with an impermeable, low-conductivity sub-base. In this instance, the sub-base has minimal electrical conductivity as well as hydraulic conductivity.

In the experiment, both ac and direct current (dc) power sources were tested. At the low voltages used, ac power was the most appropriate. When dc power was used, the earth cell behaved as a randomly discharging capacitor, making voltage readings spurious at best and extremely difficult to measure with any assurance of accuracy. When the experiment was attempted on a larger scale, a portable ac generator was used to supply the power after reducing the output power from 115 V ac to 10 V ac. The variations in voltage were such that results could not be readily ascertained. Therefore, on larger-scale projects, it is essential that a constant voltage power supply be available. Small alternator/generator systems are not acceptable due to voltage surges inherent in such systems.

In conclusion, the tests demonstrated the feasibility of a peripheral soil resistivity system to detect a leak in a bench-scale test. Requirements of this system are a steady ac power supply, compaction of the soil around electrodes, and an initial soil moisture content which allows current to pass between electrodes. A fine-grained substrate layer between the liner and a gravel substrate is required to limit the current paths to a narrow layer below the liner. Due to the scale differences between this bench test and an actual

FIGURE 7. Layout of Probes for Peripheral Resistivity Experiment

FIGURE 8. Progression of Resistivity Pairs Showing Increasing Soil Moisture

tailings pond, large-scale testing of the peripheral electrode system is required for investigating the effects of ac paths through the liner and subgrade.

OTHER POTENTIAL LEAK DETECTION SYSTEMS

Time Domain Reflectometry

Huck (1982) discusses the feasibility of using time domain reflectometry for leak detection beneath landfill liners. Parallel transmission lines would be buried in the dry, granular backfill below the liner during construction. An electrical current would be pulsed down the lines; any change in the dielectric constant of the soil in the immediate vicinity of the liner would reflect down the line. These back-reflected pulses would then be analyzed to determine the location of the dielectric change. The moisture content could conceivably be measured along each line to detect any changes caused by liner leaks. A spacing of 3 m between lines would require 3400 linear meters of transmission line per hectare (2.47 acres) of landfill. The plastic materials used for landfill liners could be used for cable jackets to protect the transmission

lines from backfill materials and leachate because exposure of the lines to leachate could render them inoperable. Continued research on this system is in progress.

Acoustic Emission

Acoustic emission monitoring is also suggested for use in liner leak detection (Huck 1982). Since fluid flow through porous media emits acoustic signals, sensors located just above the landfill liner should detect any leachate movement through a liner leak. A laboratory study by Huck identified operational parameters such as heat loss and flow rate that may be used to predict acoustic emission rates. The system requires monitoring points such as a pipe that is capped at the bottom and sealed into the landfill so the sensor can be lowered to a point just above the liner. This system is also under continuing investigation.

Fiber Optics

An advanced system applicable to monitoring liner leaks using fiber optic technology has been proposed at PNL. In this system, fiber optics would be installed in a prepared subgrade. The increase or decrease in moisture content of the soil in contact with the fiber changes the reflectivity of the outer wall of the fiber. A pulsed light is transmitted down the fiber and the time of return for reflections analyzed. Because the speed of light is known for the fiber material, the distance to the reflectance anomaly is readily calculated. Theoretically, using off-the-shelf electronics, such a change in reflectance could be located to within ± 0.6 m over a 600 m span of optical fiber.

Tensiometers

Tensiometers were considered as a possible means of detecting leaks because they are similar to moisture blocks. A tensiometer consists of a buried, sealed, porous ceramic cup with a tube connected to a manometer at the ground surface. The tube and cup are filled with water and allowed to reach equilibrium. At that time, any change in soil moisture will effect a change in tension across the porous cup, which in turn is reflected by a change in pressure in the tube, measured with a manometer or a pressure transducer. These units could be used for leak detection; however, difficulties with installation, fragility, and plugging limit their usefulness in a long-term monitoring program.

LATERAL FLOW ENHANCEMENT

Because some of the leak detectors discussed in this report would be placed below a pond liner, early leak detection is enhanced by increasing the lateral migration of fluids once they have passed through the liner. Proper choice of substrate materials based upon their hydraulic properties induces lateral flow of leaking fluid below the liner, thus allowing leak detectors to be spaced further apart.

This section briefly describes the theory of flow of fluids in partially saturated porous media and its application to lateral flow enhancement designs. Effectiveness of various substrate designs in lateral flow enhancement is reviewed.

FLUID FLOW IN PARTIALLY SATURATED POROUS MEDIA

Flow in the partially saturated zone is governed by the hydraulic conductivity and matric potential of the soil. Hydraulic conductivity is defined as the ability of a porous medium to conduct a fluid under a hydraulic gradient (a function of the porous medium and the fluid [Bear 1972]). The matric potential of a porous medium is the sum of the energy states of the fluid, primarily the elevation (gravity forces) and the difference in pressure at the air-water interfaces in each pore (capillary forces).

In partially saturated flow, the hydraulic conductivity is a function of the capillary pressure of the media. When the media become less than fully saturated with water, the larger pores are the first to drain, and the fluid must flow through the smaller pores, which are less effective conductors of fluids. Also, an increase in capillary pressure causes the fluid in some pores to be isolated from the rest of the continuous-flow network. These combined effects drastically reduce the hydraulic conductivity as the capillary pressure becomes greater. This fact may be used to investigate the behavior of fluid from a point source leak into a uranium mill tailings pond substrate. Contrasts in unsaturated hydraulic properties of various pond substrate materials and the effect that layering of the materials has on leachate behavior are discussed in this section.

The use of multiple layers as infiltration barriers has been studied by Corey and Horton (1969) and Frind et al. (1976). These researchers placed a fine-grained soil over a coarse gravel on an inclined surface to investigate the "wick effect" or capillary barrier. Due to the differences in unsaturated hydraulic conductivity, fluid moving through the fine material was restricted to lateral movement in that layer. Zaslavsky and Sinai (1981) and Yeh (1982) also report significant horizontal flow occurring from vertical infiltration into a slightly sloping, stratified media. In all of these cases, fluid flow has been assumed to be two-dimensional, however, and little work has been completed on the subject of transient fluid flow in layered, partially saturated, porous media from point sources (pinholes or tears in liner material). The most promising research is Schwille's (1967), whose laboratory work on the flow

of petroleum spills into aquifers will be applied in assessing substrate designs for lateral flow enhancement.

TECHNIQUES FOR LATERAL FLOW ENHANCEMENT

This section outlines several substrate designs for lateral flow enhancement systems. In order to compare the effectiveness of each system, the following assumptions have been made:

1. The pond bottom and sides are lined with either a synthetic or natural material to reduce seepage into the substrate.
2. Substrate material is stable, i.e., free of shrinking or swelling material, to reduce stresses on the liner due to differential compaction.
3. The substrate is placed upon a compacted material with low hydraulic conductivity.
4. Leaks are considered as point sources of constant discharge. Also, leak rates greatly exceed the areally distributed flow as a result of the low but measurable hydraulic conductivity of the liner material.

Figure 9 shows the details of the liner-substrate-subgrade system. Because of the lack of analytical or numerical solutions for the flow systems to be analyzed, this section concentrates on the qualitative aspects of each system.

Subgrade Design No. 1 - Liner, High-Conductivity Sand, Compacted Sub-Base

This scheme is described by the NRC Technical Position Paper No. 302.3, WM8101 (Scarano 1981). On the sub-base of compacted, low-conductivity

FIGURE 9. Typical Pond/Subgrade Design

material, a coarse sand is placed and smoothed. At the sand/sub-base interface, drains or leak detection pipes could be placed. The liner is placed directly on the upper sand surface.

As this system responds to a leak, the wetting front will initially be spherical but will elongate vertically as the gravity forces begin to dominate the capillary forces. Upon reaching the lower-conductivity sub-base, the wetting front will spread laterally along the interface. The extent of lateral spreading at the interface will be a function of both the leakage rate and the conductivity contrast. High leakage rates and high contrasts in conductivity between the sand and the sub-base material will enhance this lateral spreading at the interface. High matric potentials will enhance lateral spreading within the sand layer (well above the interface); however, these potentials are not often found in a coarse, sandy material.

Subgrade Design No. 2 - Liner, Low-Conductivity Layer, High-Conductivity Layer, Sub-Base

In this design, the substrate material consists of two layers--the upper a fine-grained material (typically fine sand or fine, silty sand), the lower a well-graded gravel. As a wetting front moves through the upper, fine material, the water content of the fine material at the interface will increase as progressively larger pores become filled with water. This will increase the hydraulic conductivity of the fine material. The lower gravel layer, having predominantly large pores, will remain relatively dry and its hydraulic conductivity will remain low until the capillary pressure at the interface approaches zero. In horizontally stratified layers, water will enter the gravel layer only at points on the interface where the capillary pressure exceeds the water entry pressure of the gravel (essentially zero).

To enhance lateral flow, several methods employing this effect could be used. In the simple, two-layer case described above, spreading would occur at the interface. Schwille (1967) conducted laboratory experiments on oil spills into layered media. Figure 10 shows the results of a point-source oil spill into a two-layer system as described above. Although breakthrough into Layer B occurs early in the experiment, considerable lateral spreading of the oil along the interface between Layers A and B continues long after breakthrough. This behavior would be beneficial for both leak detection and fluid removal systems since a large cross section of the substrate would become wetted, and a large portion of the leaking fluid would move into the highly conductive lower layer, where fluid could be removed by drains. The extent of lateral spreading along the interface is a function of the horizontal hydraulic gradient and conductivity of the fine layer, the thickness of the fine layer, the contrast in hydraulic properties of the upper and lower layers, as well as the leakage rate through the liner. The positive effects described by Schwille are magnified

FIGURE 10. Infiltration of Oil into a Two-Layer Media (After Schwille 1967; reprinted by permission of The Institute of Petroleum® 1967, all rights reserved)

with a water-based system because the driving force (capillary pressure) and hydraulic conductivity are greater for water than they are for oil.

For those leak detection systems that require large volumes of wetted substrate before detection is possible (moisture blocks, soil resistivity, moisture probe), multiple layering of fine over coarse material in the substrate would increase the vertical cross section of the substrate that is wetted. This is because lateral flow will occur at each fine-over-coarse-material interface. This method, however, may significantly reduce the effectiveness of leak collection systems since considerable volumes of fluids will remain dispersed in the upper parts of the substrate and little fluid may reach collection drains located in the lower parts of the substrate or at the top of the sub-base.

Subgrade Design No. 3 - Liner, Substrate Layer Decreasing in Hydraulic Conductivity with Depth, Gravel Drain Layer, Sub-Base

In this design, the liner is underlain by materials of progressively lower hydraulic conductivity which in turn overlay a gravel layer designed to aid in leak collection. This design will provide a progressively larger, wetted cross section as the wetting front moves down through the substrate. Lateral spreading of the wetting front will occur in each layer due to the increasing impedance to flow. Schwille (1967) presents laboratory verification of this phenomenon. Figure 11 shows the positions of an oil wetting front moving through progressively less conductive material (Layers A, B, and C). Since Layer D is more conductive than Layer C, lateral spreading at this interface is similar to that in Figure 10. Layer E is a sub-base saturated with water. The behavior of the wetting front in Layers D and E is not applicable to this study because

FIGURE 11. Infiltration of Oil Into a Multi-Layered (Coarse-Over-Fine) Media (After Schwille 1967; reprinted by permission of The Institute of Petroleum© 1967, all rights reserved)

leachate will behave differently than oil at the saturated sub-base. This sub-grade design has little potential for use at a tailings pond because lateral flow is less than Design No. 2, and the cost is expected to be greater.

FIGURE 11. Infiltration of Oil into a Multi-Layered (Coarse-Over-Fine) Media (After Schwille 1967; reprinted by permission of the Institute of Petroleum 1967, all rights reserved)

leachate will behave differently than oil at the saturated sub-base. This sub-grade design has little potential for use at a landfill pond because lateral flow is less than Design No. 2, and the cost is expected to be greater.

COST ESTIMATES

Overall cost effectiveness of any proposed system to detect leaking mill tailings ponds is dependent on the actions to be taken following detection. An early detection system is more capital intensive than a groundwater monitoring system but, if a leak is found, cleanup costs will be lower. In addition, the mill operator will incur capital and operating losses if the pond must be closed because a leak cannot be located. The various systems are evaluated in this light.

The cost of any proposed system will be site-specific, controlled by factors such as geology, distance from suppliers, regional labor wages, etc. The following set of typical conditions has been identified to provide a basis for comparison:

1. Pit excavation is in fluvial sand and gravel deposits.
2. Depth to groundwater is 16 m.
3. Electricity is readily available.
4. Tailing pond size is 16.2 surface hectares (40 acres).

To simplify the analysis, all engineering, design, and consulting costs are excluded from the cost analyses.

MONITORING WELLS

A minimum of four monitoring wells are necessary to meet the basic requirements set by the U.S. Environmental Protection Agency (USEPA 1980). It should be recognized that under most circumstances EPA requires additional wells to adequately monitor a disposal facility of the magnitude of a uranium mill tailings pond. Therefore, a realistic approach to monitoring-well installation will require that a minimum of 10 wells be installed. Basic specifications for the wells for the reference case are as follows:

- drilled via air rotary, rotary wash or cable tool methods
- depth 23 m
- hole diameter 25 cm (drilled)
- casing diameter 15 cm
- casing material mild steel, schedule 40
- well screen 7.6 m, stainless steel, continuous wire wrap, 15-cm baildown
- gravel packed to 1.5 m above the screen

- bentonite pellet seal 1.5 m
- cement grout from bentonite seal to surface.

The initial cost of each well, drilled and completed to the above specifications, is about \$5000 based on experience at PNL. To retrieve a sample from a well, a permanently installed submersible pump is recommended, which adds another \$1000 to the total.

A pump sampling system does not require much maintenance during its lifetime (20 years). A pump failure rate of about 5% should be anticipated. EPA sampling occurs quarterly, causing minimal wear on pumping machinery; however, using the pump this infrequently may cause pump or well failure due to incrustation. More frequent operation of the pump can reduce the probability of this occurrence. Maintenance of the well structure itself is required periodically. Electrical power requirements are minimal. Manpower required to sample 10 wells is about 1 day per sampling trip. Analytical costs for each sample of water are dependent upon the number of analyses needed and the specific constituents analyzed for. PNL typically pays \$150 for a routine well sample analysis, which does not include measurement of radionuclides. Radionuclide analysis, which should be performed on initial baseline samples, will add \$500 to \$700 per sample. The costs of a monitoring well system are summarized in Table 3. If radionuclide analyses are required for all samples, then the analytical cost will be about \$24,000/yr higher than that estimated in Table 3.

TABLE 3. Cost Estimate for Monitoring Well System

<u>Capital Expense</u>	<u>Cost, \$</u>
10 wells installed at \$5,000 ea.	50,000
10 pumps installed at \$1,000 ea.	10,000
20 baseline water analysis at \$750 ea.	15,000
<u>Operating Expense</u>	<u>Cost, \$/yr</u>
Well maintenance	250
Pump maintenance	250
Sampling, quarterly	2,000
Analyses, 40/yr	6,000

MOISTURE BLOCKS

To assure that a leak can be detected to within a 3-m x 3-m area, the instrument density needs to be 1 block/m² for a total of 162,000 moisture blocks. These instruments need to be placed near the bottom of the prepared subgrade (see Figure 12). Measurements of the soil moisture are ideally taken automatically by a small, central computing system which can then print out a map showing any anomalous changes in soil moisture.

Placing moisture blocks close enough together to detect a leak within any 3-m x 3-m plot makes this option an expensive one. Current list prices for moisture blocks range from \$6 to \$10 each, making the instrument cost alone range from $\$1.0 \times 10^6$ to $\$1.6 \times 10^6$. For this cost estimate the lower price is used. Other installation costs include a two-layer system as shown in Figure 12, wiring, and the computer-based interrogation system.

A special subgrade is needed to promote lateral spreading of moisture so that several moisture blocks are affected. Where native soil permeability is low enough (about 10^{-5} cm/s) and groundwater will not affect the moisture blocks, the subgrade shown in Figure 12a will be sufficient and least costly.

FIGURE 12. Placement of Soil Moisture Blocks in Subgrade with
a) a Low-Permeability Sub-Base and b) a High
Permeability Sub-Base

The 15-cm layer of sand is required for liner placement and does not need to be included in the cost of the leak detection system.

At a site with higher native soil permeability or a high water table, a subgrade as shown in Figure 12b would be needed to disperse a leak. A minimum layer of 15 cm coarse gravel under a 15-cm sand layer is required. Using construction costs from Godfrey (1982), the additional cost of this gravel layer, which includes buying, loading, hauling (3.3 km), and spreading, is estimated at \$421,000.

The cost estimate summarized in Table 4 assumes that no additional subgrade costs are incurred for this leak detection system. At a site requiring additional subgrade construction, as in Figure 12b, installation costs would increase significantly.

Operating costs are minor for electricity and any data maintenance required by regulatory agencies. Data stored on computer discs could be backed by hard copies. Repair of failed probes is not possible due to their location so no maintenance costs are likely.

TABLE 4. Cost Estimate for Moisture Block System

<u>Capital Expense</u>	<u>Cost, \$ x 10⁶</u>
Moisture blocks	1.0
Wiring	0.2
Switching mechanism (for sequencing measurements)	0.33
Computer based data acquisition and storage	0.1
<u>Operating Expense</u>	<u>Cost, \$/yr</u>
Labor (0.083 man-year)	8500

SOIL MOISTURE PROBE

The moisture probe system cost estimate for both low- and high-power probes is summarized in Table 5. The access tubes for soil moisture probes are usually made of either thin-wall steel or aluminum of 5-cm inside diameter; however, for corrosion resistance below a pond containing acid leachate, polyvinyl chloride pipe as used in the bench-scale demonstration is proposed. Placed on 0.6-m centers (for low-power probes) in a square 16.2-ha pond, this requires about 269,000 m of pipe; on 1-m centers (high-power probes) the pipe requirements are 162,000 m. A fine-grained sand or soil subgrade 0.5-m deep is desirable for this detection system so that lateral spread of a moisture front

TABLE 5. Cost Estimate for Soil Moisture Probe System

Capital Expense	Costs, \$ x 10 ⁶	
	Low Power	High Power
Tubing (including trenching, installation, and backfill)		
• 5 cm PVC pipe with		
1.0-m centers - 162,000 m		1.21
0.6-m centers - 269,000 m	2.01	
Meters		
• Low power auto processor at \$5000 - 2 ea.	0.01	
• Continuous logging		0.02
Drawworks	0.35	0.21
Operating Expense	Cost, \$/yr	
Manpower		
• Low power - 4 man-year	0.4	
• Continuous - 1 man-year		0.1
Maintenance	0.01	0.01

occurs, making the liner beyond the probe's detection range. For this cost estimate it is assumed that the native soil will meet the system subgrade requirements.

The cost of the probe and instrumentation is about \$5000 for the smaller instrument, which gives individual measurements at some predetermined time interval. A unit which would provide continuous measurements costs about \$20,000 (Mineral Logging Systems, Ft. Worth, Texas). Additional costs for each of these systems involves the installation of drawworks to accurately position the probes and allow them to be drawn through the tubes. The cost of such a drawworks system is approximately equal to the tubing material cost.

Because there are many mechanical parts in this method, maintenance costs can be expected to be relatively high. The manpower intensive nature of gathering the data raises operational costs. Quarterly monitoring of a 16.2-ha pond is estimated to require 2 sets of instrumentation and 2 men/shift, 2 shifts/day with the small system. Using the larger system, actual measurement time is reduced for quarterly measurements, allowing a single employee to

monitor the entire system. From this cost estimate there is no advantage in using the low-power soil moisture probe.

PERIPHERAL RESISTIVITY SYSTEM

Locating a leak within any 3-m x 3-m area requires that electrodes be placed at 30-m intervals along the perimeter. For the 16.2-ha pond, the total number of electrode combinations is about 1500. Resistivity measurements of this number of electrode combinations are best accomplished by automated machinery similar to but smaller than that required for the moisture block system.

A 0.3-m thick subgrade of fine-grained materials over a 0.3-m coarse gravel layer is required for the lateral spread of moisture from a leak and to isolate the resistance path in the layer under the liner. The subgrade preparation cost includes buying, loading, hauling (3.3 km), spreading and compacting a 0.3-m gravel layer and a 0.15-m fine-grained layer. The additional 0.15 m of the fine-grained layer is required for the liner installation and is therefore not included in the estimate for the leak detection system.

Probes made of copper bar stock cost less than \$1 each. Wiring to connect the electrodes to the central subgrade for the switching mechanism costs about \$15,000. The switching mechanism is similar to that for the moisture block system, but smaller, and costs about \$50,000. The central data processing unit would add an additional \$10,000 to the system's cost.

Because there are no mechanical components and none of the components of the proposed system are directly under the lined pond, the maintenance cost of the system is low. Yearly operational costs are minimized by the automation, probably requiring 0.083 man-year. The peripheral resistivity system cost is summarized in Table 6.

TABLE 6. Cost Estimate for Resistivity System

<u>Capital Expense</u>	<u>Cost, \$</u>
Subgrade preparation	1,120,000
Electrodes	100
Wiring	15,000
Interrogation switching	50,000
Data management system	10,000
<u>Operating Expense</u>	<u>Cost, \$/yr</u>
Labor, 0.083 man-year	8,500

SUBLINER DRAIN SYSTEM

The cost of a subliner drain system is largely dependent on the subgrade costs (and therefore the specific site). At two uranium projects with successfully demonstrated subliner drains (Bison Basin and North Platte), the compacted native soil permeability was low enough that no additional impermeable layer was required. No additional subgrade preparation costs were incurred.

The Bison Basin Project used slotted polyvinyl chloride pipe (2.5-cm dia) at 12-m intervals in a grid pattern. Using the same spacing in a parallel pipe network requires 13,500 m of slotted pipe. Pipe installation costs include trenching, placing the pipe, and compaction of a gravel backfill (Godfrey 1982). Costs for the system are summarized in Table 7.

TABLE 7. Cost Estimate for Subliner Drain System

<u>Capital Expense</u>	<u>Cost, \$</u>
PVC pipe installation	97,000
<u>Operating Expense</u>	<u>Cost \$/yr</u>
Surveillance of sump, 0.125 man-year	12,500

FIBER OPTIC SYSTEM

A fiber optic system has the potential for providing a cost effective alternative for leak detection. Optics can be placed either in the subgrade material or incorporated into the liner during its manufacture.

Current prices for usable optics range from \$0.15 to \$0.33/m. Optics 30-cm apart on the 16.2-ha pond would cost from \$80,000 to \$175,000. Instrumentation currently on the market to read the optics costs about \$20,000. No subgrade preparation is required in addition to the basic subgrade of a synthetic liner. Costs for this system are summarized in Table 8.

SUMMARY OF COST ESTIMATES

The cost estimates for the systems discussed in this section are summarized in Table 9. These estimates can serve as general comparison of installation and operating costs. However, the installation costs of the systems may vary dramatically from one site to the next, especially for systems that require special subgrades (all systems except monitoring wells). For comparative purposes, the cost of a recently constructed lined pond was \$148,000/ha or 2.4×10^6 for a 16.2 ha pond (Baldwin 1983).

TABLE 8. Cost Estimate for Fiber Optic System

Capital Expense			Cost, \$
Fiber optics, 5.3×10^5 m	@ \$0.15/m		80,000
	@ \$0.33/m		175,000
Installation	@ \$0.15/m		80,000
Analyzer scope			20,000
Operating Expense			Cost \$/yr
Labor, 0.083 man-year			8,500

TABLE 9. Comparative Costs of Typical Systems

	Capital Expense, \$ x 10^6	Operating Expense, \$ x 10^3 /yr	20-Year Operating Expense Constant, \$ x 10^6	Total, \$ x 10^6
Monitoring wells	0.075	8.5	0.17	0.25
Moisture blocks	1.63	8.5	0.17	1.8
Soil moisture probe, high power	1.44	100	2	3.44
Resistivity	1.20	8.5	0.17	1.37
Subliner drain	0.10	12.5	0.25	0.35
Fiber optics	0.18 to 0.28	8.5	0.17	0.35 to 0.45

Monitoring wells are inexpensive compared to other systems. However, the remedial actions that may be required if groundwater becomes contaminated may be very costly. The operator would presumably have to begin a program to recover and dispose of the contaminated groundwater, and the program would need to continue after decommissioning of the impoundment. Thus, even though groundwater wells are inexpensive to install, remedial action would be expensive if groundwater contamination is detected and the contamination requires containment.

The subliner drain system has a favorable cost estimate, but if the site has a permeable native soil the installation costs can rise dramatically. Because a leak cannot be pinpointed with subliner drains, the system is most applicable in evaporation ponds without soil covers. If a leak is detected, a

visual inspection after the pond is drained will reveal the leak and permit repair. The main operator repair costs would be due to transferring the liquid in the pond to another, or if that is not possible, ceasing operation until the pond is dry. The latter alternative would be costly.

The other leak detection systems which can locate leaks are best suited for ponds with a soil cover or tailings. Their use at a pond with tailings would depend on whether repair of the liner is technically and economically feasible. Of the systems, the fiber optic system and the peripheral electrode resistance system are the most favorable on the basis of installation and operating costs. Both of these systems require development, as does liner repair technology in a pond with tailings. Presumably, an evaporation pond with a soil cover and without tailings could be repaired if it were drained and if it possessed a leak-locating system. Although leak-locating systems are more expensive than wells and drains, they are the only systems that make the repair of a covered liner feasible.

An alternative to broad-scale monitoring of a pond is a detection system which monitors only at probable leak sources (i.e., field seams). Moisture blocks, moisture probes, and resistivity devices are all suited for this application. Detection system costs can be reduced by as much as 60%.

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An alternative to broad-scale monitoring of a pond is a detection system which monitors only at probable leak sources (i.e., field seams). Moisture blocks, moisture probes, and resistivity devices are all suited for this application. Detection system costs can be reduced by as much as 60%.

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