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Technology for Uranium Mill Ponds Using Geomembranes

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Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

Pacific Northwest Laboratory has analyzed the performance of polymeric membrane-lined impoundments containing tailings and leachate at active uranium mills. The U.S. Nuclear Regulatory Commission has requested this information to support licensing of impoundments. Data on the performance of lined ponds in the U.S. uranium industry, mechanisms for damage of liners, and design, installation, and inspection practices are presented in this report. Design, construction, and inspection methods that are capable of minimizing failures are also identified.

No cases of contaminated groundwater are attributed to uranium mill ponds lined with polymeric membranes (geomembranes) in the U.S. The leading causes of geomembrane problems for all industrial pond applications are faulty seams, puncture and errors during placement, improper connections to submerged structures, puncture by soils in contact with the geomembrane, and geotechnical problems due to liquids in the support soil. Although some instances of liner problems with potential for significant consequences have been identified, the concensus of mill operators and regulatory personnel is that performance of ponds with geomembranes in the U.S. uranium industry has been satisfactory.

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TECHNOLOGY FOR URANIUM MILL PONDS USING GEOMEMBRANES

EXECUTIVE SUMMARY

The objective of this report is to provide a database for design, installation, and inspection techniques for impoundments with geomembranes. Geomembranes are polymeric membranes used to prevent migration of contaminants from a pond. This report is intended to assist U.S. Nuclear Regulatory Commission (USNRC) personnel involved in licensing of uranium mill leachate isolation and tailings impoundments.

It is generally agreed that the performance of ponds with geomembranes in the U.S. uranium industry has been satisfactory. No cases of groundwater contamination have been attributed to ponds using geomembranes and only relatively minor problems have been observed to date. Several cases of faulty seams were reported in a survey of mill operators. The most dramatic problem has been sloughing of the soil cover over the liners; however, sloughing does not necessarily result in damaged liners. Other problems experienced in the uranium industry include gas uplift, puncture by various mechanisms, and wind-related damage.

Design, installation, and operation of mill ponds can be planned in ways that reduce the possibility of geomembrane failures. To assist in license reviews, PNL reviewed and compiled design and installation techniques for ponds with geomembranes. Faulty seams, damage to the geomembrane during placement, and connections to submerged structures were found to be the most frequent failure mechanisms in lined impoundments. Other frequent failure mechanisms that need to be addressed by the contractor include: punctures by cover and subgrade materials, slope instability, subsidence, bank deformation, underpressures, and damage by wind.

Because faulty seams are the most frequent cause of leaks, effort expended in improving seam quality is likely most cost effective. Techniques more sensitive than visual, air lance, or pick tests are available to examine field seams. These techniques include ultrasonic devices, pressure testing (for double seams only), and vacuum box testing. An ultrasonic impedance plane inspection technique was demonstrated which is applicable on a wide variety of geomembranes and could be adapted for field use. Pulse-echo ultrasonic inspection currently used by one U.S. geomembrane installer, was shown to be effective on lap seams of nonreinforced geomembranes. Periodic destructive tests are also important in assuring seam quality.

Concrete structures under the liner or pipes penetrating the liner below the liquid level should be entirely avoided. By avoiding these structures, a major category of failures is eliminated.

Soil covers on geomembranes in evaporation and tailing ponds are not necessary unless the geomembrane is sensitive to ultraviolet radiation. The risks of puncture during placement and sloughing after placement do not appear to outweigh the advantages of a protective soil cover in most instances. If soil

covers are implemented for special reasons, the liner requires protection from puncture by objects in both the subgrade and cover during the process of cover placement.

Generally, sand is placed directly under the geomembrane for gas venting and liquid drainage. An alternative design for embankments has advantages over the conventional sand layer. A geotextile (a permeable synthetic fabric), instead of a sand layer, will conduct gases to vents in the liner. Substitution of a geotextile for the sand layer will reduce bank deformation and provide better puncture resistance. The displacement of sand during and after liner placement will also be eliminated.

Implementation of a comprehensive quality assurance plan can reduce the frequency of occurrence of many leak mechanisms identified. It is important that the quality assurance function during subgrade preparation and geomembrane installation be performed by an organization experienced with geomembrane installation.

Incorporation of these recommendations and other suggestions in the report will help to enhance the integrity of new impoundments in the uranium industry.

1. INTRODUCTION

Uranium mining and milling operations produce large quantities of tailings and spent leachate which contain a variety of species that may contaminate the groundwater if not properly disposed. Tailings and leachate are typically disposed in ponds either lined with clay or geomembranes.

Pacific Northwest Laboratory (PNL) was contracted by the USNRC to provide a database to support USNRC licensing of uranium mill tailings and leachate impoundments using geomembranes. This project includes assessment of design and installation practices, the subject of this report. The report is intended to aid personnel at USNRC entrusted with reviewing and approving applications submitted by the uranium industry for lined ponds. Because significant changes in the proposed regulations may occur prior to their adoption, some of the recommendations in this report may not be applicable at the time the regulations are approved.

The following section of the report contains conclusions and recommendations of areas that contractors should document during design and construction of tailings and evaporation ponds using geomembranes. Subsequent sections provide the basis for these conclusions, beginning with descriptions of possible failure modes associated with impoundments with geomembranes. The observed relative frequency of failure modes is discussed so that the most critical activities in the design and construction of lined ponds can be identified. Material selection is addressed, with descriptions of available geomembranes for this application. Subsequent sections address design and installation practices for subgrades, geomembranes, and soil covers. Quality assurance techniques follow. Results of an experimental program evaluating seam inspection techniques conclude the report.

2. RECOMMENDATIONS

The following recommendations are based on the information gathered for this project from published literature, other researchers, consultants (Dr. J. P. Giroud of Geoservices, Inc., and J. Goldstein and C. Ah-line of Woodward Clyde Consultants), uranium mill operators, geomembrane manufacturers, and installers. These recommendations are intended to maximize impoundment integrity with minimal addition to the financial or regulatory burden to the uranium industry. Several recommendations may reduce impoundment costs. Because the regulations are not currently approved, future requirements for geomembranes may significantly change and the recommendations herein may not be entirely applicable.

The sequence of events in designing, constructing, and operating a lined pond is shown in Figure 1. Conclusions for assuring the adequacy of each event are discussed in this section.

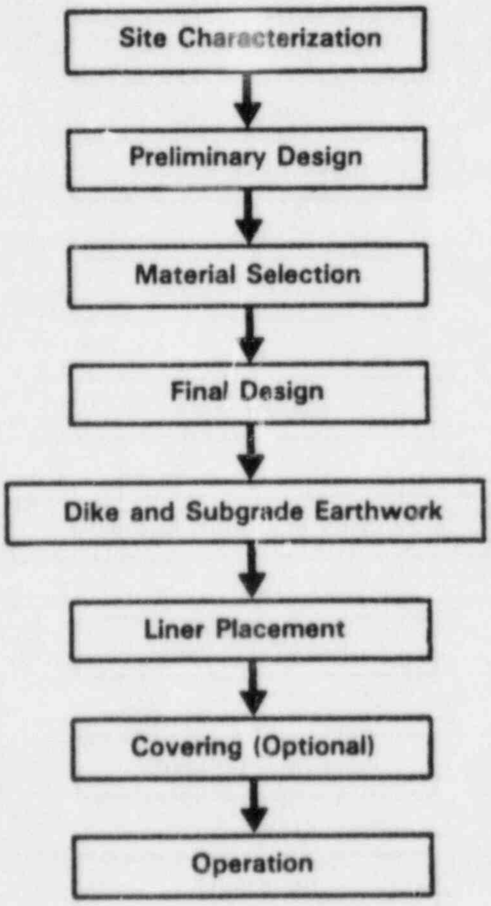


Figure 1. Phases of impoundment construction

2.1 Site Characterization

To make basic decisions regarding impoundment design and construction, certain characteristics of the site geology, hydrology, and climate must be known. The licensee or designer should provide documentation of the site characteristics and their impact on the design of the impoundment. Knowledge of native soil properties will permit a geotechnical designer to reduce the potential for failure by slope instability, sinkholes, subsidence, bank deformation, expansive clays, and differential settlement. Properties to be determined are native soil types, soil permeability, and potential for sinkholes, subsidence, and piping. The soil classification and potential for sinkholes, piping, and subsidence will affect subgrade preparation requirements and geomembrane selection. Soils with potential for subgrade movements require scarification and compaction in excess of stable native soils. In addition, a liner with high elongation may need to be chosen if subgrade movements are probable. The soil permeability must be known for design of drain-type leak detection systems. Site characterization procedures and tests are discussed by Duvel (1979) and Spigolon and Kelley (1983).

Surface hydrology will influence the pond design, requiring either diversion of surface runoff from the pond, or increased pond capacity to hold surface runoff.

Depth of groundwater is needed to assess whether a drainage system below the liner is required. The presence of springs in the area under the proposed lined site will necessitate special drainage features to protect the liner from liquid underpressures.

2.2 Preliminary Design

After the site is chosen, initial design decisions include impoundment capacity, elevation, and dimensions. Criteria for making these decisions are not within the scope of this project, however, during the study several points were raised that may influence the decisions on pond capacity and dimensions.

Waves can damage soil covers, geomembranes, and dikes, eventually leading to failure of the geomembrane. Because wave size is proportional to the size of the impoundment, the designer should consider building smaller ponds. In most cases this is not practical due to economy of scale. Therefore the designer may need to consider other options to protect the bank, geomembrane, and cover. Options include geotextile underlays, shallower slopes, and erosion resistant cover materials.

Tailings pond operating life should not be planned to exceed 20 years because of uncertainty of the service life of geomembranes beyond this time period.

If practical, ponds should be oriented with the smallest dimension parallel to the prevailing wind direction to reduce bank deformation and cover erosion by waves.

2.3 Geomembrane Selection

Geomembrane selection should be based on resistance to degradation by chemicals and weathering (ultraviolet radiation, ozone reactions, and plasticizer migration), mechanical properties, resistance to microorganisms and rodents, and seaming characteristics.

Geomembranes used today by the uranium industry include chlorosulfonated polyethylene, chlorinated polyethylene, high density polyethylene, and polyvinyl chloride. Based on performance of liners to date in the uranium industry and on accelerated aging tests being performed at PNL, significant chemical degradation over the life of a tailings pond (<20 yr) will probably not occur with acidic, neutral, or basic leachates.

However, the proposed geomembrane supplier should provide the licensee with evidence of compatibility of the proposed geomembrane, with the leachate to be contained. Simulated leachate may be used in compatibility tests, however trace species, including organics, should be included. Recommended test procedures will be published in a subsequent report. Actual experience in a similar environment may be the best indicator of geomembrane chemical stability.

If the geomembrane will be exposed, ultraviolet exposure test data should be supplied to USNRC. Stability of additives used in compounding the geomembrane should be documented. Particularly, in the case of polyvinyl chloride, the stability of the plasticizer should be documented.

The geomembrane manufacturer should supply data showing the resistance of the liner to attack by bacteria and fungi. Because rodents may attack some geomembranes, the manufacturer should also provide data showing resistance to this type of attack if burrowing rodents are present at the proposed site. Again, actual applications may provide the best indications of the material's durability.

Mechanical properties are as important as chemical stability. Unfortunately, it is not possible to directly compare thermoplastics, reinforced materials, and rubbers in side-by-side tests, because different test procedures are required for each material. In general, ponds with slopes steeper than 2.5:1 (h:v) require a geomembrane with high tensile strength (greater than 10,300 kN/m^2--i.e. high density polyethylene) or high break strength (greater than 0.53 kN--i.e. reinforced materials). In areas where differential settlements or subsidences are highly probable, materials with large elongation (polyvinyl chloride, unsupported chlorinated polyethylene, or rubbers) are desirable. Other mechanical properties that may impact the material selection are puncture resistance and low temperature flexibility.

Seaming characteristics are additional factors in material selection. Because rubbers are typically more difficult than thermoplastics to field seam and repair, thermoplastics with solvent, bodied solvent, thermal, or weld seams are preferred. Because of difficulties in seaming, using two different types of geomembranes in one pond should not be approved without adequate assurances.

Quality assurance during material procurement is important in avoiding failure due to a faulty geomembrane, such as stress cracking of high density polyethylene or poor ply adhesion of reinforced geomembranes. The geomembrane supplier needs a quality control program that examines raw feedstocks and finished goods for critical properties. The results of these tests should be supplied to the customer for inclusion in quality control documentation.

2.4 Final Design

The final design details all construction information for the pond. This includes specifications for the dike, subgrade, leak detection and drainage systems, anchor trenches, venting, sterilization, geomembrane dimensions and layout, and cover soils. This section will discuss some of the recommended specifications for major components of the final design.

Specific recommendations for embankment construction are not within the scope of this report. USNRC Regulatory Guide 3.11 (1977) discusses geotechnical methods for determining dike stability. The dikes are obviously critical to the success of the impoundment. For elastomer liners, a 3:1 (h:v) or shallower dike slope is required to minimize stresses on the liner. Polyvinyl chloride requires 3:1 or shallower slopes to hold the required soil cover. High density polyethylene and reinforced materials can be used on somewhat steeper slopes if soil covers are not used.

For the final design, leak detection requirements need to be specified by regulatory agencies. Currently available leak detection systems including monitoring wells, lysimeter wells, and drain systems are discussed by Myers et. al. (1983). A drain system below the geomembrane may be specified for either leak detection or subgrade drainage.

If liquid drainage is required due to potential for liquid underpressures, the recommended slope of the pond floor is 3 to 4%. Pipe spacing will determine the responsiveness of the system. Twelve meter (40 ft) spacing has been demonstrated effective at one uranium mill in preoperational leak detection tests. Pipes as small as 2.5 cm (1 in.) diameter have been used. The pipe requires protection from clogging by fines. This is usually accomplished by surrounding the pipe with gravel and surrounding the gravel with a geotextile filter. The layer directly under the liner should be a clean sand classified as SP by the Unified Soil Classification System (USCS) with a permeability greater than 10^{-3} cm/sec. This grade of soil is desirable to prevent puncture of the liner. The soil below the drain should have a permeability at least 100 times smaller than the sand layer so that the sand layer will become saturated as a leak occurs. This design for leak detection was successfully demonstrated in performance tests at several uranium operations.

This type of drain system will also vent gases trapped under the floor of the liner. At ponds without soil covers the design should include a gas vent system to prevent damage to the geomembrane by either gas or wind uplift. For a tailings pond, a gas vent layer is required only on the embankments, because the weight of tailings on the floor will counteract forces created by gases. The gas permeable layer may be either sand or geotextile. A geotextile may be preferable to a sand layer on the embankment, because sand layers are easily disturbed during liner placement and are prone to bank deformation after placement of the liner. Geotextiles may offer economic advantages at some sites. A minimum 1.5% slope of the floor is usually specified for gas venting. Gas vents are typically placed at 8 to 15-m (25 to 50-ft) intervals along embankments of ponds.

Subgrade sterilization is necessary unless the liner supplier can demonstrate resistance to penetration of the liner by local vegetation.

Because faulty field seams are frequently responsible for leaks, the pond design should minimize the quantity of field seams that are required. Seams should be parallel to the slope of the embankments.

To discharge tailings and leachate to the pond, pipes over the dike are recommended. The use of pipes and concrete structures (structures) penetrating the geomembrane below the freeboard is not recommended in order to avoid the frequent failure mode of differential settlement near these structures. To evenly distribute the tailings, the discharge pipes require periodic relocation. A float for the discharge line may be necessary on the large ponds as well as a safe technique to immobilize the line.

2.5 Subgrade Preparation

During construction of the subgrade, certain quality control procedures should be specified to help reduce the potential for various types of failures. These quality assurance activities should be documented and available to USNRC. Quality assurance activities include:

1) verification of removal of large rocks (>10 cm), debris, and organic matter in the subgrade, which will reduce gas production, differential settlement, erosion of subgrade soils, and liner puncture,

2) verification that soil properties (permeability, soil classification and uniformity) meet design assumptions,

3) surveying to assure specified slopes and elevations,

4) classification of borrow materials,

5) verification of specified compaction and lift depths,

6) verification of proper placement of drain pipes (if used),

7) verification of soil sterilization procedures.

More detailed discussion of quality control practices is given in Section 8 of this report.

2.6 Liner Handling and Placement

Shocks and errors during placement are a major cause of failures of geomembranes. Contractors should assure that adequate quality control requirements are implemented during liner placement to minimize geomembrane damage.

The contractor should document compliance to the manufacturer's recommended procedures for transportation of the geomembrane to the fabricator, to the site, and at the site. Upon arrival at the site, examination of each shipping container for signs of damage and puncture should be documented. If any punctures are detected, their repair should be documented.

Contractors should assure that storage time at the site is minimized. Polyvinyl chloride and chlorosulfonated polyethylene liners should be shielded from solar radiation during storage.

The contractor should supply evidence that liner samples from various panels were tested and that samples meet the manufacturer's specifications. Tests should include thickness, tensile strength, elongation, tear resistance, and factory seam strength. National Sanitation Foundation (NSF 1983) test procedures are recommended.

Prior to placement of any panel, the liner installer should document that the subgrade or that portion to be covered, meets specifications required by the manufacturer.

Since an experienced crew is vital to successful installation, documentation that crew training and experience meets contract specifications is important. The quality control inspector should verify that: crew members wear sneakers when on the liner to avoid puncturing the liner, no vehicles are used on uncovered liner, seaming solvents and fuels are stored off the liner, and solvent squirt bottles used for seaming are not refilled over the liner.

Installation procedures should assure that panels are not placed under tension. Polyvinyl chloride in particular should be installed with slack because of its shrinkage tendencies. High density polyethylene should be installed with slack because of its thermal expansion/contraction characteristics.

Seaming procedures should follow the manufacturer's recommended procedure. Particular attention should be paid to the minimum allowable seaming temperature for solvent type seams. Where seams of three layers are made, the first seam should be allowed to cure for the time period specified by the manufacturer before the second seam is begun.

Visual and nondestructive examination of 100% of the field seams are needed to detect faulty seams, the most frequent problem with geomembranes. Effective nondestructive techniques are vacuum testing, ultrasonic examination, and pressure testing (double seams only). These techniques offer significant advantages over the air lance and pick tests. Destructive tests at specified intervals should also be performed and documented.

Placement, backfilling, and compaction of anchor trenches should be observed and documented. Prior to soil cover placement (if used), a 100% visual inspection of the entire liner should be performed and documented to assure that all aspects of liner placement are satisfactory (e.g., patches, anchoring, connections, tension, seams).

2.7 Soil Covers

If polyvinyl chloride is chosen as the geomembrane, a soil cover must be used. For ultraviolet resistant materials, a cover is optional providing that the manufacturer can certify adequate lifetime if exposed. Because of the risks of puncture to the geomembrane during and after cover placement, and because vandalism potential is low at most uranium mills, the use of soil covers is not warranted, except in special cases. If soil covers are not used, the designer should show that the design of the pond eliminates the possibility of gas uplift and wind damage. A fence should prevent trespass by large and sharp-hoofed animals if they may be present at the site.

If a soil cover is chosen, a minimum depth of 0.45 m of cover material is needed to reduce damage by installation equipment. The cover material in contact with the geomembrane should contain no material larger than 6 mm (0.25 in). Slopes of the impoundment should not exceed 3:1 (h:v) for stability of the cover. The cover can be installed with either tracked or tired vehicles. The cover should be installed from the bottom of the pond and pushed up the embankment. In order to prevent puncture during installation, the smoothness of the soil below the liner must be assured.

During placement of a soil cover, the quality inspector needs to document compliance with specifications regarding procedures, soil types, and depth of the cover. Proper design and placement procedures can reduce the potential for geomembrane puncture during placement of the cover and sloughing of the cover.

2.8 Operation

Prior to license issuance for pond operation, a pond management plan should be prepared and issued to all company personnel that may be involved with pond use. This plan should prohibit dumping of any materials into the pond that are not approved by the geomembrane supplier. The plan should prescribe inspection intervals and repair techniques.

As part of the pond monitoring program, the operator should place samples of the liner in the pond to evaluate the retention of properties. One procedure uses several tubes of the material (approximately 0.3-m diameter by 10-m long) that are field seamed and closed at one end by seaming. Sand should be placed in the tube and the tube placed on the dike such that portions are exposed to leachate, a leachate-air interface, and air. Another acceptable method, although less meaningful, is submerging test coupons in the pond.

3. LINED IMPOUNDMENT FAILURE MECHANISMS

This section of the report describes failure mechanisms of tailings and evaporation ponds and other impoundments with geomembranes. A failure is defined as any breach of the geomembrane. This could range from small holes, which may have either undetectable or severe effects on the overall performance of the system, to catastrophic breaches of the liner, which may rapidly release large quantities of the contained material. Design and construction techniques that may avoid these failure mechanisms are discussed in Sections 5, 6, 7, and 8.

The information presented in this section has been collected from published literature, consultants, uranium mill operators, and geomembrane suppliers and installers. The failure modes have been divided into five categories: failure of the geomembrane, defective installation, damage to the geomembrane by contact, gas and liquid damage, and geotechnical problems. These categories and the corresponding failure mechanisms are listed in Table 1. Each failure mechanism is briefly discussed in the subsequent subsections.

3.1 Failure of the Geomembrane

This category refers to failures directly attributable to the liner without abnormal physical forces. The category contains five failure mechanisms: manufacturing defects, weathering, physical failure, chemical degradation, and mechanical failure.

3.1.1 Manufacturing Defects

Manufacturing defects include nonuniform selvage, pinholes, poor ply adhesion, and chemical defects.

Selvage is the nonreinforced edge of a reinforced material (scrim) that is required to prevent absorption of liquid (wicking) between plies of a geomembrane. In the past, the width of the selvage was difficult to control in the factory. Nonuniform selvage can cause seaming difficulties. Selvage that is too wide results in seams without any scrim reinforcement. These seams would have low tensile strength. In contrast, selvage that is too narrow can expose the scrim. Exposed scrim will draw liquid between plies (wicking) and promote delamination. Nonuniform selvage no longer appears to be a problem in the manufacture of supported materials.

Pinholes are usually the result of impurities in the calendering process. These may be caused by dust in the factory or by recycling of liner scraps containing scrim. The latter practice has been eliminated. The National Sanitation Foundation (NSF 1983) has adopted guidelines that prohibit recycling of materials containing scrim. Manufacturers have also installed strainers to remove foreign materials that might create pinholes in the calendering process. The use of two plies of geomembrane in reinforced membranes practically eliminates the possibility of pinholes in reinforced liners. Pinholes are not a frequent failure mechanism. Leakage due to pinholes is minor compared to leakage created by other failure mechanisms.

Table 1. Failure mechanisms of impoundments lined with geomembranes

Category	Failure Mechanism
Failure of the geomembrane	Manufacturing defects
	Pinholes
	Insufficient ply adhesion
	Chemical defects
	Nonuniform selvage
	Weathering
	Physical effects
	Shrinkage
	Thermal expansion, contraction
	Blistering
	Chemical degradation
	Mechanical failure
Defective installation	Improper storage
	Improper transportation
	Placement
	Seaming
	Connections to structures
	Placement of cover materials
Damage by contact	Puncture
	Shocks
	Vandalism
	Biological attack
	Rodents
	Microorganisms and insects
	Vegetation
Gas and liquid damage	Gas uplift
	Wind
	Waves
	Liquid uplift
	Overtopping
Geotechnical problems	Slope instability
	Sloughing of cover material
	Subsidence
	Differential settlement
	Expansive clays
	Seismic activity

Insufficient ply adhesion is a manufacturing problem for reinforced materials. This problem has been resolved to a large extent; however, extensive delamination of a reinforced chlorosulfonated polyethylene liner recently occurred in Canada. Delamination occurs when there is insufficient bonding between the two plies of polymer.

Delamination of a reinforced liner across the width of a panel will result in geomembrane failure. This failure mode is a result of insufficient ply adhesion. The potential for leaks by this mechanism is highest at corners of a pond, where the distance between panels is small, therefore, the amount of delamination required to produce a leak is less.

Chemical defects are inconsistencies in the chemical composition of a geomembrane. Standards for chemical and physical properties of various liners are given in the NSF Standard 54 (1983) Improved manufacturing techniques and quality assurance have reduced the occurrence of chemical defects.

3.1.2 Weathering

Weathering refers to chemical and physical changes in a liner as a result of sunlight, temperature, humidity, and soil contact. Common weathering problems include ozone deterioration of butyl rubber under tension, loss of plasticizers in polyvinyl chloride by heat and soil absorption, and ultraviolet degradation of polyvinyl chloride. Chlorosulfonated polyethylene slowly vulcanizes to an elastomeric state upon weathering, but this is not a detrimental physical change.

EMCON (1982) documents a case of poor weathering of exposed polyvinyl chloride at a landfill. The material lost plasticizer, shrunk, and became brittle.

3.1.3 Physical Failure

Physical failure mechanisms include shrinkage, thermal expansion and contraction, and blistering.

Polyvinyl chloride is prone to shrinkage due to release of tensions created in manufacturing and installation, and due to loss of plasticizer. Techniques to reduce problems related to polyvinyl chloride shrinkage are discussed in Section 4.5. Reinforced materials generally are not prone to shrinkage.

High density polyethylene has a thermal expansion coefficient that is an order of magnitude greater than other geomembranes. This material is prone to bulge or ripple when heated by solar radiation. The expansion, coupled with the material's relative stiffness, can create stresses that may damage the liner if it is not installed properly. An experienced installation contractor can employ proper techniques to avoid problems due to expansion and contraction of this material.

Blistering is a rare problem in which a localized delamination or gas bubble exists between two plies of a liner. Because blisters seldom grow, they are not a very serious problem.

3.1.4 Chemical Failures

Chemical failures of geomembranes include any mechanism where significant chemical changes in the liner occur as a result of the materials contained in the impoundment. Examples include oxidation, dissolution, extraction of plasticizers, or absorption of oils. These failures have become relatively uncommon because of increased information on chemical compatibility of various liners with specific wastes. However, there are unique situations in which chemical damage may occur. For example, evaporation of water from a pond containing trace hydrocarbons, which are harmless in a dilute state, may leave concentrated hydrocarbons that can damage the liner. Spillage of seaming solvents, gasoline, or oil can also damage a liner during construction of an impoundment. Adhesives used for seaming that are incompatible with the chemicals to be held in the impoundment can lead to failures at seams. Inadvertent dumping of chemicals into the impoundment is a possible scenario for chemical degradation. Chemical compatibility is also addressed in Section 4 of this report in the discussion of various types of liners.

3.1.5 Mechanical Failures

Mechanical failures are due to stresses on the liner caused by either improper design of the impoundment or poor choice of geomembrane. Giroud and Goldstein (1982) state that liners can be divided into two categories according to their mechanical properties. The first category comprises liners with high tensile strength and low elongation, such as reinforced geomembranes and a few nonreinforced, stiff geomembranes with 10 to 20% elongation (i.e. high density polyethylene). This class of liners is recommended where high stresses are expected, such as sites with steep slopes or sites where gas uplift may occur. The second category is geomembranes with low tensile strength but large elongation (nonreinforced elastomers), which are applicable at sites where subsidence and differential settlement may be a problem.

3.2 Defective Installation

Geomembrane failures due to defective installation include storage and transportation damage, placement damage, faulty seams, connections to structures, and placement of cover materials.

3.2.1 Improper Storage

Improper storage can result in damage to certain geomembranes. Membranes sensitive to damage by ultraviolet radiation (primarily polyvinyl chloride) should be stored out of the direct sunlight. In hot climates, plasticizers will migrate from polyvinyl chloride. Chlorosulfonated polyethylene surfaces will cure at elevated temperatures, causing adhesion of adjacent layers resulting in damage to the geomembrane when it is unfolded.

3.2.2 Transportation

Geomembranes are transported from the manufacturer to the fabricator, from the fabricator to the site, and from the site storage to the pond. There is potential for damage during handling by crates, nails, forklifts, and other machinery.

3.2.3 Damage During Placement

Damage during placement includes shocks and installation under tension. Damage by shocks includes improper handling of the material, dropping tools, overheating by heat guns, cigarette burns, and foot traffic.

Polyvinyl chloride is particularly prone to damage from installation under tension because of its shrinkage tendency. If installed initially under tension, subsequent shrinkage will create more tension that can lead to failure.

3.2.4 Faulty Seams

The quantity of field seams in a lined pond is very large. For example, field seams are typically made at 6-m intervals; therefore a 80,000 m^2 (20 acre) pond has roughly 13 km (8 miles) of field seams. This large quantity of seams represents a large potential of flaws illustrating the critical need to attain high-quality field seams in a geomembrane.

Causes of faulty seams obtained through consultants and from Kays (1977) include:

- improper adhesive
- defective adhesive
- surface contamination
- improper tack development before closure
- moisture or high humidity
- improper temperature
- inadequate contractor experience
- improper layout
- solvent evaporation from adhesive
- lack of necessary bonded width
- unbonded edges
- three-layer seams
- seams of two different geomembranes.

3.2.5 Connections to Structures

Failures frequently occur at connections to submerged structures (such as concrete structures or pipes) in lined liquid impoundments. If the geomembrane bridges any void between the structure and the soil, there is potential for high stresses causing the geomembrane to fail. Differential settlement may occur at these structures causing the geomembrane to tear. Poor sealing techniques may result in small leaks as soon as the structure is covered by liquid. A dramatic example of a failure triggered by a leak at concrete structure is discussed by Giroud and Goldstein (1982).

3.2.6 Damage by Cover Materials

Although cover materials are useful in preventing many liner problems, cover soils create problems during and after placement. Puncture of the geomembrane by stones in the cover soil or in the subgrade may occur during placement of the cover. Vehicles installing the cover may cause rocks in the cover or subgrade to puncture or tear the liner. Vehicles may also damage the liner by direct contact or by pinching or tearing the liner if sharp turns are made. Sloughing of covers can also stress the geomembrane causing tears. Sloughing of cover soils has occurred at several tailings ponds in the U.S.

3.3 Damage by Contact

Included in this category are puncture, vegetation, shocks, burrowing rodents, impingement, and vandalism.

3.3.1 Puncture by Subgrade

Stones and other sharp objects below a liner may cause punctures when the liner is stressed during installation or by impoundment contents after installation.

3.3.2 Vegetation

Vegetation from below liners is a potential failure mechanism. Shultz (1983) observed a site in the U.S. where grass had penetrated a liner from below. He states that quack grass and salt grass in particular have damaged liners. Hickey (1969) has presented data showing that roots do not appear to penetrate plastic liners from the topside.

3.3.3 Shocks

Shocks (other than during placement) by foreign objects such as tools, cigarettes, foot traffic, vehicles, sharp-hoofed animals, floating ice and debris, and hail can damage geomembranes. For example, at a site visited during this project, wind had demolished a wood float in the pond. Debris from the float, which potentially could puncture the uncovered liner, had collected at the edge of the pond. Some geomembranes are especially prone to damage by shocks during cold weather.

3.3.4 Impingement

Impingement of tailings or leachate on the liner can erode the membrane. This can occur either by normal discharge of tailings without protection of the liner or by failure of a discharge line permitting tailings to contact an unprotected liner at high velocity. One uranium mill operator described such an occurrence. A tailing discharge line ruptured and a jet of tailings and leachate bored a hole through the liner. Fortunately this occurred above the liquid level of the pond so repairs could easily be made.

3.3.5 Damage by Burrowing Animals

Burrowing rodents may cut holes in geomembranes. One U.S. uranium mill operator suspects that mice have been partially responsible for holes in the uncovered reinforced liners of chlorinated and chlorosulfonated polyethylene at his evaporation ponds. Schlegel (1983) reports results of tests with rats confined in 100 m^2 enclosures. Polyvinyl chloride membranes were buried below the enclosure and rats gnawed through the liners when burrowing. Rats also gnawed on polyvinyl chloride placed on the ground. Polyvinyl chloride without plasticizers was not attacked. Buried polyethylene liners (1-mm thick) were not penetrated by rats, even when faced with starvation. The damage to polyvinyl chloride may have been in part due to the choice of plasticizer. In other tests (Schlegel 1983), high density polyethylene specimens were exposed to rats. The rats gnawed edges of specimens but did not attack surfaces except at bends and curves. There is a scarcity of data on this topic for other geomembranes. A consultant and several geomembrane vendors indicated that rodent damage is not a common problem.

3.3.6 Microorganisms and Insects

Microorganisms have attacked polyvinyl chloride liners (Kays 1977). Kuster (1979) states that low molecular weight polyethylene supports fungal growth, and polyvinyl chloride with certain plasticizers is attacked by bacteria and fungi. Higher molecular weight polyethylene and crosslinked forms resist attack. Day (1970) cites tests where polyvinyl chloride and elastomers were attacked by bacteria. This failure mechanism is infrequent. NSF (1983) recommends that all geomembrane materials pass a soil burial test with exposure to bacteria.

Day (1970) states that termites have devoured polyvinyl chloride reservoir linings in Africa, however the problem has not been reported in the U.S.

3.3.7 Vandalism

This study, has not identified vandalism to geomembranes at U.S. uranium mills. This is largely due to the remote locations. If vandalism is a concern, it is probably best avoided by placement of a soil cover over the liner.

3.4 Damage by Gas and Liquid

This category of failure mechanisms includes damage through gas uplift, wind, waves, liquid uplift, and overtopping.

3.4.1 Gas Uplift

Gas uplift occurs with liners not covered by soil and with improper venting. Gas may collect under the liner, lift the liner, cause a tear. Sources of gas include gas generated by decay of organic material in the soil, air displaced by a rising water table, air trapped during installation, and gas generated by leaking liquid. In the case of acidic uranium tailings, carbon dioxide is released by the reaction of acid with natural carbonates in the soil. Several documented cases of gas uplift exist in the literature (Giroud 1982; Giroud and Goldstein 1982). One tailings pond observed during this study had lost its soil cover and gases trapped in the bank under the liner made the liner bulge in warm weather.

3.4.2 Wind

Wind can damage liners during installation and during pond operation if the pond does not have a soil cover. Wind damaged a liner at an active pond at one uranium mill investigated during this study. During operation of a pond with an exposed geomembrane, the low pressure created by winds may cause the liner to lift and pull out of anchor trenches if the vent and anchor systems are inadequate.

3.4.3 Waves

Waves can damage geomembranes by fatigue, abrasion, shocks against stones, sloughing of cover materials, and deformation of the dike under the liner. Waves can also cause dike damage by overtopping. Several uranium mill ponds investigated in this study have experienced bank deformation and wave erosion of cover materials. At one site, the liners on the slope had ripped, apparently because of bank deformation due to waves. The geomembranes in evaporation ponds at one mill require frequent repair of holes that are partially attributed to wave action on the exposed geomembrane.

3.4.4 Liquid Underpressures

Liquid underpressures from springs or a rising water table beneath a pond can severely stress geomembranes. One U.S. uranium mill had to engineer around a potential problem of springs under a liner. Trenches were cut in the subgrade where high groundwater was expected. Perforated pipes were placed in the trenches and covered with appropriately sized gravel blankets. The gravel layers were then covered with clay and a geomembrane. This system appears to have performed adequately.

3.4.5 Overtopping

Overtopping (or overfilling) can occur from high winds creating waves higher than the freeboard. The soil in the dike is then prone to erosion and instability. One case of overtopping was reported in a survey of U.S. uranium mills with geomembrane-lined ponds.

3.5 Geotechnical Problems

Geotechnical problems include slope instability, sloughing of soil covers, localized subsidences, differential settlements, expansive clay subgrades, and seismic damage.

3.5.1 Slope Instability

Slope instability will lead to high stresses on a geomembrane and to catastrophic failures. Unstable dikes are the result of poor design and/or improper drainage. Incorporating the the vast experience available from earth dam construction should preclude this type of failure. Recommendations for dike construction to prevent this occurrence are available (e.g. USNRC 1977 and USDI 1973).

3.5.2 Soil Cover Instability

The sloughing of soil covers can tear or puncture a geomembrane. Additionally, the protective function of the soil cover (i.e. protection from ultraviolet radiation, shocks, and vandalism) is then lost. Soil covers have sloughed at several uranium mills investigated in this study; however, damage to the liners has not occurred. This topic is discussed in more detail in Section 7.

3.5.3 Localized Subsidences

Localized subsidences are typically either circular (0.5- to 1.0-m diameter) or rectangular (0.3-m by several meters) and up to 1-m deep. They are primarily due to erosion or chemical attack of the soil in the subgrade. Smaller subsidences can be caused by collapse of underdrains.

3.5.4 Differential Settlement

Differential settlements occur around submerged structures. Improperly compacted soils may subside while the structure remains stable. This can severely stress a liner.

3.5.5 Expansive Clays

Certain clays expand or shrink with changes in moisture content. Synthetic flexible liners can survive the expansion or shrinkage of subgrade clays as long as structures are not in the system and the transition from clay to undisturbed native soil is gradual (Kays 1977).

3.5.6 Seismic Activity

Dikes built of noncohesive soil are unstable in earthquakes, and waves generated by earthquakes can damage dikes. In general, however, a flexible liner is not directly damaged by seismic activity.

3.6 Relative Frequency of Failure Mechanisms

For this project, impoundment failure mechanisms have been ranked according to their relative frequency of occurrence (see Table 2). Unfortunately, little quantitative data are available. Therefore this ranking is an estimate, based on experiences documented in the literature, and consultant experience, and opinions of others in the geomembrane industry. Regulatory agencies and mill operators should concentrate on reducing the probability of all these mechanisms; however, mechanisms at the top of the list deserve the most attention.

Note that faulty seams are the most frequent failure mode. This is due in part to the quantity of seams involved in an installation. Means to reduce this type of failure are discussed in Sections 6, 8, and 9.

The second ranked mechanism is shocks and errors during placement. Damage by these means can primarily be avoided through use of experienced installation contractors and experienced quality control personnel.

The third ranked failure mechanism (industry-wide) is connections to structures. However, we are not aware of this type of failure at U.S. uranium mill ponds. This failure mode may be avoided completely by eliminating concrete structures and pipes penetrating the liner.

Table 2. Failure mechanisms of impoundments with geomembranes in approximate order of declining frequency

Order of Declining Frequency	Failure Mechanism
1	Faulty seams
2	Shocks and errors during placement
3	Connections to structures
4	Puncturing by cover materials and subgrade anomalies
5	Liquids in support soil - slope instability, subsidence, bank deformation by waves, underpressures
6	Wind
7	Improper design for liner's mechanical properties
8	Degradation by chemicals
9	Localized subsidence
10	Damage due to improper transportation, storage
11	Uplift by gases
12	Slope and cover movements
13	Delamination, blistering
14	Vandalism
15	Vegetation
16	Animals
17	Pinholes

Puncture by soil covers and anomalies in the subgrade is the fourth ranked mechanism. Means to avoid punctures include fine finishing, proper cover gradation, and incorporation of geotextiles into the design.

Moisture in the support soil is responsible for a variety of problems such as bank instability, subsidences, differential settlements, underpressure, and bank deformation. Proper drainage is necessary to eliminate this type of problem. In arid western U.S. sites, moisture in support soils may not be a frequent problem.

The previous rankings reflect the entire spectrum of geomembrane applications. During this study, through contacts with seven mill operators with lined ponds and regulatory officials, the problems that have occurred at U.S. uranium mills were compiled (see Table 3). Many problems due to mechanisms such as faulty seams, punctures, and subsidences, cannot be identified unless the liner is examined upon decommissioning of the pond. This is not feasible in tailings ponds. Geomembranes in decommissioned uranium mill evaporation ponds have not been examined.

Table 3. Geomembrane problems in the U.S. uranium industry

Event	Number of Cases
Faulty seams	3
Wave-liner abrasion	Numerous suspected at 1 site
Rodent damage	Numerous suspected at 1 site
Sloughing of soil cover	2-no liner damage
Cover erosion	2
Wave-bank deformation	2-(1 without damage)
Animals on liner	2-(1 without damage)
Gas uplift	2
Pinholes	2
Puncture by subgrade	2
Puncture by soil cover	1
Puncture during placement	1
Puncture, source unknown	1
Impingement	1-Ruptured discharge line
Wind damage (after installation)	1
Damage by thermal expansion/contraction	1
Damage during transportation, storage	1
Overtopping	1

4. GEOMEMBRANE MATERIALS

Selection of geomembranes is based on chemical and mechanical properties, as well as resistance to weathering and biological attack. Each of these areas will be discussed in this section. Properties of currently available geomembranes will also be described.

4.1 Compatibility

Methods are not available to precisely predict the service life of geomembranes in a specific aqueous environment. The industry relies on immersion tests to select materials that are most stable. Experience obtained to date in the U.S. uranium industry has shown no chemical degradation problems with tailings and evaporation ponds (Table 4). The chlorosulfonated polyethylene geomembrane in one holding pond decomposed when kerosene was added. This is the only chemical failure identified. The subject of chemical compatibility testing will be discussed more thoroughly in a subsequent report.

Table 4. Tailings and evaporation ponds with geomembranes at U.S. uranium mills

Site	# of Ponds	Type of Pond	Type of Liner	Commission Date
1	1	Tailings	HDPE Alloy	1981
2	2	Evaporation	PVC floor-CPE sides	1976
	11	Evaporation	PVC floor-CSPE sides	1976-1979
3	1	Tailings	CSPE	
	1	Evaporation	CSPE	1984
4	1	Tailings	CPSE	1980
5	3	Evaporation	CSPE	1981
6	2	Holding	HDPE	1981
7	1	Evaporation	CSPE	1981
8	1	Tailings	CSPE sides-PVC floor	1978
9	3	Tailings	PVC	
10	3	Evaporation	CSPE	1980
11	2	Holding	CSPE, PVC	

HDPE = high density polyethylene
PVC = polyvinyl chloride
CPE = chlorinated polyethylene
CSPE = chlorosulfonated polyethylene

4.1.1 Tests with Uranium Mill Leachate

Only small amount of information has been published regarding liner compatibility tests with uranium mill leachates. Schlegel (1983) provided data on high density polyethylene tested in a solution of sulfuric acid with inorganic salts. No organic compounds were listed. Samples were immersed 6 weeks at 70°C (158°F). Weight gain was +0.76%. (Three percent is the maximum weight change Schlegel permits in this test.) Stress at yield decreased by 0.23% and stress at break increased by 1.71%, which is within their prescribed limit of 10%. Elongations at yield and break were unchanged. Schlegel concluded that the high density polyethylene would perform adequately in this environment.

Lubina (1979) states that rubber and plastic lining materials under consideration at a uranium mill were tested for tensile strength, elongation, seam strength, weight change, dimensional stability, and appearance after immersion in concentrated test liquors at elevated temperatures. Details of these tests were not reported, however, all materials were judged to have sufficient chemical resistance. The testing program did influence the choice of chlorosulfonated polyethylene with a lead curing agent, which reduces the water absorption and improves dimensional and weight stability. Watersaver (1983) presents data showing lower water absorption in uranium leachate with chlorosulfonated polyethylene made with the lead curing agent as opposed to other curing agents.

Small et al. (1981) tested liners in an oven at 100°C for 14 days and evaluated loss of properties for a uranium mill. Again details of the tests were not described. An alloy of high density polyethylene and ethylene propylene diene monomer was chosen for this application on the basis of the oven aging tests along with elongation properties, low water absorption, low seam to surface area ratio, and seaming technique.

4.1.2 Leachate Compositions

Leachate compositions will vary at each site and with each process. There are three general classes of leachate that ponds may be required to hold: acidic, neutralized, and basic. Components that may affect chemical stability of the liner include acids, bases, organics, and cations. Compositions of leachates are listed in Table 5.

Acidic leachate is composed of sulfuric acid near a pH of 2. Other components used in the process are sodium chlorate and ammonia. Organic species include kerosene, isodecanol, and aliphatic or aromatic amines. The kerosene and isodecanol are insoluble in water. Long chain amines may be slightly soluble in water, however, the low consumption rate would indicate insignificant amounts of amine are lost in the aqueous phase.

One mill using acidic leachate specified that the liner would contain a dilute sulfuric acid with a solvent complex at a concentration of 416 ppm. The solvent complex was identified at 93% kerosene and 7% aliphatic and aromatic amines.

Table 5. Uranium mill leachate composition[a]

	Acidic				Alkaline	
Species	Highland Mill[b]	USNRC Model Mill[c]	EPA TRU Values[c]	Sweetwater Mill[d]	Rio Algom[e]	Neutral[f]
Al	600	2,000	700-1,600	151-180	0.1	
As	1.8	3.5	0.2	0.4	1-2	
Ca	537	500	1.4-2.1	61-127	4-76	570
Cd	<0.1	0.2	0.08-5			
Cl	97.1	300		400-100		
CO_3					0-7,200	
Cr	2.7		0.02-2.9	2.0	<0.005	
Cu	2.3	50	0.7-8.6	1.0	0.04-7.75	
F		5		0.5-1.6	8-15	
Fe	2215	1,000	300-3,000	495-1,350		<0.10
HCO_3					200-33,000	
Hg		0.07		0.004		
K				1-610		
Mg	688		400-700	124	8.6-60	180
Mn	63.5	500	100-210	23	0.01-0.28	
Mo	<5	100	0.3-16	0.1		
Na	343	200		100-109	7,200-18,150	150
NH_3		500			<2	
Ni	3		0.13-1.4	1.3		
NO_3					0.79-71	
P	30			0.05-0.09		
Pb	<1	7	0.8-2	<1	0.25	
Se		20		0.03	0.01-0.11	
Si	233.5			186-281	5	
SO_4	12,850	30,000		9,312-9,529	4,500-8,800	1,980
V		0.1	0.1-120	2.8-3.2	0.5	
Zn	8.4	80		1.6-31		
pH	1.8	2.0		0.9-1.99	10.2-10.8	6.5
Alkalinity as $CaCO_3$					27,100	
Total dissolved solids						4,000
Radionuclides, pCi/L						
Pb-210		250		1,541		
Po-210		250		361	58-65	
U		3,300		5.4 (ppm)	2.8-180 (ppm)	
Ra-226		250		47.99	480-530	
Th-230		90,000		3035	6.9-10.2	
Bi-210		250				

(a) Values in parts per million (ppm) unless otherwise noted.
(b) Gee et al. (1980).
(c) USNRC (1980).
(d) Provided by mill.
(e) From trip report, Williams and Associates, Inc., 3-30-83.
(f) Final Environment Impact Statement Sherwood Uranium Project Spokane Indian Reservation, August 19, 1976.

The fate of trace amounts of kerosene in acidic leachate was investigated in a small experiment at PNL to determine if kerosene would concentrate in a pond. Acid leachate (2.2 ppm organic carbon) was saturated with kerosene. The saturated leachate contained 223 ppm organic carbon. The saturated leachate was evaporated at room temperature to half of its original volume. The evaporated leachate contained 11 ppm organic carbon. This experiment demonstrates that kerosene should not concentrate in an evaporation pond; therefore, degradation by accumulation of kerosene should not occur.

Acidic leachate may be neutralized to precipitate radium and other components. At least one U.S. mill has neutralized acidic leachate with lime. In Table 5, note the decrease in certain cation components and total dissolved solids compared to acidic leachate.

A number of mills and in situ operations use alkaline leaches. The major component of alkaline leachates is usually sodium carbonate/bicarbonate. Total dissolved solids in alkaline leachate are lower than acidic leachate and pH is between 10 and 11.

4.2 Mechanical Property Requirements

These requirements will depend on the site and design of the impoundment. Sites with structures penetrating the geomembrane, or with high probability of subsidences, need a material with high elongation (polyvinyl chloride, rubbers, and elasticized polyolefin are in this category). Sites with steep slopes (greater than 2.5:1) or with potential for gas uplift need high tensile strength material (reinforced materials, high density polyethylene, ethylene interpolymer alloy).

Reinforcement of geomembranes increases the tensile strength, however the three most important functions of reinforcement are increased resistance to puncture, shrinkage, and tearing (Kays 1977). Various options are available for scrims. Burke (1982) discusses the performance of chlorosulfonated polyethylene geomembranes with various scrims. By changing the scrim, the tensile-elongation properties can be adjusted for the desired performance. For example, the scrim of Type 2 in Figure 2 may provide enough tensile strength for steep slopes while providing twice the elongation of the higher density scrim for better performance on pond floors.

Cope et al. (1984) state that scrims of greater density than 10 x 10 (1000 denier) should not be used because strike-through or bonding between plies is difficult to achieve. Poor strike-through may result in delamination.

Puncture resistance is an important mechanical property. Puncture resistance is a subject on which geomembrane manufacturers disagree. Hickey (1969) presents data from two types of puncture tests with four different materials. These data show the relative material puncture resistance of the liners is different for the two tests. For this reason, the NSF (1983) has not adopted a standard test for puncture resistance.

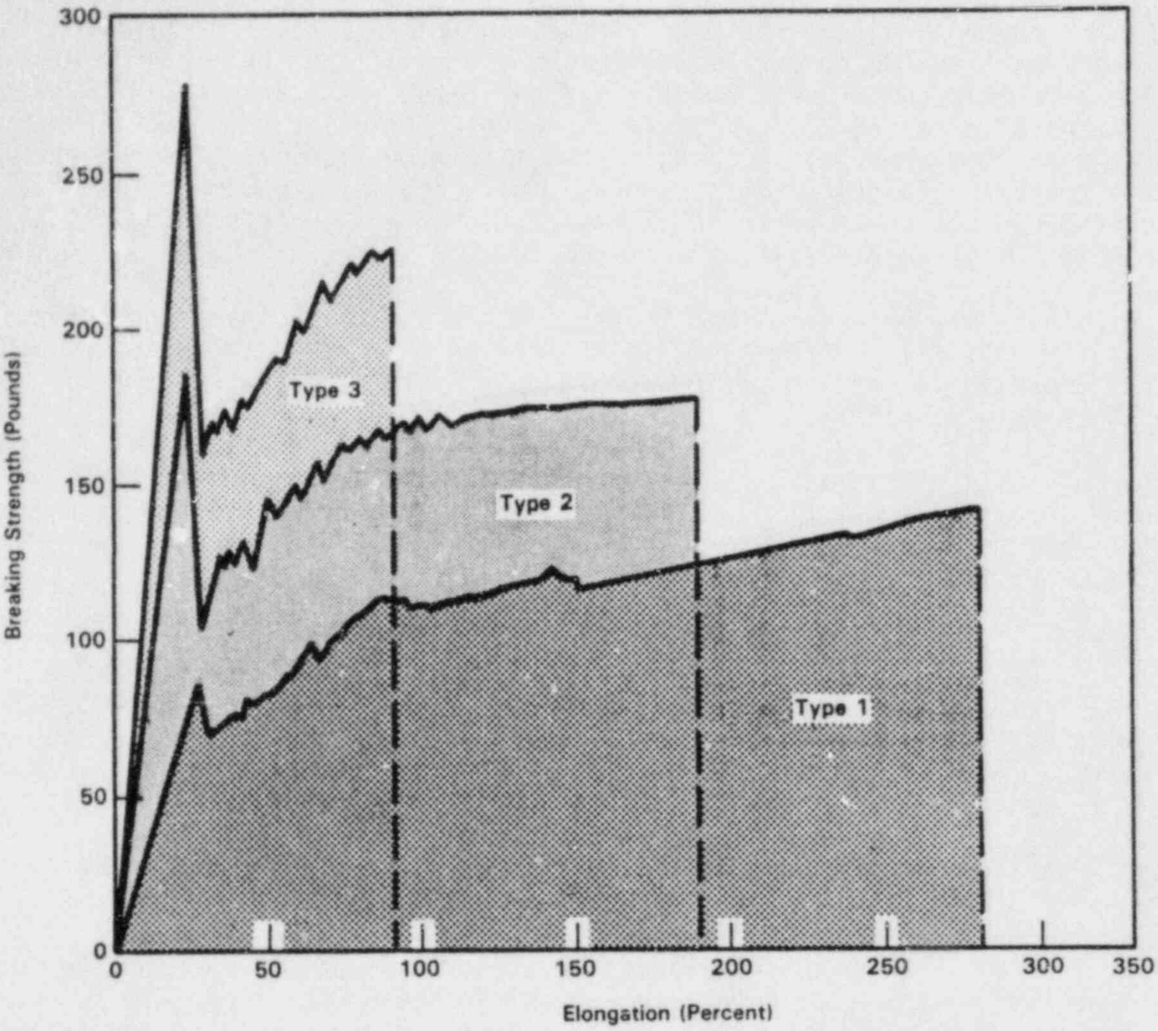


Figure 2. Tensile performance of three different reinforcing scrims (Burke 1982)

There are several types of puncture that a geomembrane should resist. During installation, a sudden point stressing as from a dropped tool may occur. Slower stresses from foot traffic or vehicular traffic may also damage the liner. Additionally, a sustained stress as from liquid head in a pond may cause a rupture of a liner over an anomalous subgrade. Methods of testing the puncture resistance of geomembranes are to be discussed in a subsequent report.

4.3 Weathering Resistance

The resistance of the geomembrane to weathering is vital, especially when there is no soil cover. The best data on weathering resistance comes from actual applications. Most geomembrane vendors include information on resistance to ultraviolet degradation and oxidation by ozone. Material on the market that is most susceptible to weathering is polyvinyl chloride, however its performance as a canal liner (when covered) has been satisfactory for up to 19 years (Morrison 1984).

4.4 Resistance to Microorganisms

One of the failure mechanisms mentioned in Section 3 was microbial attack. Kuster (1979), Schnabel (1981) and Kelen (1983) discuss the effects of microorganisms on different polymers. Before a material is chosen for a uranium mill pond liner, resistance to attack by microorganisms should be demonstrated. To determine the resistance of a geomembrane to microorganisms, NSF (1983) recommends that ASTM D-3083 (ASTM 1984) be used. The test should include factory seams.

4.5 Types of Synthetic Liners

The uranium milling industry has used only polyvinyl chloride, chlorosulfonated polyethylene, high density polyethylene, high density polyethylene alloy, and chlorinated polyethylene in evaporation and tailings ponds. However, the choice of available geomembranes is much larger and is constantly changing. For wastes and hazardous wastes, the NSF (1983) has developed standards for the following materials:

- butyl rubber
- polychloroprene (neoprene)
- ethylene propylene diene rubber (EPDM)
- epichlorohydrin polymers
- high density polyethylene (HDPE) and HDPE-alloy
- polyvinyl chloride (PVC) and oil resistant PVC
- thermoplastic nitrile-PVC
- chlorosulfonated polyethylene (CSPE), low water absorption CSPE
- chlorinated polyethylene (CPE), supported and unsupported
- CPE-alloy
- polyethylene ethylene propylene alloy
- ethylene interpolymer alloy

Another material, thermoplastic EPDM, is listed in the NSF standard, however, it is apparently no longer being produced. Therefore we have not included information on this material. The market for geomembranes is constantly changing: therefore, changes in the NSF standard are likely in the future.

For all these liners, the chemical resistance to acidic and caustic uranium mill leachates is expected to be good, according to available manufacturers' data and experience in the uranium industry. Therefore other properties (seaming properties, weathering properties, biological resistance, mechanical properties, and cost) may determine the choice of liner.

Table 6 summarizes the seaming techniques which may be used with the various geomembranes. The most frequently used techniques for each geomembrane are discussed in the following sections.

Table 6. Techniques for factory and field seams

Geomembrane	Type	Solvent	Bodied Solvent	Solvent Cements	Contact Cements	Vulcanizing Adhesives	Tapes	Heat Sealed	Dielectric	Extrusion Weld
Butyl Rubber	Factory				●	●				
	Field				●	●	●			
Ethylene Propylene Rubber	Factory				●	●				
	Field				●	●	●			
Neoprene	Factory				●					
	Field				●					
Epichlorohydrin	Factory							● Steam		
	Field					●				
Chlorinated Polyethylene	Factory	●	●	●	●			●	●	
	Field	●	●	●	●		●	●		
Chlorosulfonated Polyethylene	Factory	●	●	●	●			●	●	
	Field	●	●	●	●		●	●		
High Density Polyethylene	Factory							●		●
	Field							●		●
High Density Polyethylene Alloy	Factory									●
	Field									●
Polyvinyl Chloride	Factory	●	●	●	●			●	●	
	Field	●	●	●	●			●		
Polyethylene Ethylene Propylene Alloy	Factory							●		
	Field							●		
Ethylene Interpolymer Alloy	Factory							●	●	
	Field							●	●	

Source: Adapted from Cope et al. (1984)

Each type of liner is briefly discussed in the following subsections. For comparison of the minimum specifications for these materials refer to the NSF (1983) Standard 54.

4.5.1 Rubber Liners

This category includes butyl, polychloroprene, EPDM, and epichlorohydrin. These materials typically have high elongation, which makes them desirable for applications with high probability of differential settlement or subsidence.

These materials are typically available in 1.5-m (5-ft) wide sheets. They are seamed by a lap-type seam with vulcanizing adhesives as depicted in Figure 3. For this reason, the rubbers are difficult to seam and repair. With the development of materials that are easier to seam, the popularity of the rubbers has declined in recent years. Their future use in the uranium industry is unlikely.

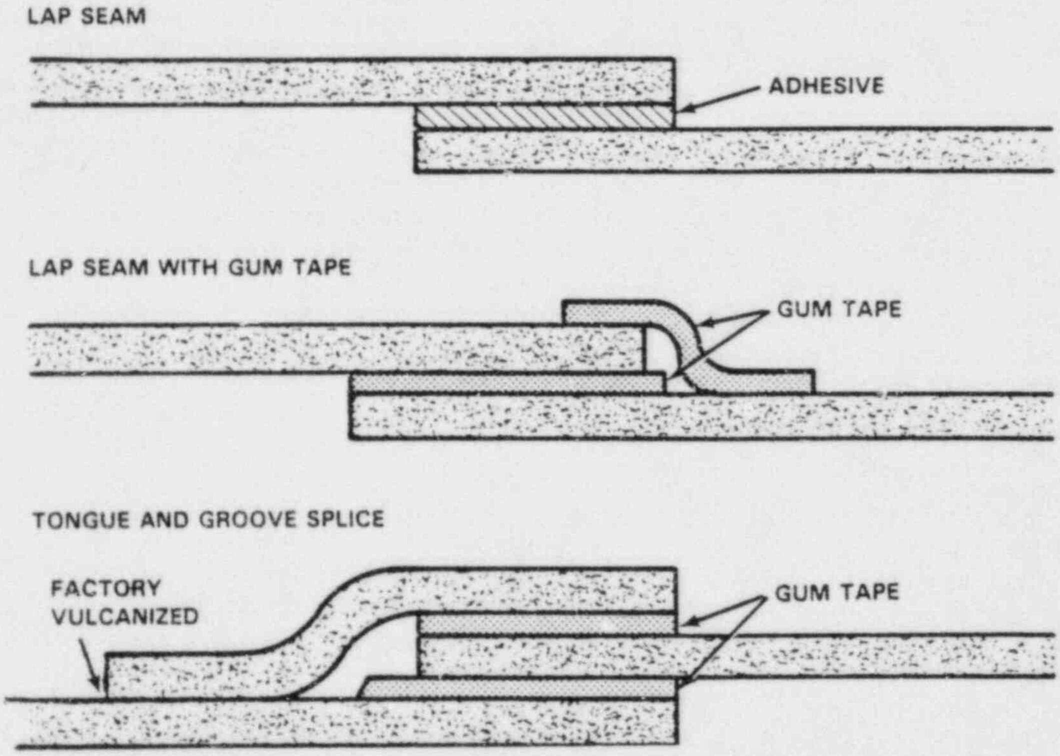
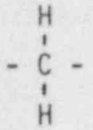


Figure 3. Typical field seams for rubber liners

4.5.2 High Density Polyethylene

HDPE is a relatively new geomembrane. It should not be confused with polyethylene or low density polyethylene as it has different properties.

HDPE is a thermoplastic consisting of a repeating unit of:



$$\begin{array}{c} H \\ | \\ -\,C\,- \\ | \\ H \end{array}$$

The only additive in HDPE is carbon black (~2 wt%) for ultraviolet stability. It contains no fillers or plasticizers. There is also an alloy of HDPE on the market, which is discussed in the next section.

In the U.S. uranium industry there are no tailings ponds with HDPE geomembranes. One mill has used HDPE for leachate holding ponds. The material has also been used in a uranium tailings pond in Canada.

HPDE is a stiff, black thermoplastic available in thicknesses of 0.51 to 3 mm (0.020 to 0.120 in.). The NSF standard only lists larger thicknesses, but is apparently being amended. The minimum thickness for ponds recommended by one manufacturer is 1 mm, however, another manufacturer allows thinner liners. It has high resistance to a wide variety of chemicals. Water absorption is low, and tensile strength is high. Resistance to damage by rodents is good.

As discussed in the section on failure mechanisms, HDPE has a coefficient of thermal expansion that is about one order of magnitude higher than other geomembranes. Schlegel (1983) reports thermal expansion is about 0.0001/°C. Combined with the relative stiffness of the material, bulging may occur when the installed liner is heated. The bulging may stress seams. Bulging is not observed in other liners due to their higher flexibility. To avoid problems due to this phenomenon, two installers contacted in this study stated that liners are installed in cooler weather (at night if necessary). If the liner is covered by soil or fluid, temperature extremes are lowered and thermal expansion/contraction is not as great.

Minimum specified HDPE yield stress is 10,000 kN/m^2 (1500 psi) at 10% elongation, however, it breaks at elongations greater than 600%. In practice, the material may yield at nicks or surface irregularities at lower stresses. HDPE is reportedly prone to stress cracking problems (Cope 1984), although no documented cases of this occurring in the geomembrane industry were obtained in this study.

Schlegel (1983) provided data demonstrating the high resistance to damage by rodent gnawing, termite attack, fungus growth, and root penetration.

HDPE is seamed in the field by either thermal welds or extrusion welds. After placement, it requires time to relax prior to seaming. Examples of HDPE seams are shown in Figure 4. For extrusion welds, the two panels to be seamed are preheated and melted HDPE resin is extruded either between sheets for the lap weld, or on the edge for the fillet weld. Both techniques result in a weld of homogenous HDPE that is thicker and therefore stronger than the original material. The lap weld is typically 5-cm (2-in.) wide. The thermal weld, which one manufacturer recommends, is actually a double seam with a 1.3-cm void

Lap-Welded Seam

Fillet-Welded Seam

Double Seam

Figure 4. High density polyethylene field seams

between two thermal welds about 1.3-cm wide. As with all materials, dirt and moisture can interfere with seaming. Improper preheating can also produce poor seams.

One installer using lap seams inspects the welds by pulse-echo ultrasonic testing to assure adequate bonding. Another installer inspects double seams by sealing one end of the void and pumping air into the other end. Pressure loss indicates the presence of a faulty seam. A third installer uses a vacuum box for nondestructive seam inspection.

The welding and thermal seaming techniques permit seaming operations on HDPE at lower ambient temperatures than most other geomembranes.

HDPE is available in unseamed portions up to 10-m (33-ft) wide, compared to 2-m (6-ft) widths for most other materials. This reduces the quantity of factory seams to zero, however, more field seams may be required.

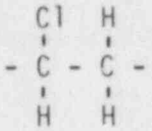
4.5.3 HDPE-Alloy

This material is an alloy of HDPE and EDPM. The reason for alloying is to provide increased elastomeric properties to the HDPE. This alloy also contains about 4% carbon black to impart resistance to ultraviolet radiation. The material is available in 0.76-, 1.01-, and 1.5-mm (0.030-, 0.040-, and 0.060-in.) thicknesses. HDPE-alloy (1-mm thick) has been used at a uranium mill tailings pond with acidic leachate in the U.S. There have been no visual signs of chemical degradation or weathering of this geomembrane since operations began in 1981.

HDPE-alloy is available in sheets 7-m (23-ft) wide from the factory. Field seams are made by extrusion fillet welds and seams are examined by vacuum testing.

4.5.4 Polyvinyl Chloride

PVC is the most commonly used geomembrane because of its low cost and proven performance for many installations. PVC has been used to line ponds since 1952. It has been used extensively by the USBR as a canal lining. The repeating unit of this thermoplastic is:



$$-\underset{\mathrm{H}}{\overset{\mathrm{Cl}}{\mathrm{C}}}-\underset{\mathrm{H}}{\overset{\mathrm{H}}{\mathrm{C}}}-$$

However, PVC geomembranes contain other additives, such as plasticizers (25-35%), fillers, extenders, biocides, and stabilizers (1-5%), which modify the properties. The variety of components results in numerous varieties of PVC on the market today, and requires compatibility and performance testing for liners from each supplier under consideration. An oil resistant PVC alloy is available as well as a nitrile rubber-PVC blend. Both of these materials offer properties that are not required of liners at mill tailings ponds. Because of their additional expense, it is unlikely that they would be used at a uranium mill.

One U.S. mill uses PVC exclusively for its tailings ponds. Another mill uses PVC on the floor of its tailings pond, and one mill uses PVC on the floor of a number of evaporation ponds.

The material is available in both reinforced and nonreinforced forms, the latter being most commonly used. Nonreinforced PVC is not recommended for slopes greater than 2.5:1. Thicknesses of 0.25 to 1.14 mm (0.010 to 0.045 in.) are available.

PVC is resistant to inorganic acids and bases. PVC apparently has good chemical resistance to acidic uranium leachate, because users at U.S. mills have reported no problems with the material in service up to 8 years. It should also be acceptable for neutral and alkaline leachates.

One feature of PVC is that plasticizers slowly diffuse from the liner, leaving it brittle. It is also susceptible to photo-oxidation by ultraviolet radiation. For these reasons, PVC must be covered at all installations, and during storage. Elevated temperatures, by direct exposure to the sun, increase the diffusion of plasticizers from the PVC.

The stability of plasticizers may vary dramatically. For PVC geomembranes, nonvolatile plasticizers are critical.

An example of PVC service life is reported by Morrison (1984) reviewing performance of PVC canal liners. Morrison has examined PVC liners in service for up to 19 years. He found up to 46% loss in plasticizer and significant property changes. In seepage tests from various canals, the seepage rate was shown to increase with time.

The material is available in approximately 1.9-m (6-ft) wide sheets. The sheets are joined into larger panels by the fabricator. Factory seams are made by solvents, or heat or dielectric bonding. Fabricators make panels 21 to 30-m wide weighing up to 1800 kg (4000 lb). The fabricated panels are usually accordion-pleated and packaged in wooden crates or cardboard boxes on skids.

Field panels are overlapped between 15 and 30 cm (6 and 12 in.) and the seamed portion is usually 5-cm (2-in.) wide. Field seams are usually made with solvents, however, thermal techniques are sometimes used.

As discussed in the section on failures, PVC is prone to shrinkage. Shrinkage tendencies can be reduced by reducing tension during the manufacturing process, i.e. making sure the material is not rolled under tension. To reduce shrinkage problems in the field, PVC is installed with slack.

PVC shows good elongation and very good puncture resistance. Tensile strength is adequate for liners of tailings and evaporation ponds.

As mentioned earlier, rodent and fungi may damage PVC. The manufacturer should supply the customer with documented resistance of his PVC to these failure mechanisms.

4.5.5 Chlorinated Polyethylene

CPE was first introduced as a liner in 1965. It has been used in the U.S. uranium industry to line embankments of ponds with PVC floors.

CPE is made by reacting high density polyethylene in solution with chlorine gas. The chloride content of CPE resin is 25-45%. CPE is compounded with rubber, polyethylene, or PVC, however it is greater than 45% CPE resin. No plasticizers are required. NSF (1983) recognizes both CPE and a CPE alloy with different properties. Because of differences in formulations, the CPE chosen for a uranium mill application should be tested to demonstrate chemical resistance in the expected environment. CPE is sold primarily as a supported membrane 0.91-mm (0.036-in.) thick. It has good puncture resistance and tensile strength when reinforced with a scrim. CPE offers improved stress cracking resistance over polyethylene and improved cold impact resistance over PVC (Haxo 1980).

The resin supplier reports good sulfuric acid resistance and caustic resistance. CPE apparently has good resistance to acidic uranium mill leachate, not having degraded in evaporation ponds at one U.S. uranium mill. It is used without soil covers and has good weathering characteristics. Resistance to mold, mildew, fungi, and bacteria is good.

CPE is available in 1.2 to 1.5-m wide rolls for fabrication into larger panels. It is factory seamed by solvent, bodied solvent, and by dielectric means up to widths of 30 m. Solvent and bodied solvent seams are used in the field. As with any reinforced material, any exposed scrim must be flood coated prior to exposure to liquid to prevent wicking. This is a requirement for patches that are cut from extra liner stock without selvaged edges. EMCON (1982) presents data showing good weathering characteristics for CPE.

4.5.6 Chlorosulfonated Polyethylene

CSPE is a popular liner that has been used for many evaporation ponds and three tailings ponds in the U.S. uranium industry. It is available in a low water absorption formulation sometimes referred to as "industrial grade." The material has reportedly fared well with acidic, alkaline, and neutralized leachates. A CSPE liner degraded rapidly when kerosene was added to a holding pond at one U.S. uranium mill.

CSPE is similar to a thermoplastic, however, it gradually cures to an elastomeric state on the surface. It is formed by contacting polyethylene with chlorine and sulfur dioxide. The chlorine (35% by weight) provides elastomeric properties and the sulfur (1 to 1.4% by weight) provides crosslinking sites.

A primary constituent of CSPE geomembranes is carbon black which functions as a strengthening agent and protects the CSPE from ultraviolet damage. Other materials are present in small quantities needed for processing CSPE. Curing agents (usually magnesium oxide or lead phthalate) are used to promote a slow surface crosslinking of the product.

The material possesses good weathering characteristics and resistance to acid, alkali, mold mildew, fungi, and bacteria. However, performance will depend to some degree on the specific formula for compounding. Like all liners, each manufacturer will have different formulations with different properties.

CSPE is manufactured in rolls about 1.5-m wide. Fabricators make wider panels (up to 30 m) by factory seaming. Techniques for factory seaming include heat, dielectric, solvent, and bodied solvent. The bodied solvent is typically CSPE dissolved in xylene. Factory seams are typically 2.5 to 3.8 cm (1 to 1.5 in.) reinforced bonded width.

Field seams are solvent or bodied solvent lap seams. Fifteen cm (6 in.) of overlap is the standard with 5 to 10 cm (2 to 4 in.) of bonded width. CSPE was plagued with seaming problems early in its use as a geomembrane. These problems apparently have been resolved. When seaming CSPE that has been subjected to sunlight or heat, it is necessary to remove the vulcanized top layer by wiping with trichloroethylene or perchloroethylene.

For use as a geomembrane, CSPE is made with a polyester scrim to provide tensile strength. It is available in 0.91 mm (0.036 in.), 3-ply versions and thicker 3- and 5-ply versions. The scrim also helps reduce shrinkage tendencies of CSPE to less than 2%, which is an acceptable value. The ply adhesion of CSPE is an important parameter to be tested prior to installation, so delamination occurrences can be avoided.

Because of the vulcanization of CSPE, special storage requirements are necessary. The material should be stored under white plastic covers to prevent high temperatures and to reduce exposure to ultraviolet radiation. At higher temperatures, the folded material may stick to itself and be damaged when unfolded.

4.5.7 Polyethylene Ethylene Propylene Alloy (PEEP-A)

This material is often referred to as polyolefin or elasticized polyolefin. It currently has only one supplier in the U.S. and is available in 0.51- and 0.76-mm (0.020- and 0.030-in.) thicknesses.

Polyolefin is a black, slick, nonreinforced thermoplastic, which has good outdoor weathering properties (having passed 10^6 Langleys exposure). It is seamed (factory and field) with a hot wedge welder using heat and pressure. The seam is a 5-cm (2-in.) overlap with 1.25 cm (0.5 in.) of contact area. A loose flap is permitted on both the top and bottom side.

Tensile strength and elongation are similar to HDPE. It has high elongation (greater than 500% at 20 mil thickness).

Haxo et al. (1983) demonstrated the material resistance to alkalis, acids, and weathering. Haxo states that the material has had problems in low temperatures and high winds.

4.5.8 Ethylene Interpolymer Alloy

This material has been used extensively in the tension membrane and air supported structure markets, however, it is relatively new in the liner market and has not been used at any uranium mills. It is considered a supported elasticized polyolefin alloy. The support fabric is polyester in a dense weave, with high tensile strength and low elongation. It is more flexible than polyethylene and elasticized polyolefin. The producer claims the plasticizer in this material is non-extractable. Seaming is done by thermal or dielectric means. Resistance to high temperature (71°C), kerosene, and sulfuric acid is reportedly good. Its puncture resistance is high. The material comes in two grades based on polyester fabric density of 170 and 225 g/m^2. The manufacturer states that this material is more expensive than most other geomembranes.

5. IMPOUNDMENT AND SUBGRADE DESIGN AND CONSTRUCTION

5.1 Site Characterization

For proper design and construction, and adequate cost estimates a variety of factors need to be considered. These include:

- site hydrology
- characterization of native soils (classification, shear strength, consolidation, permeability, sedimentation, erosion characteristics
- availability of construction soils
- climate
- vegetation
- animals
- seismology

The depth to groundwater must be known. Presence of springs, or high groundwater will necessitate special subgrade drainage requirements. Lubina (1979) describes a case where a designer for a uranium mill suspected springs at the proposed pond site, so drains were required below the liner to prevent reverse hydrostatic uplift.

The site's soils will have a bearing on leak detection requirements, geomembrane selection, and dike design. Soil borings have been generally used by designers to sample soils. The permeabilities of the native soils are needed primarily for design of leak detection and drainage systems, and assessment of the effects of leaks. The uniformity and consolidation characteristics of soils at the site will affect subgrade and embankment requirements. Shear strength is critical for dike design. Erosion characteristics need to be determined to assess dike and subgrade stability. For example, karstic soils will require extra subgrade construction requirements to reduce the possibility of forming sinkholes (Giroud and Goldstein 1982, Cope 1984, USDI 1973).

The climatology of the site will have several effects on the design and construction of the pond. The pond should be oriented with its narrowest dimension in the direction of the prevailing wind to reduce wave size thereby reducing the potential for damage by waves. Earthwork may be restricted in extremely hot weather, during periods of rainfall, and in freezing weather. Placement of the liner should be done in weather conditions that are optimal for seaming; in some locations this may limit placement of the liner to several summer months.

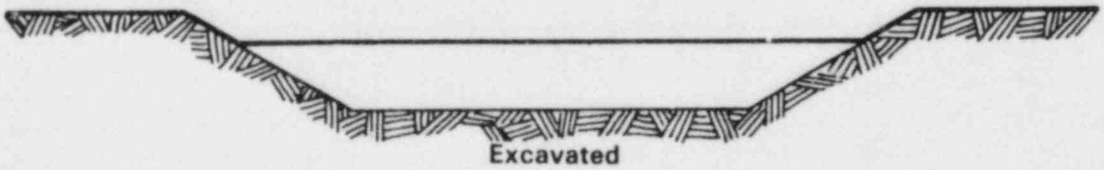
The availability of certain soils may affect design. For instance, Baldwin (1983) reports that hauling pea gravel to a uranium mill evaporation pond was more expensive than using a geotextile for a gas venting layer. Therefore a geotextile replaced a planned pea gravel layer.

Local vegetation may affect the choice of soil sterilant and sterilant application rates. The wildlife will also affect design requirements. The potential for damage by sharp hoofed animals may necessitate the use of perimeter fences for ponds without soil covers. The presence of burrowing rodents may affect material selection.

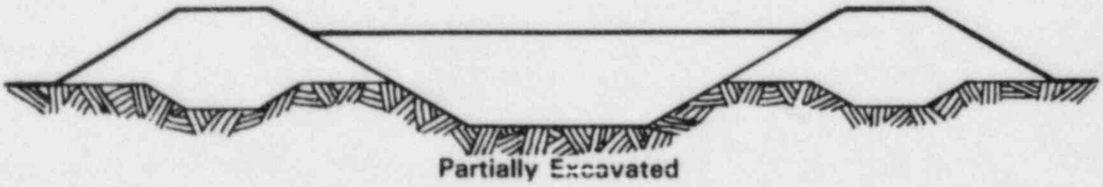
5.2 Types of Impoundments and Capacity

Three basic types of impoundments, which may be used in the uranium industry, are excavated, partially excavated, and cross-valley as depicted in Figure 5. The excavated pond has been used to a large degree because of its inherent safety. This type of impoundment contains all liquids below-grade; therefore, there is no dike prone to catastrophic failure. The partially excavated system is less expensive to construct for the same capacity as the excavated impoundment. The liquid level in this system may rise above the natural terrain. Finally, the cross-valley impoundment is popular because of its low cost, requiring a dike across a valley with no upstream dike. The U.S. uranium industry has examples of each system. The decision of which type of impoundment to use depends primarily on the site topography and hydrology.

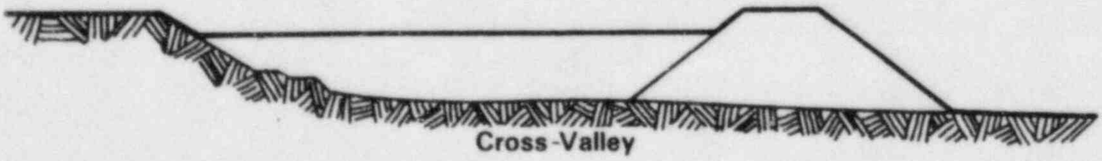
The precise service life of geomembranes can not be accurately predicted. The chemical and weathering resistance of a liner are usually specified for



Excavated



Partially Excavated



Cross-Valley

Figure 5. Three types of impoundments

20 years by manufacturers, if properly installed and used. Therefore, tailings ponds should be intended for no more than 20 years active life because of uncertainty in the service life beyond this time period. Most tailings ponds have operating lines much less than 20 years.

Evaporation pond size is determined by evaporative surface area requirements. The tailings pond operating life, capacity and dimensions are to a degree determined by the uranium reserve in the area, and the site geography. However, other considerations in pond sizing should include the advantages and disadvantages of large and small ponds. Smaller ponds offer advantages of lower initial cost, lower financial risk in case of failures, and reduced damage by wave action. Of course the disadvantage is the higher capital cost for the required pond capacity.

Rainfall and surface runoff must be figured into the capacity of evaporation and tailings ponds. Above-grade and partially excavated impoundments with perimeter dikes only need to accommodate rainfall as surface runoff would not enter the impoundment. If the impoundment is located on a flood plain of a river or stream, the potential of floods and flood damage to the embankments must be addressed.

The cross-valley impoundment must have capacity to hold runoff or else the runoff must be diverted. Examples of both situations are found in the U.S. uranium industry. If the impoundment is to contain runoff, the pond should have capacity for a "design storm." Guidelines for determining the design storm may be specified by state regulatory agencies. USDI (1975) lists storm design criteria for coal refuse impoundments (see Table 7). The amount of rainfall from the various design storms is available from the U.S. Weather Bureau (1963).

Duvel (1979) states that minimum freeboard (after inflow from the design storm) is usually 0.9 to 1.5 m. Federal or state regulations will specify the minimum freeboard requirement.

5.3 Subgrade

Subgrade construction procedures used at seven U.S. uranium mill sites are presented in Table 8. The subgrade performance at all these sites has apparently been satisfactory to date as no problems due to improper subgrades have been reported.

Note at Site 5, a different approach was used. For long-term integrity, a clay layer was placed directly under the lining. A drain system under the clay layer is used to eliminate liquid under pressure.

Expansive soils should be generally avoided to reduce shrink-swell action. It is desirable to have homogenous soils free of organic matter. Frequently used soil tests include: Atterberg limits, grain size, density, strength, settlement, permeability, organic content, and neutralizing capacity.

Table 7. Minimum design storm criteria for long-term disposal impoundments

1. Impoundment Size Classification

	Impoundment Size		
Category	Maximum Volume of Stored Water During Design Storm (ac-ft)		Maximum Depth of Water During Design Storm (ft)
Small	50	and	20
Intermediate	50 and 1,000	or	20 and 40
Large	1,000	or	40

2. Hazard Potential Classification

Category	Description
a. Low Hazard Potential	Facilities located in rural or agricultural areas where failure would cause only slight damage, such as to farm buildings, forest or agricultural land, or minor roads.
b. Moderate Hazard Potential	Facilities located in predominantly rural areas where failure may damage isolated homes, main highways or minor railroads disrupting service or relatively important facilities.
c. High Hazard Potential	Facilities located where a failure could be reasonably expected to cause loss of life, serious damage to house, industrial and commercial buildings, important utilities, highways and railroads.

3. Recommended Design Storm for Long-Term Conditions

Impoundment Size	Hazard Potential	Minimum Design Storm Based on Precipitation[a]	Additional Criterion
Small	a. Low	Opp	
	b. Moderate	1/2 PMP	
	c. High	PMP	The indicated storm is appropriate only if the combination of spillways and decants for the facility can evacuate 90% of the maximum volume of stored storm water within 10 days.
Inter-mediate	a. Low	OPP	
	b. Moderate	1/2 PMP	
	c. High	PMP	
Large	a. Low	1/2 PMP	
	b. Moderate	PMP	
	c. High	PMP	

(a) In areas of the U.S. west of the 105th meridian, both the six-hr duration PMP and one-hr PMTS (probable maximum thunderstorm) duration storms shall be evaluated and the more critical of the two shall be used for design purposes. OPP stands for a storm with one percent probability of occurring each year. PMP stands for a probable maximum precipitation (6 hr duration).

Source: USDI, Engineering and Design Manual Coal Refuse Disposal Facilities, prepared by E. D'Appolonia Consulting Engineer for U.S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

Table 8. Subgrade construction procedures at seven uranium operations

Site	Procedures
1 (evaporation)	Remove 0.3 m of topsoil from site; grade to tolerance of ±0.03 m; test subgrade permeability; install drain network; cover with pea gravel.
2 (evaporation)	Scarify 0.3 m of natural soil; recompact to 100% standard Procter density placed within optimum to ±2% moisture content; measure permeability; install drain network; install 0.15 m coarse sand.
3 (evaporation)	Grade slope at 2.5% to center lowline; compact to 90% of maximum dry density at optimum moisture; sterilize soil; scarify and reroll; install geotextile.
4 (evaporation)	Excavate; remove roots, brush, loose earth, and rocks; scarify 0.15 m; bring to optimum moisture; compact [illegible] 95% maximum dry density.
5 (tailings, cross valley)	Excavate to approximate grade; trench for [illegible] drains; inspect for open cracks and seal [illegible]stall drains; place clay in 0.15-m lifts; compa[illegible]
6 (tailings, excavation)	Excavate pond; add sand where needed; ster[illegible] needed; sterilize surface: roll surface.
7 (tailings, cross valley)	Clear vegetation; remove soil with organic constitue[illegible] compact to 95% of maximum dry density.

Excavation follows the site preparation activities (grubbing, clearing, construction of roads). At this point, large rocks, roots, organic matter, and other debris are removed. One installer contacted in this study recommended that no large rocks be within 10 cm of the liner. Roots and organic matter will decay, and this will result in both gas generation and settlement of the soil.

Compaction is usually specified at 95% of Proctor Density (determined by either ASTM D-698 or D-1557) near optimum moisture content for canal and reservoir applications (USDI 1973). A variety of compaction specifications have been used for uranium mill ponds. If a drain type leak detection system will be used, the permeability of the soil must be determined. The permeability of the base should be at least two orders of magnitude lower than the permeable layer containing the drains (Myers et al. 1983).

The texture of the base is important if the liner will be placed directly on this base. As discussed above, in most cases another layer of high permeability soil will be used for gas venting, liquid drainage, and liner protection. Carr and Gunkel (1983) have studied the effects of subgrade materials on geomembranes subjected to up to 30 passes of tracked and tired vehicles. They concluded sandy silt and medium-fine sand (USCS) with no particles larger than 0.95 cm (0.375 in.) cause the fewest punctures with traffic above the liner. NSF (1983) recommends a minimum 15-cm sand layer directly below the liner in all cases. Geotextiles further reduce puncture frequency (Collins and Newkirk 1982).

USEPA (Cope 1984) recommends drainage layers above synthetic liners at landfills so leachate can be collected and below liners for leak detection. Drain systems above the liner are not used in the uranium industry unless provisions for dewatering tailings are desired. The recommended USEPA design for drain systems is a slope greater than or equal to 2% with clean sand (SP, Unified Soil Classification System) with less than 5% passing the No. 100 sieve. A minimum 15-cm thick layer of sand is recommended by USEPA, who also suggest pipe spacing of 15 to 60 m. Fifteen to 20-m spacing is recommended by others (Burke 1982, Williams 1982). Polyvinyl chloride pipe is the logical material for drain pipes for uranium mill tailings.

In ponds with perforated pipe leak detection systems, compaction of a sand layer may damage the pipe. Haxo (1980) states that traffic over drain pipes should be avoided. Haxo also described a method to analyze compression forces on a buried pipe. In two uranium mill evaporation ponds with drain systems, the permeable layer was not compacted. If compaction of a sand layer over perforated pipes is specified, the designer should demonstrate that the pipes will not be damaged. The U.S. Bureau of Reclamation (USBR) recommends 70% relative density for sand layers for canal construction (USDI 1973).

An alternative to a sand layer for liquid drainage is the geotextile net. Methods to design for drainage by a geotextile net are presented by Giroud (1981). He states that geotextile nets have transmissivities of about 0.001 to 0.01 m^2/sec. This would provide more drainage capacity than a sand layer 15-cm deep with a permeability of 7×10^{-4} m/sec. The geotextile net may be prone to fouling by soil which may reduce its hydraulic conductivity. Further investigation of this phenomena may be warranted.

Prior to geotextile or geomembrane placement, the subgrade requires fine finishing and sterilization. Fine finishing entails smooth rolling or raking and inspection for dirt clods and rocks. Haxo (1980) recommends only rounded particles 6-mm (0.25-in.) diameter or smaller be exposed if a geomembrane will be placed directly on the base. If geotextiles are used, the size criterion can be less stringent.

5.4 Soil Sterilization

To reduce the probability of puncture due to vegetation below the geomembrane, the liner industry generally recommends the soil sterilization prior to placing the geotextile or geomembrane. The sterilant that has been used for this function at uranium mill ponds is bromacil, a substituted urea. EPA stated that local agricultural experts should recommend sterilants for the specific sites.

Bromacil is available in a powder form to be wetted and sprayed onto the site. A supplier of bromacil gives directions for weed control under pond liners. Table 9 lists the recommended application rates for control of various weeds.

On moist soils, bromacil is to be applied after final grading, just before placing the liner, using at least 935 L of water per hectare (100 gal per acre). In dry soils, incorporate bromacil into the soil to a 10 to 15-cm (4 to 6-in.) depth, by either tilling or water addition.

Shultz (1983) states that quack and salt grasses can damage liners. On this basis, application rates of 28 to 34 kg per hectare (25 to 30 lb per acre) are recommended. Staff (1983) recommends sterilization for polyvinyl chloride, chlorosulfonated polyethylene, and chlorinated polyethylene liners if nut or quack grasses are present. Some geomembranes, especially thicker ones, are not prone to puncture by vegetation. There have been no broad-scoped studies comparing performance of various liners, so the customer must assume that sterilization is necessary unless the supplier provides evidence to the contrary.

Table 9. Bromacil application rates

kg/ha	(lb/acre)	Weeds Controlled
7-11	(6-10)	Annuals: cheat, crabgrass, downy brome, foxtail, lambsquarters, puncturevine, ragweed, ryegrass, turkey mullein, wild oats
11-17	(10-15)	Perennials: bahiagrass, broomsedge, dandelion, dog fennel, goldenrod, plantain, purpletop, quackgrass, red top, smooth brome, wild carrot
28-34	(25-30)	Bermudagrass, bouncingbet, brackenfern, dallisgrass, dogbane, horsetail, johnsongrass, nutsedge, salt grass, and vaseygrass

5.5 Vent Systems

Vent systems are needed primarily to release gas from under the geomembrane at ponds without soil covers. Mechanisms for gas accumulation under a geomembrane are described in Section 3.4.1.

A drain type leak detection system provides a mechanism for gas to escape from the floor of a pond. Gas may also become trapped under the liner on the embankment as we observed at one uranium mill where the soil cover had slipped off the liner. A vent system will also hold the liner down in winds by equalizing pressures above and below the liner (Kays 1977), thereby eliminating another potential failure mechanism.

A gas-permeable layer is required under the liner to conduct gases to vents located on the berm. This is often accomplished by a 15-cm deep sand layer, which also is used for liquid drainage. One uranium mill has used a geotextile underlay to provide the gas-permeable layer (Baldwin 1983). This design was more economical than hauling pea gravel from offsite. The use of geotextiles instead of a sand layer on embankments is an attractive alternative for another reason. Sand layers on embankments are prone to deformation during installation and during operation by wave action. Giroud (1981, 1982) discusses requirements for designing vent layers made of geotextiles.

Examples of vents are shown in Figure 6. These vents are placed within 0.3 m of the crest of the berm at 8 to 15-m (25 to 50-ft) intervals. Kays (1977) states that the vertical tube vent is more effective than the covered hole vent for pressure equalization.

If gas is to be vented and no liquid drainage under the pond is required, then the slope of the pond floor can be decreased to 1.5% according to Burke (1981). Baldwin (1983) reports a 2.5% slope was used at an evaporation pond with a geotextile for venting. Small (1980) recommends a 2.5% slope for gas venting.

Koerner (1984) shows that air transmissivity of geotextiles is not greatly affected by normal stresses (up to 120 kN/m^2 (2,500 psf). Air permeability of one geotextile ranges from 25 to 200 cm/sec under various air pressure differentials. At low air pressure differentials as would occur during gas venting or wind equalization, an air transmissivity of 0.029 m^3/m/min was measured. Transmissivity in this range should be adequate for venting gas trapped under the liner. However, the ability to rapidly equalize pressures is a more complex problem. Combined with an adequately sized anchor trench, a vent system using a geotextile should hold down a liner during high winds. Baldwin (1983) states that at one site, sandfilled geomembrane tubes were placed on the liner to provide additional anchorage. The geotextile at this site would transmit air at 6.5 m^3/m/min when stressed under 4.5 m of water head.

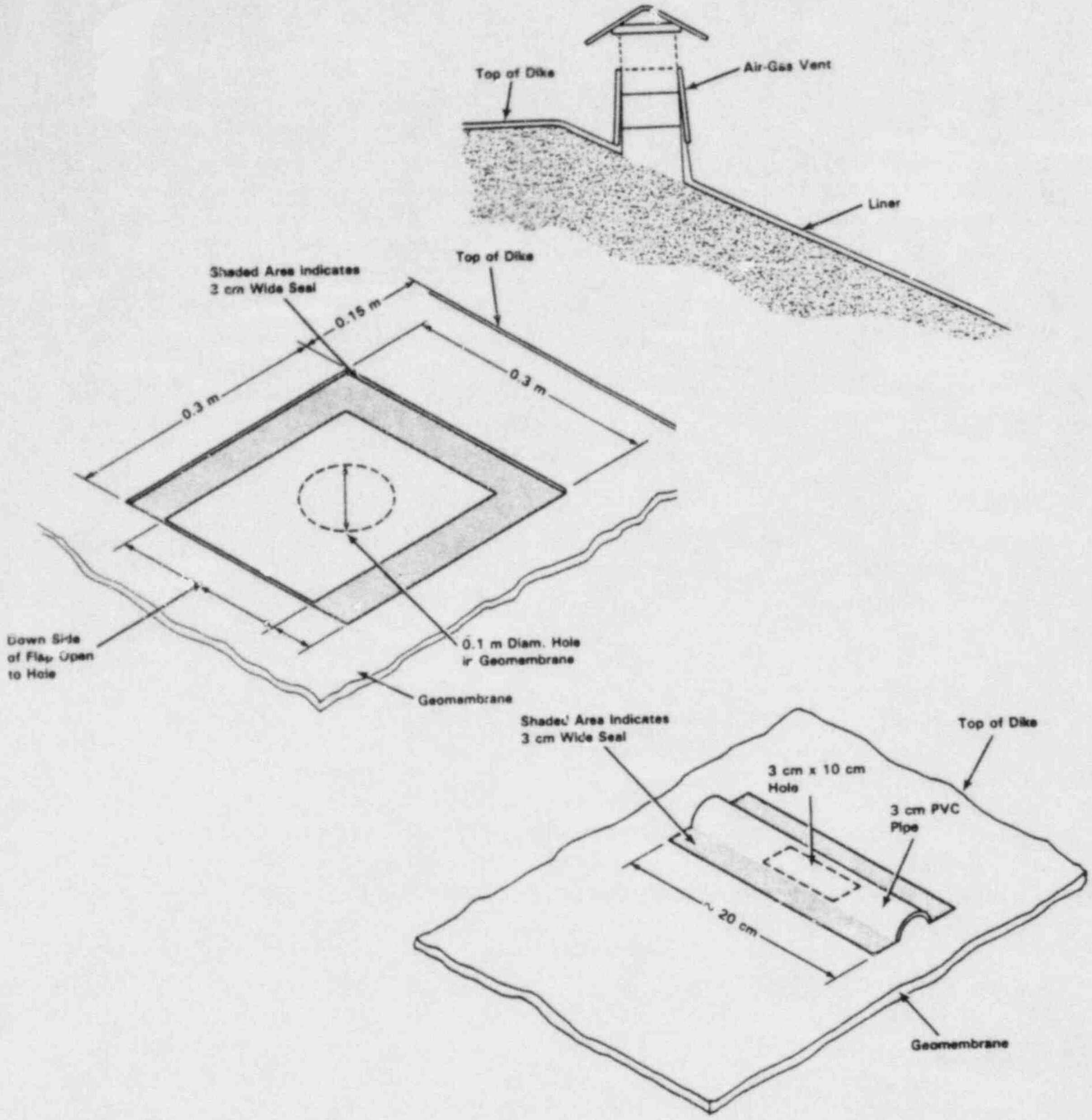


Figure 6. Examples of three types of vents

6. GEOMEMBRANE HANDLING AND PLACEMENT

6.1 Transportation

To prevent damage during transportation, proper shipping and inspection procedures are required. Narrow rolls are transported from manufacturers to fabricators. Wide rolls (> 5 m) are transported from fabricators to sites, usually protected by a thick sheet of the same material. Some geomembranes are folded instead of rolled. Folded geomembranes are usually shipped in banded, cardboard crates on pallets. In all cases, careful inspection of the received goods is mandatory. With broken crates, careful examination for holes created by nails, splinters, and tacks is necessary. Where holes are discovered, the inspector must carefully examine subsequent layers for damage.

6.2 Storage

It is desirable to minimize geomembrane storage time at sites, due to potential for damage by either weather or vandalism. Storage should be in a secure area to prevent vandalism. Polyvinyl chloride and chlorosulfonated polyethylene require special storage requirements. Chlorosulfonated polyethylene should be kept from direct solar heating to reduce the curing rate of its surfaces. Polyvinyl chloride is prone to ultraviolet damage and loss of plasticizers. Shultz (1983) recommends shelter from direct sunlight by light colored plastic.

6.3 Geomembrane Positioning

Boxed, folded liners are usually moved by truck to the location where they are to be installed. The box is opened and vertical sides are removed. The panel is unfolded in one direction by holding it while the vehicle slowly drives forward. Then the crew unfolds it in the second direction and floats it into position by trapping air underneath the liner. The liner is temporarily anchored with sandbags or sandfilled tubes while the next panel is being placed. Then seaming can begin.

To allow the panel to be gripped without damage and to provide a strong grip to move the panel, an installer will roll a dowel on the edge of the geomembrane. This permits a strong grip while it avoids stressing a small area of the geomembrane.

Rolled geomembranes are typically rolled from spools supported in the air by cranes on vehicles. Care must be taken to prevent the equipment from damaging the edges of the geomembrane while it is being unrolled.

The liner should not be installed under tension. Polyvinyl chloride which is especially prone to shrinkage, should be installed with slack. High density polyethylene requires allowance for thermal contraction and expansion. If installed in hot weather, slack should be included.

Any holes created during placement should be immediately marked, and patched as soon as practical. Patches of reinforced materials require the edges to be "painted" with materials provided by the manufacturer for this purpose. The paint covers exposed scrim and thereby prevents wicking. The final inspection should verify that all patches have been painted.

Liners should not be placed more than one panel ahead of seaming operations to avoid wind damage to unanchored panels.

6.4 Seaming

The layout of the panels (in the design stage) is important in avoiding several of the seaming problems discussed in Section 3. To avoid seam stresses during and after seaming, seams should only be parallel to the slope of the dike as shown in Figure 7. Shultz (1983) states that reinforced material can be placed so seams are horizontal on slopes less than 4 horizontal to 1 vertical.

In the corners of impoundments of reinforced geomembranes, the use of cap strips over the seams is a means of reducing the probability of delamination in these locations.

A geotechnical consulting engineer contacted during this project showed evidence of leaks below three layer seams at a pond. Seams of three layers of material cannot be entirely avoided except at small impoundments. At the intersection of three sheets, two sheets should be allowed to achieve a strong

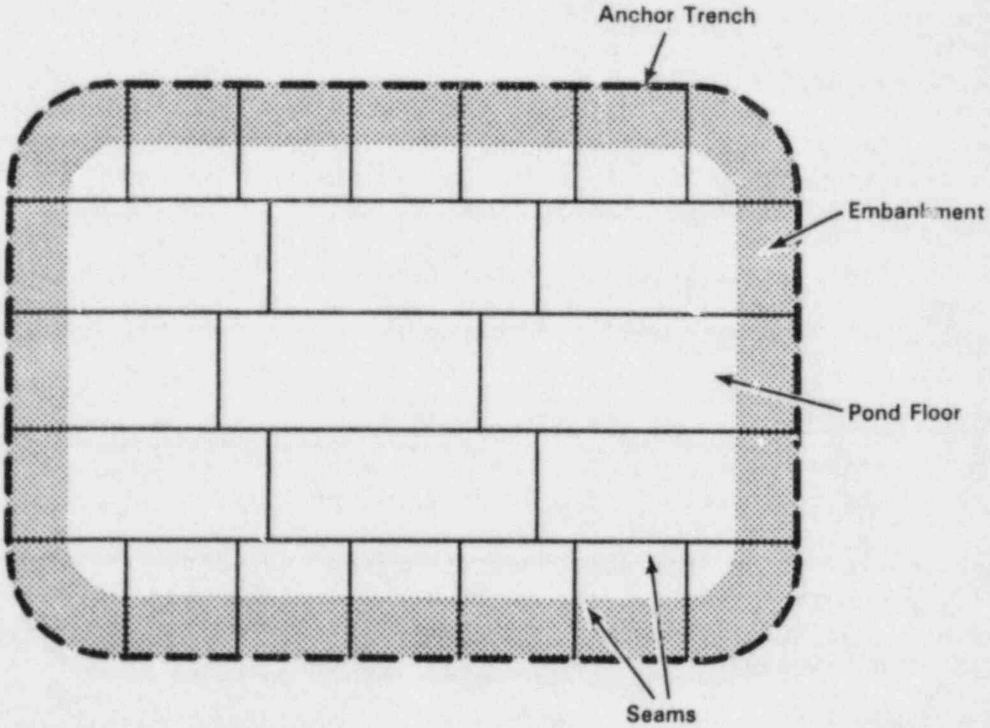


Figure 7. Illustration of field seams parallel to the slope of the dike

bond before the third is bonded to them. A patch over the three-layer seam was suggested by the consultant for additional assurance against leaks.

Seams should be made according to the manufacturer's recommended technique using recommended adhesives, solvents, or welding equipment. Materials can be seamed by a variety of techniques as shown in Table 6 (Section 4). Prior to installation, exposure tests in the simulated environment should be completed to assure that the seams are not affected by the liquid to be contained.

Shultz (1983) collected data on seaming operations at 14 impoundments under construction. He observed that seaming operations proceeded under conditions that were in violation of the manufacturers' recommendations at some sites. This should not be allowed to occur. If temperatures are too low or conditions are too wet the installer should cease seaming operations. If this is not done the quality inspector should request operations cease. An exception would be permitted if the seaming crew has tents that adequately shelter the operation.

For most solvent lap seams a smooth surface is required. Typically a 2.5 cm x 25 cm x 6 m (1 in. x 10 in. x 20 ft) plank is used under the surface of the materials to be seamed. The geomembrane is cleaned of dirt and moisture using rags or brushes. Certain materials (ethylene propylene diene monomer and chlorosulfonated polyethylene) may require removal of the surface cure by solvent washing prior to seaming. Two workers apply slight tension to the liner over the length of the plank while a third person applies solvent between the films. Staff (1983) recommends a solvent rate of 3 ml per meter (1 fl oz per 30 ft) for polyvinyl chloride, chlorinated polyethylene, and chlorosulfonated polyethylene seams. Then hand pressure is applied. Some installers use small rollers in a direction perpendicular to the edge of the panel to work out wrinkles and air bubbles. The edges are inspected and resealed if necessary prior to moving to the next section. Staff (1983) states 5 to 15 minutes is required to develop shear strength. After 0.5 hr, seams should be closely inspected for voids.

The other major categories of field seams are thermal and weld type seams. Each manufacturer of these seams has specialized equipment to seam by these techniques. Most manufacturers also have requirements for preheat temperatures that are monitored by the seaming personnel or recorded by instruments on the seaming machine to assure temperature limits are maintained.

Sand, dirt, and moisture in the seam can result in poor quality seams. Prior to seaming an area, the surfaces must be wiped clean. In windy or rainy conditions, seaming may need to be postponed.

Seaming systems using contact adhesives require the adhesive to develop a degree of tack before contacting with the mating piece. Quality of these types of seams is more difficult to control than other seams.

Most joining systems have a minimum seaming temperature. Below this temperature, seaming is difficult and there is a high probability of creating faulty seams. Installers typically use heat guns to preheat materials to be seamed. It is vital that the temperature guidelines of the manufacturer be followed.

This means that for many materials, seam fabrication and patching operations can only be conducted in the warmer months. Typical minimum recommended temperatures range from 7° to 16°C (45° to 60°F).

Seaming two different kinds of materials together is difficult. Several U.S. mills have used combinations of polyvinyl chloride on the floors of ponds and reinforced materials (chlorinated or chlorosulfonated polyethylene) on the embankments. A consultant reported a situation where polyvinyl chloride was seamed to chlorinated polyethylene. The polyvinyl chloride aged, shrunk, and cracked at the seams. NSF (1983) does not recommend seams of two different geomembranes.

Elastomers are prone to seam defects called "fishmouths." These are created when unequal tensions in two sheets being seamed together cause the sheet with lower tension to pop up at intervals along the seam. When fishmouths form, they must be cut out and patched.

Lack of necessary bond width may create a weak seam, which is susceptible to failure. Most seams are specified at 15 cm (6 in.) of overlap and 5 cm (2 in.) of seamed width.

If the top edge of a seam is loose, dirt will accumulate under the edge and possibly damage the liner and the seam. Fortunately, this type of flaw is very easy to detect and repair.

Evaporation of solvent from the adhesive system, either in the applicator bottle, storage bottle, or on the geomembrane, can result in an inadequate bond. Solvent evaporation from applicator bottles should be insignificant during normal use because it is used at a fast rate. If not in use, applicator bottles should be either capped or emptied. Storage bottles should be capped whenever not being used. Too much evaporation of solvent from the geomembrane can only be eliminated by the experience of the seaming crew.

From this discussion of a variety of possible problems with seams, it is apparent that the experience of the seaming crew is vital. There is an increasing trend by installers to utilize permanent, experienced seaming crews instead of hiring from the local labor force.

6.5 Anchor Trenches

There are two popular techniques for anchoring geomembranes. These are the rectangular trench and the v-trench. Another more expensive method is anchoring to concrete, which is not practiced for tailings and evaporation ponds. A fourth method is anchoring by placing liner under the road along the pond perimeter. This method will reduce the amount of water entering the dike soil, thus promoting stability. This concept has not been practiced in the uranium industry to our knowledge. Apparently the expense of the additional geomembrane is prohibitive. At moist sites the concept may be more practical.

The two popular anchor trench designs are shown in Figure 8. The rectangular trench is cut with a trenching machine or backhoe. The v-trench is cut with a road grader or bulldozer with a tilted blade. The excavated soil is placed on

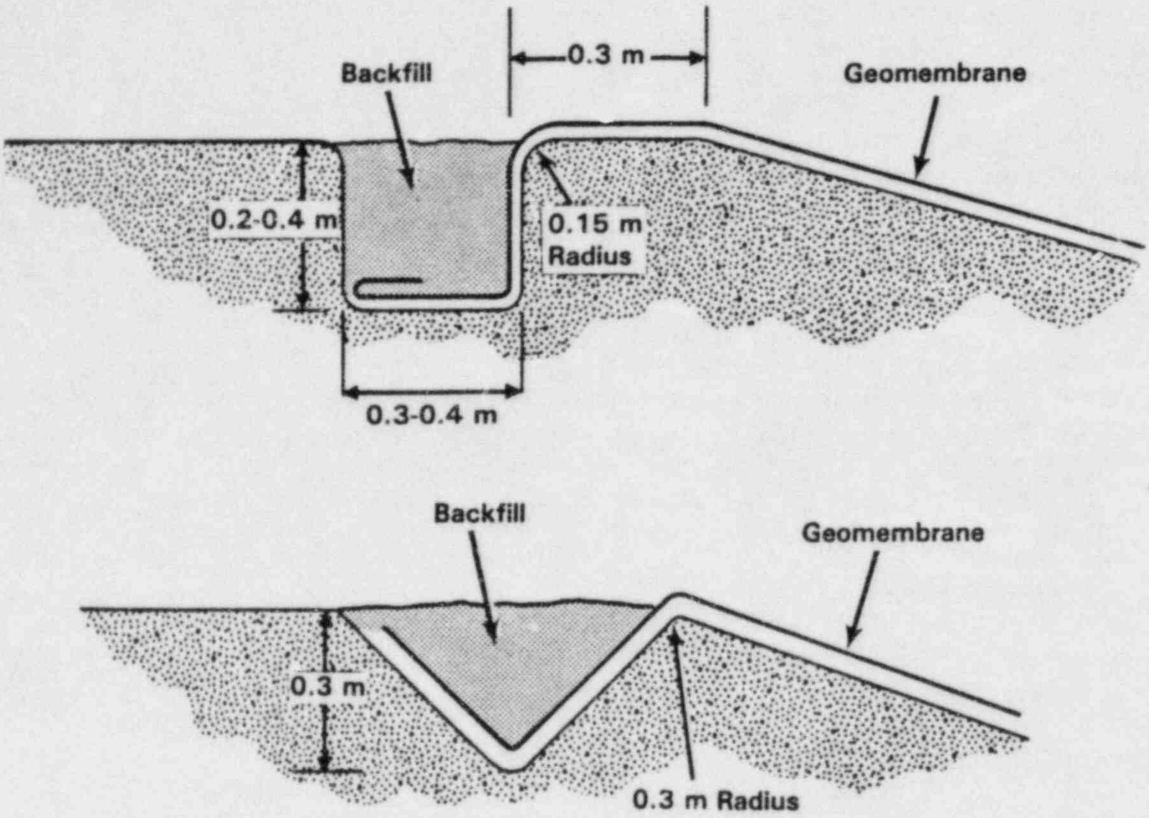


Figure 8. Schematics of rectangular and v-trenches

the side away from the impoundment. After the liner is placed and seamed, the excavated soil is used to backfill the trench. It is important that the field seam be completed before the trench is backfilled, to allow the seaming crew flexibility to move the panels if required. The backfill is usually compacted by the weight of the backfill equipment.

The size of the trenches varies from 20 to 60-cm (8 to 24-in.) deep and 15 to 30-cm (6 to 12-in.) wide. The trench is cut a minimum of 30 cm (12 in.) from the crest of the dike. Kays (1977) recommends a 15 cm (6 in.) minimum radius curve at the edge of the trench that the liner covers, to prevent stressing the liner when folded into the trench.

The v-trench is likewise built 30 to 40-cm (12 to 16-in.) deep. If the trench is at the crest of the berm, Kays (1977) recommends a 30 cm (12 in.) minimum radius curve where the liner bends over the crest.

Giroud (1977) develops the following equation to size anchor trenches that will hold in strong winds where vents or soil covers are not used:

$$S = 1.5 \times 10^{-6} \times L \times V^2$$

where S = cross-sectional area of the trench, m^2
L = length of liner from anchor to floor or minimum liquid level, m
V = wind velocity, km/h

Sizing the anchor trench by this method is recommended where the liner is uncovered and the pond does not contain gas vents. Standard sized trenches will be adequate with uncovered liners containing vents. If geomembranes have soil covers, the anchor trench must be large enough to resist pullout by forces created by the cover. Koerner (1984) and Giroud (1984) discuss the solution of this problem although the values for analytical solution of this problem are not available for a variety of conditions.

Some installers may place the anchor trench below the crest of the berm. This technique is less desirable because of potential damage due to overtopping. This design should not necessarily be excluded, but mill operators should make sure involved personnel know the maximum pond level allowable, and that this level can not be surpassed.

6.6 Connections to Structures

As discussed previously, failures are very common at submerged structures. These types of failures may have catastrophic consequences, as they result in erosion of subgrades and embankments. The soil around the structure may settle, causing large stresses on the liner unless it is free to elongate. Structures aren't generally used in uranium mill ponds and their future use is not recommended. NSF (1983) states that structures should be avoided if possible.

If, however, penetrations through the liner are required, the following design practices are recommended. Compaction of the surrounding soils is vital, to reduce the probability of differential subsidence. The geomembrane chosen should have high elongation properties, and slack liner should be present. The connection should eliminate seepage between the liner and the penetrating structure. Any seepage will increase the risk of differential settlement. The liner should be placed so there is no "bridging" of the liner over gaps or voids between the structure and the soil. Small (1980) recommends a geotextile be placed around the structure prior to placing the liner. When designing the structure, all materials exposed to fluid should be resistant to corrosion by the fluid.

An example of the recommended connection to a pipe is shown in Figure 9. To connect to pipes, specially made geomembrane collars are available.

6.7 Tailings and Leachate Delivery

Two mills, which were visited during this study, had tailings discharge system that consisted of polyethylene pipes supported by floats. The discharge could be moved to different locations in the pond for uniform tailings deposition. It was necessary to anchor this floating discharge system by guy lines to prevent drifting in the wind.

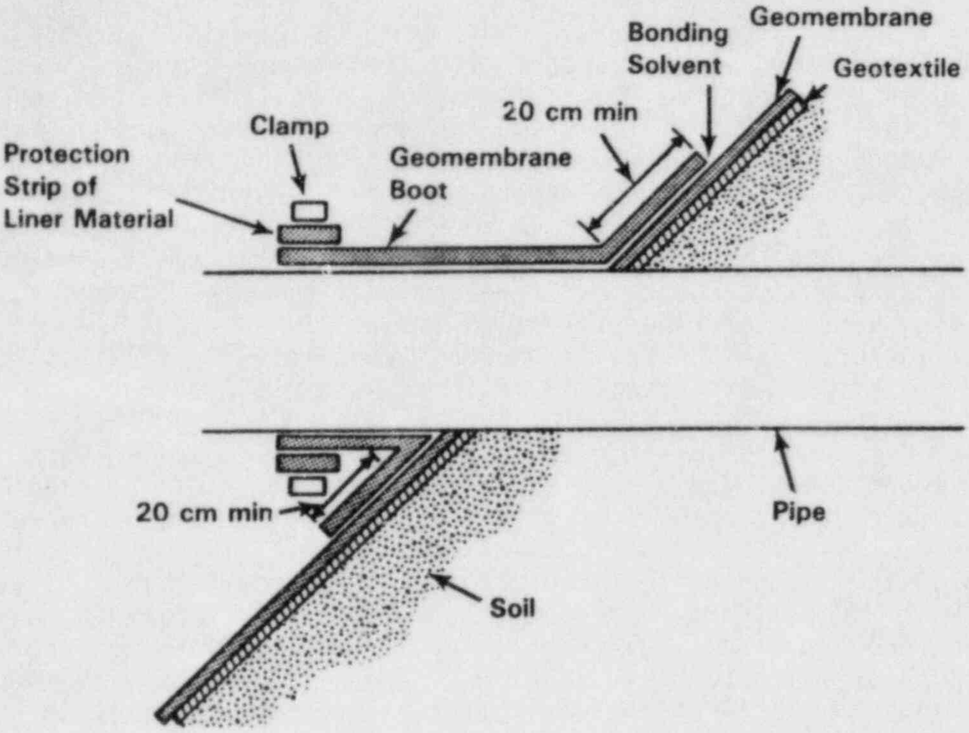


Figure 9. Connection to a pipe penetrating a geomembrane

One system uses styrofoam supports (0.2 m^3) at 2.3-m intervals on the discharge line. During initial tailings deposition, the pipes were supported by sawhorses on a soil cover to prevent burying the line in tailings. Guy lines, adjusted with portable hand-cranks, position the lines.

7. SOIL COVERS

Functions of liner covers include protection from damage by ultraviolet radiation, wind uplift, gas uplift, bank deformation, foot traffic, ice, animal traffic, floating debris, and vandalism. In addition, Haxo (1980) states that a cover may reduce the rate of chemical degradation of a liner by providing a diffusion zone for reactants to penetrate before reaching the geomembrane.

Some problems are also associated with soil covers. These include sloughing of the cover and puncture of the geomembrane during placement of the cover. Of course one disadvantage of liner covers is the additional cost that is incurred during installation. At an evaporation pond (containing no tailings), location and repair of leaks are more feasible if there is no soil cover.

At least four U.S. uranium mills have tailings ponds with soil covers over geomembranes. Two of these ponds have experienced sloughing of their soil covers. No liner damage has been associated with the sloughing action. The construction characteristics of these soil cover systems are listed in Table 10. At Sites 1 and 2, the sloughing that has occurred is attributed respectively to a rapid snow melt and very heavy precipitation. At Site 4, although no sloughing has occurred, some wave erosion of the cover is evident. The operator stated that routine cover maintenance is required. The operator also attempts to deposit tailings initially at the toe (base) of the embankment to increase the stability of the cover soil.

Table 10. Characteristics of soil covers at lined uranium tailings ponds

Site	Geomembrane	Type of Soil	Depth of Soil, m	Slope (v:h)	Sloughing
1	HDPE alloy	sand+spray	0.3-0.6	1:3	yes
2	CSPE reinforced	clay-silt	0.3	1:3	yes
3	CSPE reinforced	sand+spray	0.3-0.46	1:3	no
4	PVC	clay-silt	0.6	1:3	no

Ponds 1 and 3 are very close to each other and were built similarly except that different geomembranes were used. Each pond used a cohesive spray to resist cover erosion. Sloughing which has occurred at Site 1 and not Site 3 may be due to the difference in the frictional characteristics of the liner. High density polyethylene-alloy is a smooth, slick material, whereas chlorosulfonated polyethylene has texture due to its scrim. It appears that the textured geomembrane may hold the soil cover better at steeper slopes than the smooth material.

Evaporation ponds in the uranium industry typically do not have soil covers. One mill has ponds with polyvinyl chloride floors that require soil cover, however, the dikes are lined with ultraviolet resistant geomembranes and are not covered.

One uranium mill operator reported that the liner at his site was punctured during placement of cover materials. To prevent puncture of a liner during placement of the soil cover, the soil must be free of large rocks and sharp particles. Cover materials should be screened to remove particles greater than 0.5-cm (0.25-in) diameter. In addition, the subgrade below the liner must be smooth. Geotextiles below and above the liner will protect the liner from puncture but represent additional cost.

Figure 10 shows the typical soil cover design for canals as used by the USBR (1974), which has extensive experience with covers on polyvinyl chloride and polyethylene-lined canals. The covers are installed by draglines, conveyors, or trucks. Compaction is not required, however, dragging may be used to smooth the cover. It is interesting to note several differences between this design and the soil covers typically used for ponds. First, the slope is 2:1 or less whereas the slope for covered ponds is usually only 3:1 or shallower. Another difference is the two layer system. The upper layer is coarser and provides drainage and erosion protection. The lower layer is usually less permeable native soil.

Other differences are the dimensions of the dike, which are significantly smaller than tailings and evaporation ponds. The canal is not prone to wave damage to the cover due to its narrow dimension.

Giroud (1984) and Martin (1984) describe techniques to analyze the forces on a soil cover/geomembrane system. The stability analysis techniques address the most unstable case where the toe of the dike is submerged. Koerner presents some soil stability data on various geomembranes. Unfortunately, not enough data exist on the various geomembranes with varieties of soils and moisture contents. Therefore, a designer must rely on designs of successful previous installations.

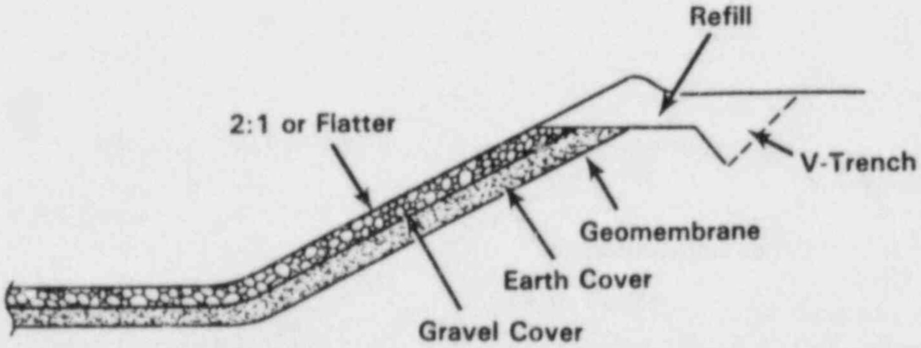


Figure 10. Typical soil cover for a canal with a geomembrane

The generally accepted procedures for cover design and installation are:

1. The use of cohesive soil will minimize wind and water erosion and sloughing potential. Clays have performed better than sands. A coarser layer over the cohesive layer [as in the USBR design or as discussed by Small 1980] may be applicable. This two-layer construction technique has been used only at one uranium mill and only on the top 3 m of the dike. Kays (1977) states that compaction is desirable, however the USBR does not specify compaction for covers on canal liners. Compactive efforts would increase the risk of puncture by the subgrade or cover soils.

2. The use of cohesive sprays may be useful in reducing sloughing potential. These may require application on regular intervals for continued effectiveness. These have been used successfully at one tailings pond and unsuccessfully at another.

3. A maximum slope of 1 vertical to 3 horizontal should be used on ponds with covers (Haxo 1980, Small 1980). Some geomembranes may require even shallower slopes.

4. One meter deep access roads into the pond for heavy equipment should be used (Watersaver 1982).

5. Tracked or tired vehicles can be used on the covered liner, but they should always operate on layers 0.45-m thick according to Small (1980) and Haxo (1980). Tracked vehicles create the least stress on liners. The U.S. Army Engineer Waterway Engineering Station (Carr and Gunke[illegible] 1983) tested geomembranes over various subgrade soils. All materials that were tested were prone to some puncture by installation equipment operating on sand covers 0.15- to 0.45-m deep. These tests did not include thicker liners protected by geotextiles on the bottom side.

6. Sharp turns by haulers and dozers should be avoided because of the potential to rupture or pinch the liner.

7. Materials should be pushed up the slope starting at the bottom of the pond.

8. Heavy equipment should not be operated on wet cover material.

9. Small (1980) states soil moisture should be at or below the optimum moisture content for compaction.

Because of uncertainties in the stability of soil covers and because of the potential for damage to the geomembrane, PNL does not recommend the use of soil covers if the geomembrane supplier can warrant the weatherability of the material if exposed. Absence of soil covers will necessitate a well-designed gas vent system on dikes of tailings ponds, and on floors and dikes of evaporation ponds to prevent wind and gas uplift.

8. QUALITY ASSURANCE

Because the most frequent failure mechanisms are due to seaming and placement, a key to a high quality impoundment is an effective quality assurance program. This program should document observations of all aspects of pond construction including earthwork, geomembrane procurement and placement, covering (if used), and pond operation. Each area is discussed in this section.

8.1 Earthwork

Quality control of earthwork requires an inspector who determines whether design specifications are satisfied. The inspector's functions do not include evaluation of specifications. The inspector must communicate with designers and the construction crew for properly performing his task. It is necessary that the inspector for earthwork to be familiar with specifications, design, construction principles, and field and laboratory tests. He must forward soil test results that are not consistent with design assumptions to the design group so adjustments can be made. Proper quality assurance during earthwork can reduce the occurrence of failures due to subgrade puncture, liquid and gas uplift, wind and wave damage, slope instability, subsidence, and expansive clays.

Earthwork activities may be divided into: 1) site preparation, 2) excavation, 3) foundation work, and 4) placement of permeable fill. Quality control requirements for each activity are discussed.

8.1.1 Site Preparation

Site preparation includes clearing, grubbing, stripping, and grading in order to prepare for excavation, dike construction, and alteration of site drainage. Spigolon (1983) recommends:

- observation of exposed ground to confirm assumptions of design (visual/manual techniques (ASTM D-2488-69) are usually adequate),
- observation of surface contouring measurements (surveying) for drainage,
- observation of performance of surface drainage system during first rainfall.

8.1.2 Excavation

Excavation quality control requirements by Spigolon include:

- detailed observation of exposed material using field consistency tests, grain size distribution, and/or Atterberg limits,
- observations of construction surveys for trench location, slopes of dikes and floors,

- observations of soil movements such as heaving, cracking, slaking sluffing, creep,

- observations of erosion controls such as perimeter ditches and cohesive soil sprays.

Inspection of the excavated area for organic matter, debris, large rocks, and foreign objects requires only visual inspection and written documentation. At this point the quality inspector should also verify that soils in the base are consistent with the assumptions used for the design of the pond. Evaluation of the potential for sinkholes, subsidence, and erosion should be made.

Verification of the slope should be performed by surveying crews and documented for the quality control record.

8.1.3 Foundation

The typical impoundment foundation will consist of compacted native soil. Spigolon states the following quality control requirements for the base:

- borrow materials should be tested for compliance with the specifications,

- weather conditions should be recorded (rainfall, heat, wind, or freezing may affect compaction),

- equipment type, size, and compatibility with soils should be recorded,

- loose lift thickness should be measured,

- compactive effort (i.e. number of passes of equipment) should be recorded,

- soil density and water content measured and recorded,

- location and elevation of each test should be recorded.

For adequate compaction, the specified soil moisture content is vital. The soil moisture content may be determined in the field by several techniques such as oven drying, moisture gages, or the Proctor needle test.

Compaction is usually specified at 95% of maximum density at or near (±2%) optimum moisture content for the soil as determined by the Standard or Modified Proctor Tests (ASTM D-698 or D-1557). Usually compaction specifications will require a certain number of passes of a specified piece of equipment. The inspector must verify that the specified number of compaction equipment passes are made. Compliance to density specifications is determined by field density tests. The most frequently used technique is the Field Sand Cone Method (ASTM D-1556).

The frequency of density tests used by the USBR (USDI 1974) for canal construction is:

1) sample all areas that are likely to be unacceptable,

2) perform at least one density test per shift,

3) for soil linings, perform one test per 770 m^3 (1,000 cubic yards) of earthfill,

4) for embankments, perform one test per 1500 m^3 (2,000 cubic yards) placed,

5) for backfill, perform one test per 770 m^3 (1,000 cubic yards) of soil,

6) perform one permeability test for each 10 density tests.

These test frequencies are included as guidelines for similar types of construction. Haxo states that usually each compacted lift is 1 to 10 density tests are performed for every 1,900 m^2 (20,000 ft^2). Spigolon and Kelley (1983) discuss a method to calculate the frequency of tests on the basis of the cost of tests, cost of earthwork, and experience of the crew with the type of earthwork.

The USBR (USDI 1974) lists areas that are probable for improper compaction. These include areas where:

- compacting equipment turns
- too thick a layer is compacted
- improper water content exists
- less than specified passes are made
- dirt clogged rollers were used
- oversized material exists
- soils were placed when frozen
- compaction was performed by rollers that possible lost part of their ballast
- material is inconsistent with the rest of the subgrade.

8.1.4 Permeable Fill

The permeable fill and drain pipes will require quality control specifications similar to the foundation:

- borrow materials should be classified,

- the permeable layer should be inspected for imperfections and recorded,

- slope and depth should be verified and recorded,

- drainage pipes should be inspected for proper placement,

- compaction or relative density specifications should be verified.

For the sand layer of canals, the U.S. Bureau of Reclamation (USDI 1973) recommends relative density tests and gradation analyses (one test per 77 m^3 of sand). After placement alignment problem procedures are verified, the frequency of tests can be reduced to one test per 7,700 m^3 (10,000 cubic yards).

8.2 Geomembrane Procurement and Placement

The mill operator may avoid potential problems with geomembranes by specifying quality assurance requirements during procurement. These potential problems are: chemical inconsistency, pinholes, insufficient ply adhesion, and insufficient mechanical properties as discussed in Section 3.1. NSF (1983) has adopted standards for geomembrane properties. Tests for various properties should be completed and documented by the supplier. Actual test results should be submitted for the project quality control record.

The quality of a geomembrane will be related to the quality control in its manufacture. Quality control should include: 1) assurance that specified formulations are used, 2) verification of raw materials, and 3) testing of sheets. Liner classifications include many formulations with the same name. The quality control inspector should assure that the formulation chosen (on the basis of chemical and physical tests, and prior experience) is the formulation that is supplied. Raw materials supplied to a sheet manufacturer, need to be tested to determine if they meet certain minimum requirements. Schmidt (1983) recommends that each batch of raw materials be tested for important properties. An example is in the manufacturer of high density polyethylene. Raw materials, which do not meet certain requirements, may result in an increased probability of stress cracking. Schmidt (1983) recommends that each roll of sheet be tested for thickness and physical properties at least once per shift. Physical tests include tensile properties, elongation, puncture resistance, tear resistance, volatile content, and ply adhesion. The manufacturer should satisfy the customer as to the adequacy of manufacturing quality control.

The geomembrane supplier provides the customer with quality assurance documentation confirming physical tests on the lot of material supplied. These test results should meet or exceed the specifications in the supplier's literature. Schmidt (1983) recommends in addition that the manufacturer label each pallet or roll of material with: 1) product type, 2) thickness, 3) batch code, 4) date, and 5) dimensions. He states that the manufacturer should save samples from each batch of raw material for future reference, in case problems arise.

At this stage the inspector must verify that proper transportation and storage techniques are used and any potentially damaged goods are inspected. He must verify that proper seaming materials and procedures are used. Records of weather, site conditions, equipment, and number of personnel should be maintained daily according to one manufacturer and installer (Schmidt 1983). The inspector must also observe the placement operations. Seam inspection requirements should be documented, and 100% visual inspection of the liner should be completed.

This stage of inspection is critical because one of the major modes of failure is punctures and shocks during placement. Because the integrity of the crew is important in avoiding punctures, the inspector should observe and verify that placement rules are followed. For example, all crew should wear rubber-soled shoes. Solvents should not be transferred above the liner. There are many practices to be observed during installation. Other failure modes that can be reduced by a quality assurance inspection during placement include placement of the liner in tension, improper seaming conditions and techniques, improper seaming solvents, improper overlap, poor connections to structures, and wind damage.

8.3 Field Seam Inspection

Because faulty seams are a frequent mechanism for failure of lined ponds, improved inspection of seams is expected to be one of the most productive leak avoidance measures. In this section, techniques presently used for seam inspection at field installations are described. Results of a testing program on several novel seam inspection techniques are presented in Section 9.

8.3.1 Destructive Testing

Destructive tests consist of peel and shear tests according to NSF (1983) recommended procedures. This inspection technique is typically used daily on random seam samples cut from an installed liner to assure that proper solvents and techniques are being used or that seaming equipment is operating properly. This requires patching of the locations where the sample is taken. It should be noted that samples which meet specified seam strengths may not necessarily be leak free. Schmidt (1983) states seams are usually cut out every 60 to 90 m.

8.3.2 Visual

Visual examination can be used to detect large bubbles and fishmouths, however, it is ineffective for detecting most flaws. Visual inspection of 100% of field seams is the general industry practice.

8.3.3 Air Lance

The air lance technique shown in Figure 11 is a popular device for seam inspection, primarily because it is rapid and simple. A jet of air is blown at the edge of the top piece on a seam. Any openings become inflated and easily visible. The operator may also hear a change in the sound of the jet when a flaw is detected. The air lance requires a careful operator to detect unbonds, and

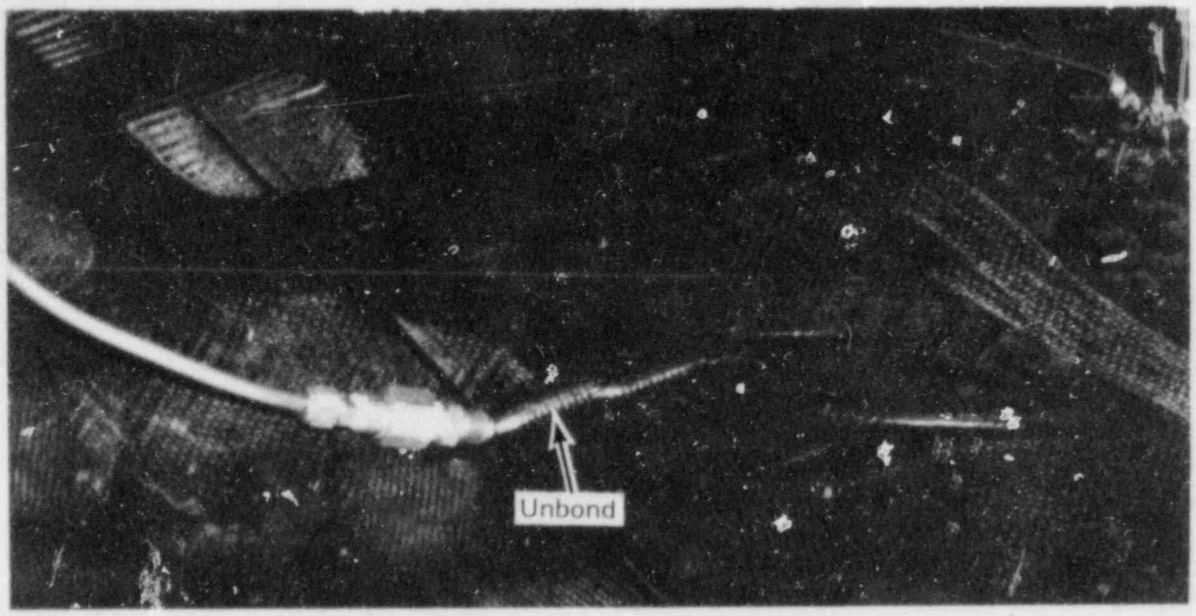


Figure 11. Air lance detection of a flawed seam

works only if the defect is open on the top surface of a seam. Therefore a large unbonded area may go undetected by this technique.

8.3.4 Pick Test

This method detects the same defect types as an air lance, but requires less operator skill. To look for unbonds, a dull object (such as a nail with the sharp point ground off) is slid along the edge of the top piece on a seam. Wherever an open unbond exists, the pick digs into the opening. Detectability is equal to the air lance, but the pick test does not determine the size of unbonds.

8.3.5 Vacuum Chamber

In the vacuum test, a gasketed chamber is placed over a section of seam that has been coated with liquid soap. The chamber, which has a transparent top, is then partially evacuated using an air pump (see Figure 12). Any unbonds that extend across the seam are then indicated by the presence of soap bubbles. This test is very sensitive to small leaks, and has the additional feature of stressing the seam to cause marginally bonded areas to become unbonded, thereby indicating a leak. The technique utilizes chambers of lengths varying from 1 m to 6 m. It should be noted that a leak free seam still may lack adequate strength, therefore destructive tests are usually specified in addition to vacuum tests.

8.3.6 Monitor Welding Parameters

For seams that are thermally joined or extrusion welded, certain key parameters need to be controlled to permit a good bond to form. These parameters may include extrudate temperature, hot air temperature, seaming rate, sheet

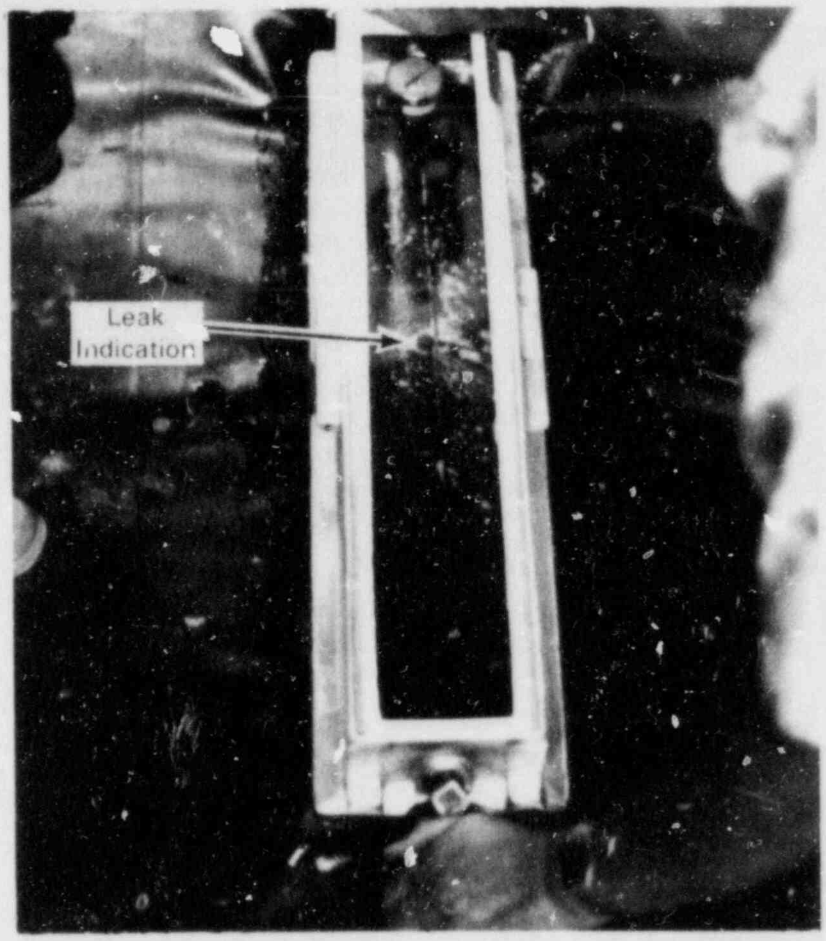


Figure 12. Vacuum chamber detection of a flawed seam

temperature, and contact pressure. While the control of welding parameters cannot guarantee a good bond, this technique is useful because any violation of the parameters assures a poor bond.

8.3.7 Pulse-echo Ultrasonics

This technique involves transmitting an ultrasonic pulse of energy into the seam and interpreting the returned echo on a time-based cathode ray tube. A well-bonded area produces an echo later in time than an unbond because the ultrasound pulse travels round-trip through two sheet thicknesses, whereas at an unbonded area the echo returns after a round-trip through only the top sheet (see Figures 13a and 13b). Pulse-echo ultrasonic testing is currently being used by one high density polyethylene installer on extrusion welded lap seams.

8.3.8 Pressure Test

One high density polyethylene installation technique produces a double seam (see Section 4.5.3). This seam can be closed at one end and pressurized with air from the other. This technique provides the advantage of stressing the

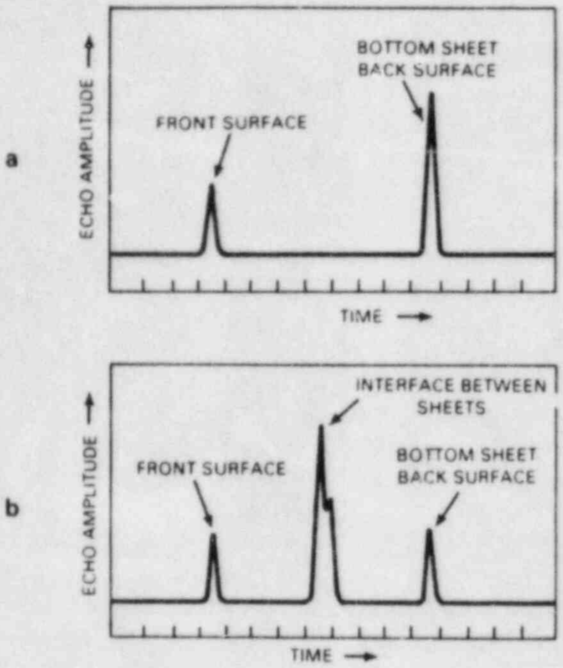


Figure 13. Sketches of a typical pulse-echo ultrasonic screen display for a) a well bonded seam and b) a faulty bond on nonreinforced material

seam to identify marginally bonded areas. The procedure calls for raising the pressure to 0.21 MPa (30 psi). The seam is rejected if pressure loss over 18 minutes is greater than 0.03 MPa (4 psi).

8.3.9 Spark Test

One HDPE installer uses a 30 kV power supply to detect shorts to ground through fillet weld seams. This technique apparently will locate pinholes and air gaps.

8.4 Cover Placement

Failure mechanisms related to cover placement and cover motions include puncture from subgrade and cover soils, and damage by sloughing of the cover. Quality control in covering operations may reduce occurrences of failures by these mechanisms. Items suggested for testing, observation, and documentation are:

- soil classification verification,
- soil depth verification,
- compliance with equipment specifications,

- compliance with requirements for operation of equipment on the liner (i.e. vehicles do not operate on exposed liner, no sharp turns, and other items discussed in Section 7).

8.5 Pond Operation

Burke (1981) recommends a Pond Use Management Plan listing procedures for operation and maintenance of the pond. The suggested plan specifically addresses the inspection requirements, repair procedures, pond drawdown procedures, and requirements for operating and checking the leak detection system.

The plan should address the possible off-normal processing conditions. An example would be whether a conventional acid-leach mill can dispose kerosene and other organic species in the pond. Actions to be taken in abnormal conditions should be prescribed.

Inspection should be on a regular basis, with additional inspections required after severe storms (especially wind storms), and after off-normal conditions or unusual occurrences. Duvel (1979) states that inspections should be performed during each shift at power plant ponds and should include logging of: freeboard, fence and gate conditions, uniformity of sludge deposition, condition of sumps and weirs, weather conditions, and presence of foreign objects. Myers (1983) recommends that daily inspection of drain type leak detection systems be performed. The inspector should note bank damage, soil cover sloughing, condition of exposed liner, and performance of the leak detection system. Any repairs should be documented.

The plan should prohibit dumping of wastes other than those specifically allowed by the geomembrane manufacturer. The plan should emphasize that changes in the chemicals used in processing may affect the liner. All proposed process changes should be approved by technical personnel only after consequences to the pond liner have been considered.

The plan should also include the reporting procedure for observed misuse of the pond or observed damage.

Rapid drawdown of a pond may be possible at sites with evaporation ponds. The plan should specify maximum drawdown rates. Rapid drawdown may lead to sloughing of covers and gas uplift.

The plan should be distributed and explained to all personnel that may possibly use the pond, including maintenance personnel, engineers, managers, and new hires.

Haxo (1980) recommends that coupons be immersed in the pond for future property evaluation. Burke (1981) recommends an exposure test where tubes, approximately 30 cm in diameter, are made of the liner material. The tubes are sealed at one end and ballast is added. Then tubes can be placed on the dike so that they are exposed to leachate, air, and the air/leachate interface. This type of test has an advantage over the coupon test in that the effects of the three different exposures can be evaluated. Both types of tests should include field seams.

The liquid contents of the pond should be analyzed on a regular basis. Monitoring frequency on a quarterly basis during normal operation should be adequate. During off-normal conditions, and process changes, more frequent analyses may be justified.

8.6 Documentation

One place to draw experience from construction of related types of projects is the Bureau of Reclamation. The USBR requires documentation of all phases of the construction of lined canals and earthen reservoirs USDI (1974). The results of all portions of a quality assurance program are documented in a final construction report. This report includes daily inspection reports of subgrade excavation, soil tests and verification, surveying, compaction, visual observations, design changes, and photographs documenting construction. In the case of a pond with a geomembrane, USEPA (Cope et al. 1984) recommends that other important documentation consists of acceptance of the earthwork by the liner installer, the implementation of the pond operation plan, seam inspection results, verification of proper placement procedures (including transportation and storage), and final as built drawings.

Schmidt (1983) recommends that geomembrane manufacturers document raw material properties, and certification that the raw materials tested were used for the supplied lot of material. Certification of compliance with minimum sheet specifications should be provided.

9. SEAM INSPECTION PROGRAM

An experimental program was conducted to examine potential improved field seam inspection techniques which offer advantages over frequently used inspection techniques discussed in Section 8.3. The program consisted of laboratory screening of novel techniques and testing the most promising instruments under field conditions. This work is discussed in previous reports (Spanner 1984, Mitchell and Spanner 1984).

9.1 Screening Program

The screening program tested a variety of nondestructive instruments on specially prepared seams with intentional flaws.

9.1.1 Seam Samples

Four types of geomembranes were studied in the screening program: (polyvinyl chloride, high density polyethylene, chlorinated polyethylene, and chlorosulfonated polyethylene). Of these four materials, the chlorinated polyethylene and the chlorosulfonated polyethylene were reinforced with 10 x 10, 1000 denier, polyester scrim. Thickness of the materials was between 0.76 and 0.91 mm except for some of the high density polyethylene, which was 1.5-mm thick.

A commercial liner installer prepared seam samples, each about 0.5-m long, using appropriate field seaming procedures for each type of material. Some of the seams were made with no intentional defects (unbonds), but most of them were intentionally flawed. The defect types included sand, moisture, lack of glue, and masking tape. The masking tape was used to make carefully sized circular defects of from 0.95 to 3.8-cm diameter and strip defects 0.34- to 0.63-cm wide. All seams were nominally 7.6-cm wide. High density polyethylene is extrusion or heat welded rather than glued in field installations, so samples of two types of field welds were procured from high density polyethylene installers for this research. The two weld types were lap welds and fillet welds (see Section 4.5.2), and some of these seams included intentional defects such as moisture, sand, and poor welding technique.

9.1.2 Results of Techniques Investigated in Screening Program

Pulse-Echo Ultrasonic Testing. This technique is described in Section 8.3.7. The technique has only been used commercially by one high density polyethylene installer so it was included in this program to be tested with other geomembranes.

This technique worked well on both the nonreinforced materials with lap seams that were tested (polyvinyl chloride and high density polyethylene with extrusion lap welds). Some parties have criticized this technique claiming that it can not detect the difference between a sound seam and two unbonded layers pressed tightly together, however this claim could not be verified in this seam inspection program.

Infrared Video. An infrared video camera system allows the detection of different temperatures within the seam. One cause of temperature differences is heat transfer rate differences resulting from areas that are not intimately bonded. An infrared seam inspection system would consist of viewing the length of each seam while looking for areas that are cooler than most of the seam. This technique worked only marginally in the laboratory, and in the field too many effects besides bond quality would tend to mask the temperature differences caused by a poor bond. Two likely masking effects are moist areas under the liner and nonuniform contact between the liner and the substrate. This technique was field tested by the Bureau of Reclamation (Morrison et al. 1981) with similar results.

Proprietary Acoustic Instruments. Four different commercial instruments using acoustic principles were tested on the seam samples in the laboratory. While each instrument was unique in some ways, they had several features in common. Each operated at relatively low frequency, less than 100 kHz. All of the instruments operated without a wet coupling medium between the transducer and the test piece. The instruments, designed for the aerospace industry, apply acoustic energy to the area being tested. Reflected energy is measured and displayed on a screen or a meter. None of the four instruments was capable of determining with any consistency the quality of any of the sample seams.

Ultrasonic Resonance. In this technique, a tone-burst pulse of many cycles of ultrasonic energy is transmitted into a seam by a transducer. The length of the reflected pulse varies as the quality of the bond varies, allowing the operator to determine the quality of the area under the transducer. The technique worked well on nonreinforced polyvinyl chloride but did not work on reinforced materials. It is about as effective as pulse-echo ultrasonic examination, except interpretation is more difficult.

Ultrasonic Impedance Plane Analysis. This inspection method worked on the lap seams of all the materials (including reinforced geomembranes) in the screening phase. The principle behind this technique is that a well-bonded seam possesses a certain acoustic impedance and any other area that is not well-bonded possesses a different acoustic impedance. The instrument used is capable of digitally "remembering" the characteristic impedance of the well-bonded area and of seam defects indicating visually whenever an unbonded area is detected. The primary readout on the instrument is a cathode ray tube screen, where a digital "flying dot" represents the tip of an acoustic impedance vector corresponding to the characteristic phase and amplitude of a test area's acoustic impedance. The other visual indications of bond integrity are a light-emitting diode alarm on a probe and a meter that can display either relative amplitude, phase, or the vertically resolved component of an impedance vector.

To use the ultrasonic impedance plane instrument, it must first be calibrated for the particular material and bond type to be inspected. The first step in calibration is to place the transducer (or probe) on a well-bonded area and adjust the display so that the dot displayed for a good bond is at the center of the screen. Next, the transducer is placed on an unbonded area and the dot address of the unbond is stored on the screen. Another dot is then likewise stored to represent when the transducer is not acoustically coupled to the piece under test. After all likely dot addresses (up to eight) are stored, the display, alarm light, and meter can be adjusted to give the most convenient outputs. A useful modification of this procedure in the field was to squirt ultrasonic gel couplant between the liner layers to simulate a well-bonded area. Calibration was then carried out as described above while sliding the transducer between the bonded area and the unbonded area.

When inspecting a seam with this instrument, the operator scans the transducer over the seam while watching transducer position and the probe alarm light. If a preset adjustable threshold is exceeded, the light glows, which alerts the operator to look at the screen. He can then determine from the displayed dot position what the condition of the bond is in the area beneath the probe. If the area is unbonded, the flying dot will be in the vicinity of the calibration dot corresponding to an unbond condition. If the probe is somehow not acoustically coupled to the test piece (lack of liquid couplant, rough surface, etc.), the flying dot will be in the vicinity of the stored dot corresponding to an uncoupled transducer. Watching the alarm light while moving the probe, the operator can mark the boundaries of the unbonded area with a grease pencil.

The probe used with this instrument is very similar to a conventional ultrasonic transducer, except that it operates at a lower frequency than most and has a built-in, alarm triggered, light-emitting diode. Several probes are available for the instrument, but only one was used for this research. The probe used was 95-mm diameter with a frequency range from 160 to 185 kHz. A liquid couplant is required with this instrument to get the ultrasound energy through the specimen/transducer interface. We found tap water to be a good couplant and used it in our experiments.

9.2 Field Demonstration

The second phase of this research was demonstration of nondestructive testing techniques in the field on actual field seams. Several advantages were gained by participating in a USEPA-sponsored research experiment that was being performed by the U.S. Bureau of Reclamation (USBR) in Denver, Colorado. In the USBR project, a commercial geomembrane installer was contracted to fabricate field seams for a variety of materials. One major advantage to participating in this experiment was that we were allowed to remove sections of the seams after nondestructive testing so that they could be destructively evaluated in the USBR laboratories. This helped greatly in establishing the validity of the techniques demonstrated. Another advantage was that the performance of six seam inspection techniques (air lance, vacuum, pick, visual, pulse-echo ultrasonics, and ultrasonic impedance plane analysis) was compared on certain materials. The third benefit was the large assortment of materials that were available for testing, including field seams of the four materials that were considered in the screening phase of this research. Testing was performed on a loose sand floor over hard-packed soil inside an open metal building.

At the USBR laboratories, a conventional pulse-echo ultrasonic unit and the instrument that operates on the ultrasonic impedance plane principle were demonstrated. The pulse-echo instrument was a Krautkramer-Branson USL-38, while the ultrasonic impedance plane instrument was an NDT Instruments Bondascope 2100. For these demonstrations, the pulse-echo frequency was between 5 and 15 MHz and the ultrasonic impedance plane frequency was 167 kHz.

Two types of couplant (gel couplant for pulse-echo and tap water for ultrasonic impedance plane testing) were used to help transmit ultrasonic energy into the materials. The gel couplant was also used between two liner layers to simulate a good bond when calibrating the ultrasonic impedance plane instrument. The only modification we made to either instrument was a transducer holder built for the ultrasonic impedance plane transducer. As shown in Figures 14 and 15, the holder is a transparent block that has a water supply line attached to it. A cavity around the transducer retains water so that adequate acoustic coupling is assured at all times. The transducer holder allows the operator to observe the alarm light and is more comfortable for the operator to hold, so it helped increase the ultrasonic impedance plane inspection rate while preventing false alarms from lack of couplant.

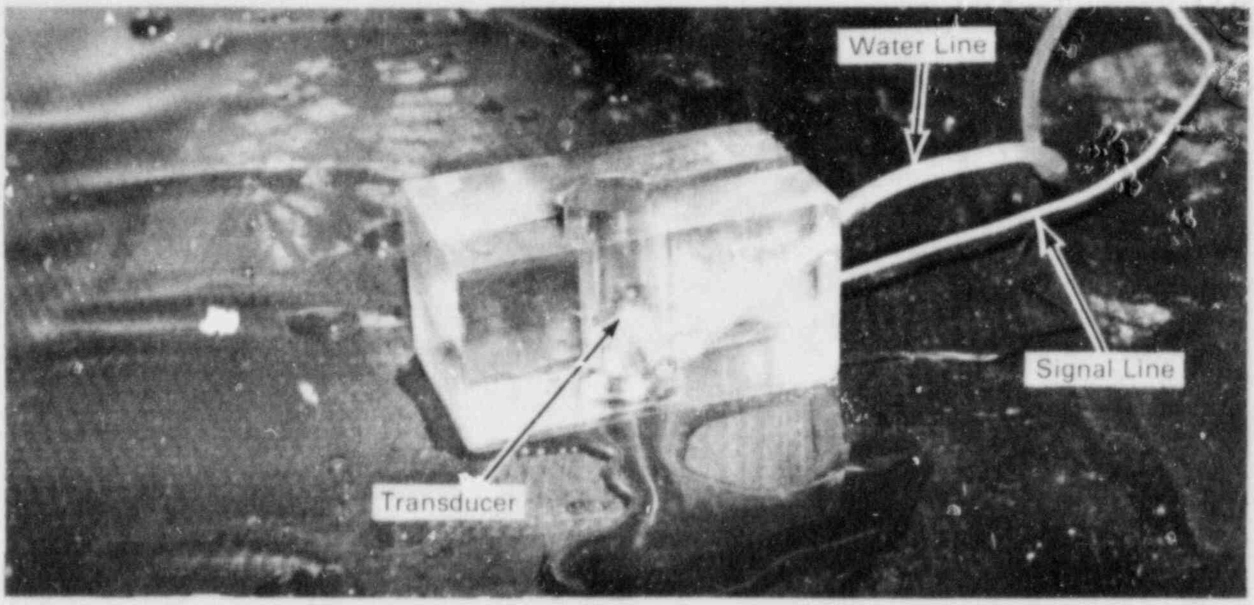


Figure 14. Transducer holder for ultrasonic impedance plane instrument

The pulse-echo technique worked well on the nonreinforced materials (PVC and elasticized polyolefin). It does not work on fillet-welded HDPE seams. These high density polyethylene seams do not contain flat, uniform surfaces required for pulse-echo inspection. The pulse-echo technique does not work on reinforced material due to interference in the reflection of sound by the scrim.

The ultrasonic impedance plane technique worked on nearly all materials tested, including geomembranes with scrims. It detected unbonds as small as 6 mm in diameter, regardless of location within the seam. Destructive analyses of indicated flaws showed either voids or greatly reduced peel strength. This device also does not work on fillet-welded high density polyethylene seams due to the non-uniform seam surface. The technique also did not work well on some materials with wider spaced scrims.

Figure 15. Ultrasonic impedance plane instrument being used for seam inspection

When properly calibrated, this instrument requires less operator skill than the pulse-echo ultrasonic instrument and is slightly faster. On 76-mm wide seams, our inspection rate reached 1 m of seam per minute using a 10-mm diameter transducer mounted in the transducer holder. The equipment for this technique is more expensive than the pulse-echo equipment. Even though many seam flaws were found during the field demonstration, very few would have been considered of rejectable size according to acceptance criteria followed by most liner installers. However, due to the frequency of seam failures, acceptance criteria may need to be more strict to reduce the occurrence of this type of failure.

9.3 Requirements for Implementation of Pulse-Echo and Ultrasonic Impedance Plane Techniques

As mentioned earlier, the pulse-echo technique has been used by one high density polyethylene installer. It can readily be adapted for field use on other nonreinforced geomembranes. Installers would need to develop acceptance criteria for each type of material. One possible inspection scenario might be marking all flaws at a site and performing destructive peel tests on the largest flaws.

The ultrasonic impedance plane inspection instrument can also be readily adapted for field use. Inspection rates may need to be increased, possibly by development of wider transducers. As with the pulse-echo technique, seam acceptance criteria for each material will need to be developed.

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13 ABSTRACT (200 words or less)

Pacific Northwest Laboratory has analyzed the performance of polymeric membrane-lined impoundments containing tailings and leachate at active uranium mills. The U.S. Nuclear Regulatory Commission has requested this information to support licensing of impoundments. Data on the performance of lined ponds in the U.S. uranium industry, mechanisms for damage of liners, and design, installation, and inspection practices are presented in this report. Design, construction, and inspection methods that are capable of minimizing failures are also identified.

No cases of contaminated groundwater are attributed to uranium mill ponds lined with polymeric membranes (geomembranes) in the U.S. The leading causes of geomembrane problems for all industrial pond applications are faulty seams, puncture and errors during placement, improper connections to submerged structures, puncture by soils in contact with the geomembrane, and geotechnical problems due to liquids in the support soil. Although some instances of liner problems with potential for significant consequences have been identified, the concensus of mill operators and regulatory personnel is that performance of ponds with geomembranes in the U.S. uranium industry has been satisfactory.

14 DOCUMENT ANALYSIS – a KEYWORDS/DESCRIPTORS

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evaporation pond

b IDENTIFIERS/OPEN ENDED TERMS

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TECHNOLOGY FOR URANIUM MILL PONDS USING GEOMEMBRANES

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