DOE/MC/29121 -- 5126
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# Remote Mining for In-Situ Waste Containment

## Final Report

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October 1995

Work Performed Under Contract No.: DE-AC21-92MC29121

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
West Virginia University Research Corporation
Morgantown, West Virginia

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## Executive Summary

This document presents the findings of a study conducted at West Virginia University to determine the feasibility of using a combination of longwall mining and standard landfill lining technologies to mitigate contamination of groundwater supplies by leachates from hazardous waste sites. The work described herein was completed with the assistance of and in cooperation with three industrial partners. Joy Technologies, Inc. and Westfalia Mining Progress, Inc. are two of the world's leading producers of longwall mining equipment. Gundle Lining Systems, Inc. is a major producer of synthetic liner systems for industrial and municipal landfills.

The basic concept is to mine under a hazardous waste site using longwall mining methods currently used in the coal mining industry. During this operation, a multi layer impermeable barrier would be installed, along with a leachate collection system. The excavated area would then be backfilled with spoil from the mining process. The leachate collection system is a horizontally permeable layer placed on top of the impermeable barrier. Leachate reaching this layer would be drained to a sump and pumped to the surface for treatment. Horizontal migration of contaminants would be prevented by the installation of slurry walls or grout pile walls around the perimeter of the site. These systems are described in detail in the Appendix to the Final Report.

The bottom barrier will be placed below the contaminant plume to minimze worker exposure. A high level remote control will further minimze worker risk. Installation of an effective bottom barrier will contain the migrating plume in its entirety.

The containment technique proposed in this project is the only technique currently being evaluated that will provide in situ and complete containment of hazardous, radioactive, or mixed waste. Our proposed containment system will prevent the further migration of leachate emanating from the existing waste, and allow the collection, and quantification of the leachate volume as well as analysis of the leachate quality.

Alternative techniques may include solidification/stabilization, deep-soil mixing, in situ vitrification, and soil-saw barriers. Excavation of the contaminated soils for the stabilization/solidification process poses several problems that range from being a slow and dangerous process to generating airborne contaminated dust and vaporized volatiles to the storage dilemma of the contaminated waste. At the same time, other than the stabilization/solidification technique and deep-soil mixing (USEPA, 1989) all other technologies are in the development phase and, at best, have been attempted on small scales (LaGrega et al, 1994). Suffice to say that none of these alternative techniques provide for positive containment of waste, i.e., no certainty that the technique will capture the contaminant and will continue to contain it. These techniques can only be applied to areas of limited size and relatively shallow contaminant depth (Shackelford, 1994; and Murdoch, et al., 1994). In addition, they require some degree of excavation, drilling, and installations through the waste. Paustenbach et al. (1992) and Roughton (1993) indicated that the risk of exposure to workers handling and implementing remedial measures may exceed that presented to humans should the contaminants

simply remain in the subsurface.

While these technologies certainly have potential at many of the 26,500 contaminated acres for which the U.S. Department of Energy is responsible, our proposed technique provides unique advantages. By comparison, our proposed technique is a combination of proven and well-established longwall mining scheme and the regulatory-accepted liner systems for above ground waste containment. No "digging" or drilling through the waste is required and implementing our technique will specifically prevent the further migration of leachate emanating from the existing waste, and allow the collection and quantification of the leachate volume as well as analysis of the leachate quality. The depth of installation is basically limited by the current limitations on the depth of lateral confinement.

Our proposed technique for the placement of the bottom barrier will be interfaced with the already existing or developing technology for lateral barriers, and its cost will be incremental beyond the cost of the lateral barriers. There are presently no other alternatives for complete and positive in situ and subsurface containment, collection and quantification of leachate for which cost comparisons can be established.

## Introduction

The isolation of contaminants from groundwater supplies is a topic of increasing concern and urgency. Not only must the cleanup be thorough, but stringent precautions must be taken to protect human workers from exposure to the contaminants (Roughton 1993). Contamination of groundwater supplies has already occurred in hundreds of sites in the United States and is a threat at many more. The scope of the problem can be illustrated by the US Department of Energy's (DOE) concerns (US DOE 1990):

1. 500 DOE facilities require long-term decontamination and decommissioning.
2. There are 3,700 DOE release sites which require remedial action.
3. There are 5,000 properties associated with toxic tailings.
4. Overall, 26,500 acres are known to be contaminated.

Remediation strategies have typically involved one of two techniques: excavation and removal, or in-situ containment. Excavation is often a slow and dangerous job sometimes generating airborne contamination in the form of dust and vaporized volatiles. Large volumes of soil must generally be removed and treated along with the waste materials, adding to the cost and complexity (Shapot et al. 1989). In addition, transporting the materials to a treatment facility, introduces the inherent risks of hazardous waste transportation (Harwood and Russell 1989).

In situ containment of hazardous waste is preferable if it can be reliably, safely and economically accomplished. Solidification and stabilization through grouting or deep soil mixing have been applied to contain wastes (US EPA 1989). Additionally, in situ vitrification has been proposed and attempted on small scales (LaGrega et al. 1994). All of these approaches have a valid applications; however, they are typically feasible for relatively limited size sites and in addition, none of the methods provide positive containment of the contaminants, i.e., there is no certainty that the technique captured all of the contaminant.

This project involved the feasibility study of a wide-area, three-dimensional containment system which can be retrofitted around and under existing contaminant sites. The technique adapts longwall mining technology to allow tunneling under and around a contaminated site with simultaneous placement of a low-permeability hydraulic barrier and a liquids collection system.

Conventional longwall development is first implemented, i.e., vertical shafts are sunk and development tunnels mined at the bottom of these shafts (fig 1). A longwall of support shields advances with a mining shearer while placement of a hydraulic barrier, liquids collection system and backfilling are performed behind the shields (Fig 2). The backfill serves to protect the hydraulic barrier and the minimize surface subsidence within the site perimeter. A vertical barrier must be constructed and joined to the horizontal hydraulic barrier. Conventional slurry walls, vertical HDPE curtains or grout curtains may be utilized. The bottom and side barriers isolate the site from groundwater inflows and prevent the horizontal and vertical migration of contaminants. A collection system for liquids directs the contaminants into a sump where they

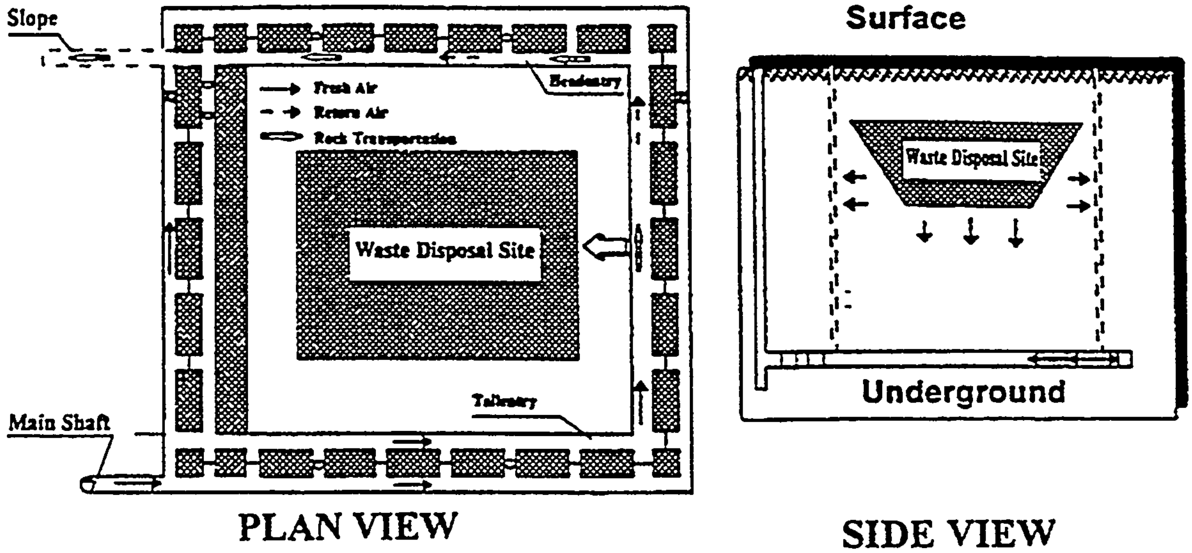


Figure 1 - Conventional longwall development illustrating the vertical shafts and development tunnels.

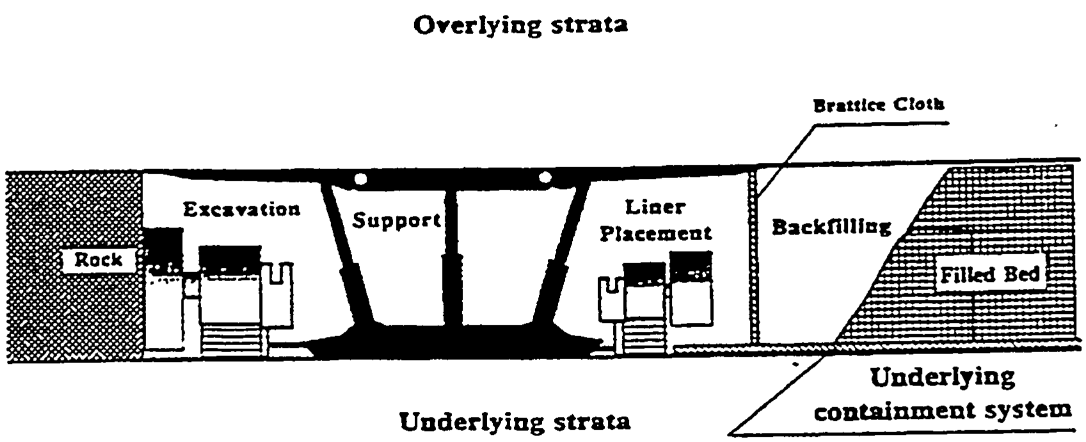


Figure 2 - Profile of the roof support shield, mining shearer, placement of the hydraulic barrier, liquids collection system and backfilling operation.

are removed and treated. Designs are being undertaken so that the mining and containment system will be placed remotely through the incorporation of robotic technologies. From the mining aspect, most of the remote techniques have been developed and are in operation. The challenge remains in the installation of the barrier-liquid collection systems.

## Background

Since the time of the Manhattan Project, the US government has been responsible for the defense related applications of nuclear technology. Agencies such as the Atomic Energy Commission and now the Department of Energy (DOE) manage the production of nuclear weapons. While national defense took precedence over environmental concerns until recently, DOE's policy over the last three years recognizes its obligation to the environment and its obligation to remediate its backlog of hazardous sites. It is recognized that unless significant technological advances are made, available funds for remediation will be severely inadequate.

Production of nuclear materials for weapons and nuclear fuels generates radioactive and non-radioactive waste products. Some of these materials are extremely toxic and persistent. The toxicity of nuclear materials creates problems both in their isolation from groundwater and in the cleanup of existing pollution sources. Not only must the cleanup be very thorough, but stringent precautions must be taken to protect human workers from exposure to the materials.

The isolation of chemical and radioactive contaminants from groundwater supplies is a topic of increasing concern and urgency. Contamination of groundwater supplies has already occurred in hundreds of sites in this country and is a threat in many more. Remediation strategies have typically involved one of two techniques: excavation and retrieval, or in-situ containment. Excavation is a slow and dangerous job. The contents of containers are often unknown, and may be flammable, explosive, and toxic. Excavation equipment may puncture rusting containers spreading the contents. Excavation usually generates airborne contamination in the form of dust and vaporized volatiles. Large volumes of soil must generally be removed and treated along with the waste materials, adding to the cost and complexity. Often, it is necessary to transport the materials to a treatment facility, introducing the inherent risks of hazardous waste transportation.

In-situ containment of hazardous wastes is preferable if it can be reliably and safely accomplished. A wide variety of techniques have been considered, ranging from steam or chemical injection to implantation of biological agents to vitrification of the soil by massive electric currents. *This project presents a novel approach to the strategy of in-situ containment which uses concepts from the mining, robotics, and commercial landfill industries to isolate a waste site. Longwall mining equipment would be adapted to allow tunneling under and around a waste site, and construction of an inert, low-permeability barrier.* The barrier will prevent the horizontal and vertical spread of leachates from the waste site by isolating them from ground water flows. A leachate collection system placed along the bottom of the containment would pump collected liquid to the surface for treatment.

This concept was developed by the authors at West Virginia University and evaluated through this project. The project was sponsored by the U.S. Department of Energy, and began in November, 1992. Here, we describe the system concepts, the design objectives and constraints, and the technical issues which must be resolved before the system can be implemented as well as our planned approach to the solution.

## Methodology

An exercise of developing mission scenarios for the application of the concept identified four key technical fronts for study. These technical fronts help identify specific adaptations to longwall mining procedures and equipment. These four fronts are:

1. Mining procedure and equipment modifications
2. Containment system placement
3. Materials movement and handling
4. Level of automation and human interfaces

## Results and Discussion

This section will address subsequent technical issues in the context of automation, robotics and teleoperation applications.

### Mining Procedure and Equipment Modifications

Longwall mining is already a highly automated process. The longwall system is comprised of a pair of rotary drum shearers mounted on a rail system attached to a pan type chain conveyor. The shearer moves back and forth across the mining face, which may be up to 1000 feet long. The shearer cuts coal which falls down into the pan conveyor and is transported to the end of the face and then down an entry tunnel and eventually to the surface. Hydraulic jacks are attached to the pan line and follow the shearer through the seam. The jacks, or shields as they are called, extend out over the conveyor and support the roof, creating a moving tunnel under which the mining activities are carried out. Shield and conveyor movement is accomplished by alternately extending the hydraulic ram to push the conveyor/shearer forward and then retracting the ram to pull the shield forward. Raising and lowering the shield sections is used to strategically create or eliminate friction between the roof and the shield sections to facilitate the movements.

In a coal mine, the roof is allowed to collapse directly behind the shields. Current mining methods incorporate automatic control of shearer, shield and conveyor functions. A human operator oversees the process, and several other humans are present at the face to position the shearer cutting drums, monitor shield operations, and to monitor and move ancillary equipment such as the hydraulic and electrical power systems, water pumping equipment and ventillation control systems. Humans are also required for equipment repair, removal of conveyor jams, surveying and other support activities.

The procedure we are developing will follow nearly identical procedures in the cutting and gob transport phases. Cutting speeds will be reduced to accommodate the hardness of the rock. We are currently investigating the relationships between cutting practices and rock fragmentation characteristics, bit wear and cutting power required. It is desirable to reduce the size of the "won" rock fragments to no more than a few inches in circumference so as to alleviate conveyor jams and reduce the amount of crushing required for use of the gob as backfill. We hope to be able to eliminate the two humans who are needed in coal mines to position the shearer drums. In a coal mine, one operator generally operates each cutter to keep the shearer cutting in the coal seam while removing all of the coal. In our application, the seam will comprise a nearly homogeneous stratum of soft rock, and there will be no need to sense the seam interface. We will be more concerned with maintaining a minimum mining height and smooth floor and ceiling surfaces to facilitate liner placement and backfilling operations. The shearer operators' positions are among the most dangerous since the shearer operates under unsupported roof. One of the major modifications to coal mining procedure will be a shift in priorities. In coal mining, the primary concern is on production, i.e. speed of excavation of the coal. In this application, the primary emphasis will be placed on the control of the geometry of the excavation and the precise placement of the liner layer. Thus mining will be considerably slower than with coal. We expect to be able to mine approximately nine meters per day.

In our application, the shields will be reconfigured to provide roof support behind the shield hydraulic equipment. This space is necessary to prevent subsidence during the liner/leachate collection system placement operations. Outrigger cylinders will be required on the shields to facilitate more precise location and orientation of the shields than is required for coal mining. Equipment for liner placement and backfilling is currently being designed to operate in the space behind the shields. Figure 3 shows the current conceptual design of this equipment. It will probably be necessary to have humans working in this area to perform monitoring, quality control, repair, and some operations functions. These aspects will be discussed in more detail in the next section.

<u>Containment System Placement</u>

The vertical containment system will be built up of several layers of materials, all of which are commercially available in roll form. Figure 4 shows the structure of the bottom seal system. The bottom seal will be composed of rolls of HDPE with a bentonite clay backing.

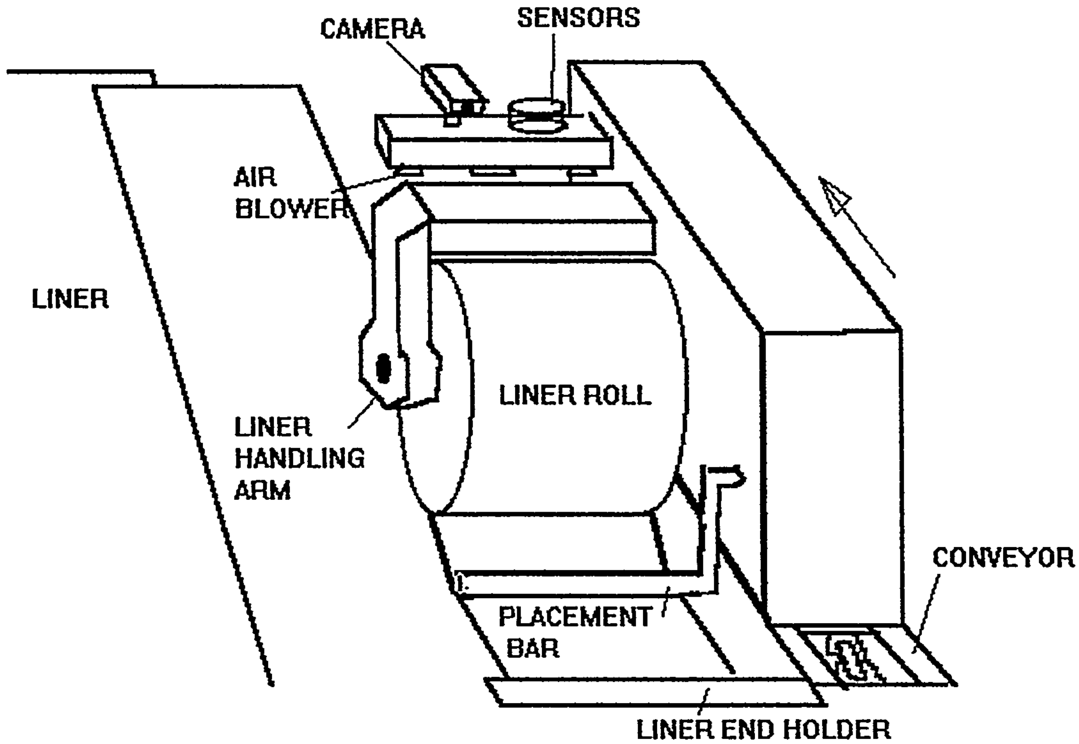


Figure 3. Conceptual Design of Liner Placement System.

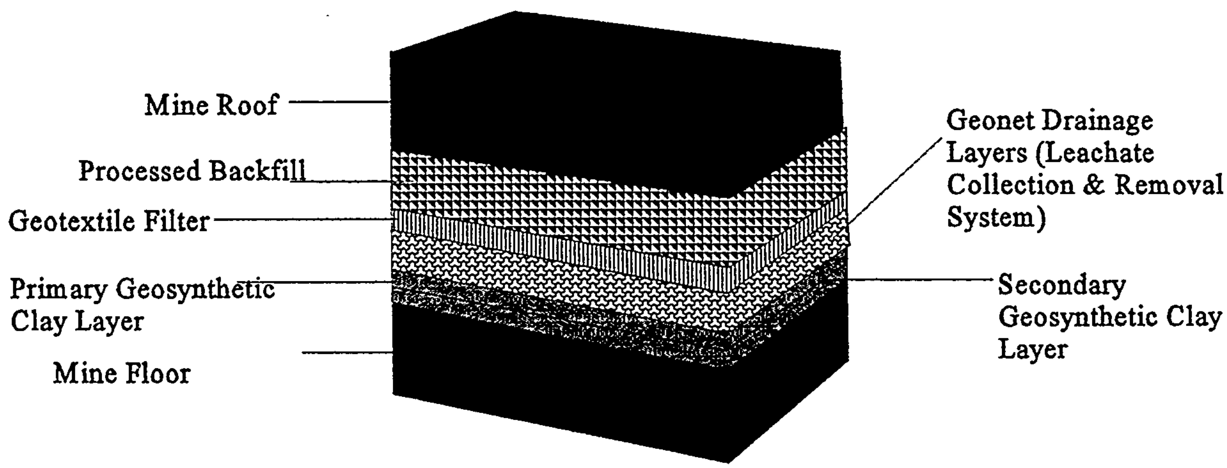


Figure 4. Structure of Bottom Barrier for Remote Longwall Mining In Situ Containment.

These materials are manufactured by Gundle Lining Inc. under the tradename Gundseal (TM). The Gundseal will be unrolled with the clay liner down in an overlapping pattern. The bentonite is a hygroscopic material which physically swells to about 400% of its original size when it comes into contach with water. The HDPE will provide the primary impervious layer, with the bentonite serving to seal the seams between the HDPE sheets. This system is felt to be more reliable than attempting to hot weld the seams together underground as is currently the practice in sealing surface impoundments.

Above the HDPE barrier layer, several layers of HDPE mesh will be placed to provide a low resistance horizontal flow path for leachates to reach the sump area. The HDPE mesh is also manufactured in roll form by Gundle under the tradename Geonet. Above the Geonet will be placed an inert Geotextile layer which will serve to prevent rock fines from blinding the Geonet layer. Above the textile layer will be backfill. We are studying the feasibility of using processed gob from the mining operation as backfill.

The current concept for the liner placement calls for the roll material to be placed on a spindle which is mounted to a rail similar to that which carries the shearer. The spindle then traverses the length of the face, unrolling the liner materials one layer at a time. The spindle will be capable of extension to allow overlapping of successive layers as is required for proper sealing. During this time, no shearing will take place, as it is necessary that all of the shields be in precise alignment to prevent buckling or gaps in the liner layers.

The horizontal containment system is less clearly defined at this point. We are studying the use of either slurry walls or vertical HDPE curtains. Both methods require trenching from the surface and are thus limited to depths of approximately 100 feet or less. If greater depths are required we are investigating the use of continuous mining machines to create perimeter tunnels which could be used for vertical barrier placement. The concepts here are not yet fully developed and the approach will in any case be extremely site-specific.

Materials Movement and Handling

Material handling can be broken into several distinct classifications. Removal of gob from the mining face will be done using standard belt conveyors and elevators. The gob material will be transported to the surface where it will be processed for reinjection to the space behind the mining operation as backfill. Processing will consist of crushing and screening to obtain correctly sized materials. We are studying several options for the backfilling operation, ranging from pnuematic injection of the dry gob to various mixtures of gob with water, grouts or other materials. No firm decision on this aspect has yet been made.

In addition to bulk materials, there will be considerable need for the transport of supplies, replacement parts and equipment. Transport of liner materials will be the most common. We expect to automate this task almost completely using tracked or rubber tired vehicles to carry rolls of liner materials from the supply shafts to the mining area. We will springboard this task from work done earlier at WVU on autonomous mine vehicle navigation by Banta, Nutter et al.

Similar vehicles will be used to carry supplies, repair parts and perhaps personnel to and from the face.

Level of Automation and Human Interfaces

We do not expect to be able to completely automate the processes described above. Nevertheless, we intend to implement the highest level of automation which is practical for the sake of removing human beings from a dangerous environment. In at least one aspect, the methods we are proposing will be less dangerous than the conditions in a coal mine, since the rock strata will not produce methane or flammable dust. Our intent is to mine well below the level where the influx of hazardous materials is likely during the mining procedure, however it is impossible to predict precisely the locations of vertical groundwater plumes or rock fissures which might compromise this strategy. In any case, underground mining is a dangerous endeavor and warrants extraordinary efforts to reduce human risk.

Since the equipment and procedure modifications required for this method have not yet been fully determined, it is impossible to provide a detailed picture of all of the automation aspects that will be employed; nevertheless, we present below a list of target activities that are currently under investigation for automation or teleoperation applications.

1. Headgate Operation. Most of the controls for the longwall system are housed at the Headgate Operator's station at one end of the longwall face. Modern mining control systems provide readouts of all shearer parameters, conveyor parameters, and shield parameters, plus access to ancillary support equipment conditions. We are investigating the feasibility of moving these monitoring and control functions to the surface to allow teleoperation of the major mining activities. This investigation is in a very preliminary phase at present.

2. Shearer Operation. As noted earlier, the shearer operators work in one of the most dangerous locations in the mine, in close proximity to powerful cutting equipment, the conveyor and unsupported roof. Until recently, human presence was necessitated in coal mines to detect the upper and lower boundaries of the coal seam. No such sensing task is required in our application, leading to the hope that the shearer control task can be relegated to machines rather than people. It will probably be necessary to use video cameras to monitor the cutting operation, but we will strive to move that monitoring process to the surface.

3. Material Transport. We are confident that transport of materials and supplies from the supply shaft to the face area can be almost entirely automated using robotic vehicles. Some human presence will probably be required at the face to supervise loading of the liner materials onto the spindle, perform quality control of the liner placement, and oversee the backfilling operations.

4. Maintenance and Ancillary Support. These tasks will be the most difficult to automate, since they require a variety of skills, manual dexterity and mobility. Repair of

hydraulic hoses on the shields, for example, requires significant strength and flexibility to transport tools and parts through cramped quarters while stepping over hydraulic cylinders and avoiding moving machinery. It is difficult to envision these tasks being performed competently, much less quickly by a machine. On the other hand, some of the less demanding tasks may be amenable to teleoperation. We do not see full automation of most of them as being feasible in the near future.

## Conclusions

This report has presented a preliminary design concept for isolation of hazardous waste dumps from groundwater supplies. The concept uses a combination of technologies from the fields of mining, landfill and robotics. If successful, the technique would constitute an *in situ* containment system, i.e. physical removal of the waste materials and contaminated soil from the site would be unnecessary. The methods are not proposed as permanent, but rather as a method that could be implemented in the relatively near term and provide 50 to 100 years of protection from groundwater contamination. While complete automation of the process is not considered feasible at this time, we expect to use considerably more automation than is currently practiced in either the mining or landfill industries. Detailed descriptions of the systems and their components can be found in the Appendix to this report.

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# Tables

## Figures

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# Executive Summary

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The basic concept is to mine under the site using longwall mining methods currently used in coal mining. During this operation, a multilayer impermeable barrier would be installed, along with a leachate collection system. The excavated area would then be backfilled with spoil from the mining process. The leachate collection system is a horizontally permeable layer placed on top of the impermeable barrier. Leachate reaching this layer would be drained to a sump and pumped to the surface for treatment. Horizontal migration of contaminants would be prevented by the installation of slurry walls or grout pile walls around the perimeter of the site. These systems are described in more detail in this and documents submitted previously under this contract.

The report is presented in two volumes. Volume 1 discusses the mining and material handling systems which would be required to excavate beneath the waste site and emplace an impermeable liner and leachate collection system. Volume 2 covers various options explored for the liner materials for a barrier beneath the site and for barriers around the site to contain vertical and horizontal migration of the hazardous materials. The system is considered by the investigating team to offer distinct advantages over currently practiced methods such as excavation if certain site constraints are met. Among those advantages are:

1. Reduced volume of material to be excavated, treated and stored;
2. Reduced risk of exposure of workers to contaminants;
3. Reduced risk of airborne contaminant release;
4. Reduced cost per volume of material isolated.

This volume covers the technical issues involved in site layout, excavation, roof support, liner placement, materials handling, controls, communications and backfilling. In each of these areas, the requirements for the proposed system are analyzed with respect to the availability of existing technologies and the need for development or adaptation of those existing systems.

Our findings show that the area requiring the greatest amount of development work will be that of accurately placing the liner system in the area behind the roof support shields. Virtually all other subsystems consist primarily of applications or modifications of existing technology rather than the development of new technologies. Even in the case of liner placement, the development requirements are seen more as technology adaptations; no major technological breakthroughs will be required to develop a functioning system. Furthermore, there is a significant body of experience with the majority of this equipment already extant in the mining community. Trained, skilled teams are necessary for the setup and operation of these complex systems. Such a workforce is already largely available.

This is not to say that the development of a prototype will be trivial. The system will be more highly automated than any conventional mining system in operation today. It will be large and complex, with hundreds of individual components to be coordinated. The integration of all of these components into an efficient and reliable entity will be a major engineering undertaking. We believe, however that the concepts presented here merit development based on the following criteria:

1. The systems are based on proven existing technologies and equipment; their success will not rely on the development of new, breakthrough methods or machinery;
2. Relatively rapid deployment of the technology is possible; we estimate that a prototype system can be assembled for proof of concept demonstrations in approximately two years;
3. The technology is appropriate for containment of relatively large sites which would be prohibitively expensive to treat by excavation;
4. Opportunities for industrial partnership in the development of these systems are guaranteed; the manufacturers involved in this study have already committed significant resources to this work and have expressed strong interest in developing these concepts as an adjunct to their present businesses;
5. Similar support of the concepts has been expressed by representatives of the United Mine Workers Union, whose members comprise a highly trained and skilled workforce available for operation of the equipment;
6. The chances of successful containment of waste materials are high, especially in comparison with unproven, experimental methods such as in-situ vitrification.
7. The cost of developing a laboratory scale proof of concept system is relatively low--WVU has already secured cost-sharing commitments from the private sector which would allow development of such a system to be completed at a cost to the government of less than $4 million. Much of the equipment purchased or developed in such an effort could be placed in service for underground demonstration and eventual active duty.

We do not suggest that the methods presented herein constitute a panacea for the containment of all hazardous wastes. Due to the size of the equipment involved, they are best suited to sites covering tens of thousands of square feet. Smaller sites would most probably be uneconomic to treat using these techniques. In addition, certain geological requirements are necessary for this system to be practical. Nevertheless, numerous sites exist in the US and abroad for which the system proposed herein would be appropriate.

The problem of groundwater contamination by hazardous materials is already serious and is growing daily. Significant contamination of major aquifers is imminent both in the US and in numerous foreign countries. We believe that the concepts presented in this report constitute a viable near-term solution to the irreversible and devastating consequences of poisoning our most crucial natural resource. We recommend that an immediate and intensive development program for this technology be undertaken.

# 1.0 UNDERGROUND LONGWALL PANEL LAYOUT

## 1.1 SCOPE AND ROLE

In order to prevent or curtail environmental damage caused by the contamination of leachates from the hazardous waste pits or trenches, the areas around and beneath the waste sites must be completely sealed. This can be achieved by cutting a layer of rock beneath it and placing a layer of artificial sealing material on the cut floor to isolate the waste storage site above from the strata below. Considering all the factors involved, a combination of a longwall sealing system and a vertical trenching method could be the best alternative to the current methods. Figure 1.1 shows the present German technique for horizontal liner placement by a roadheader system. The longwall sealing system may be better than the German technique as far as worker safety, time and cost effectiveness are concerned. This will be determined as the project progresses.

## 1.2 ALTERNATIVES AND PROCEDURES

### 1.2.1 SYSTEM DEVELOPMENT

Development work for the preparation of the longwall face includes:

a) Access to the desired depth from the surface by means of either a shaft or a slope or both.
b) Entries ( two-entry system ) are developed on either side of the panel.
c) The set up room of the longwall face is made by joining the ends of those entries at the end of the panel.
d) Design of adequate support for the shaft, slope and entries.

Figure 1.2 shows a plan view for the shaft, the slope, entries and the longwall face. The depth at which mining will occur will be determined by considering the following factors:

a) The lowest major infiltration point of the leachate,
b) The activity of the longwall sealing operation should not disturb the integrity of the waste site, and
c) The rock layer to be cut and the immediate roof is a medium-strong stratum (i.e. medium-strong or strong shale or medium-strong sandyshale) but is not a strong stratum (i.e. hard sandyshale, limestone or sandstone).

Anticipated depth for the horizontal liner placement is 300 ft. For any underground mining operation at least two openings to the surface are required. One is generally a production shaft, which is used for transportation of men and material and the other (a shaft or a slope) is used primarily for ventilation. The number of openings in a mine depends directly on the daily production rate, maintaining a safe working environment, and the dimensions of the mining area.

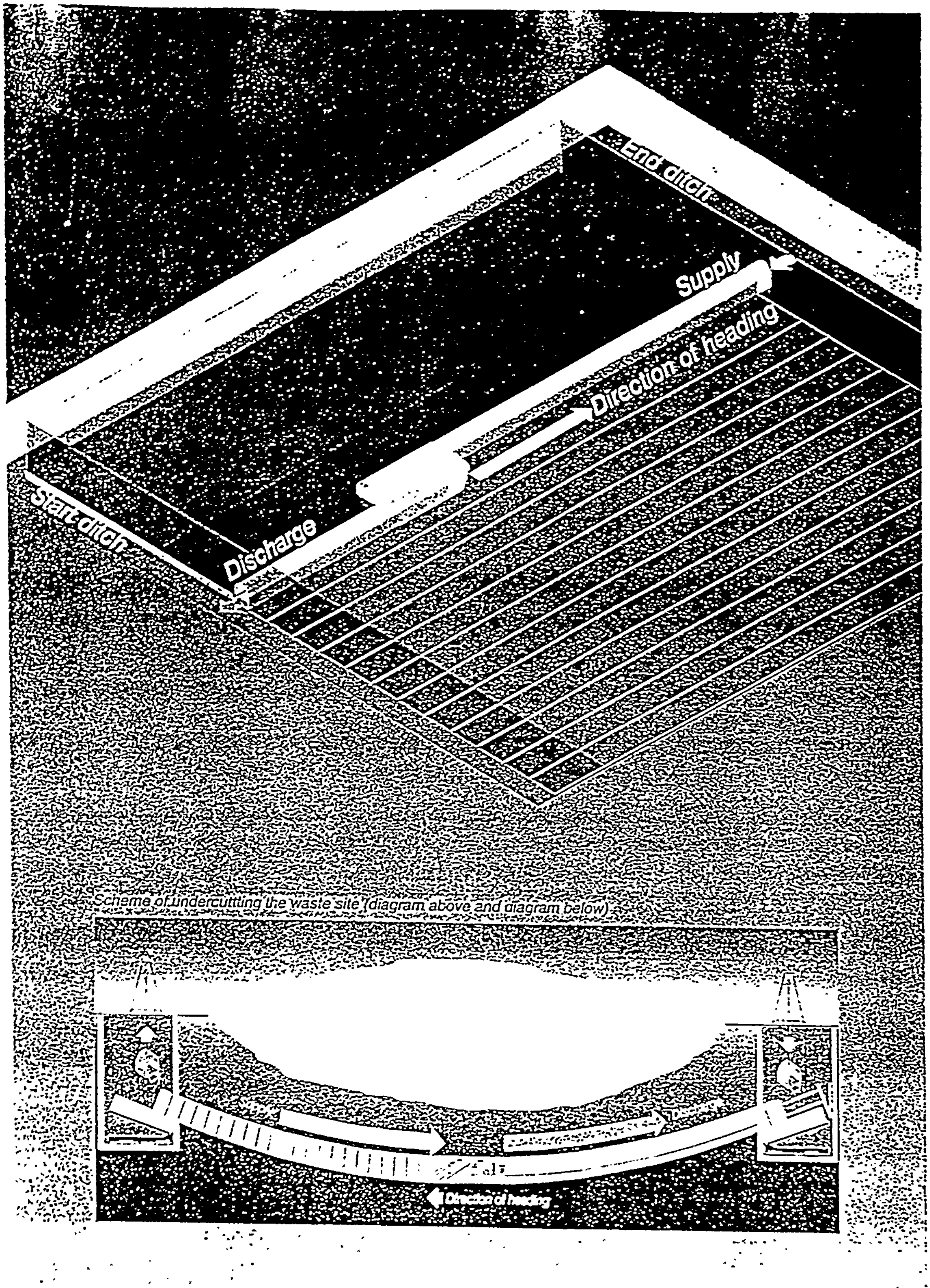


Figure 1.1 Present technique by a Roadheader System (by E. Heitkamp GmbH, Westfalia Becorit Industrietechnik GmbH and the Grundbauinstitut in Dortmund, 1993).

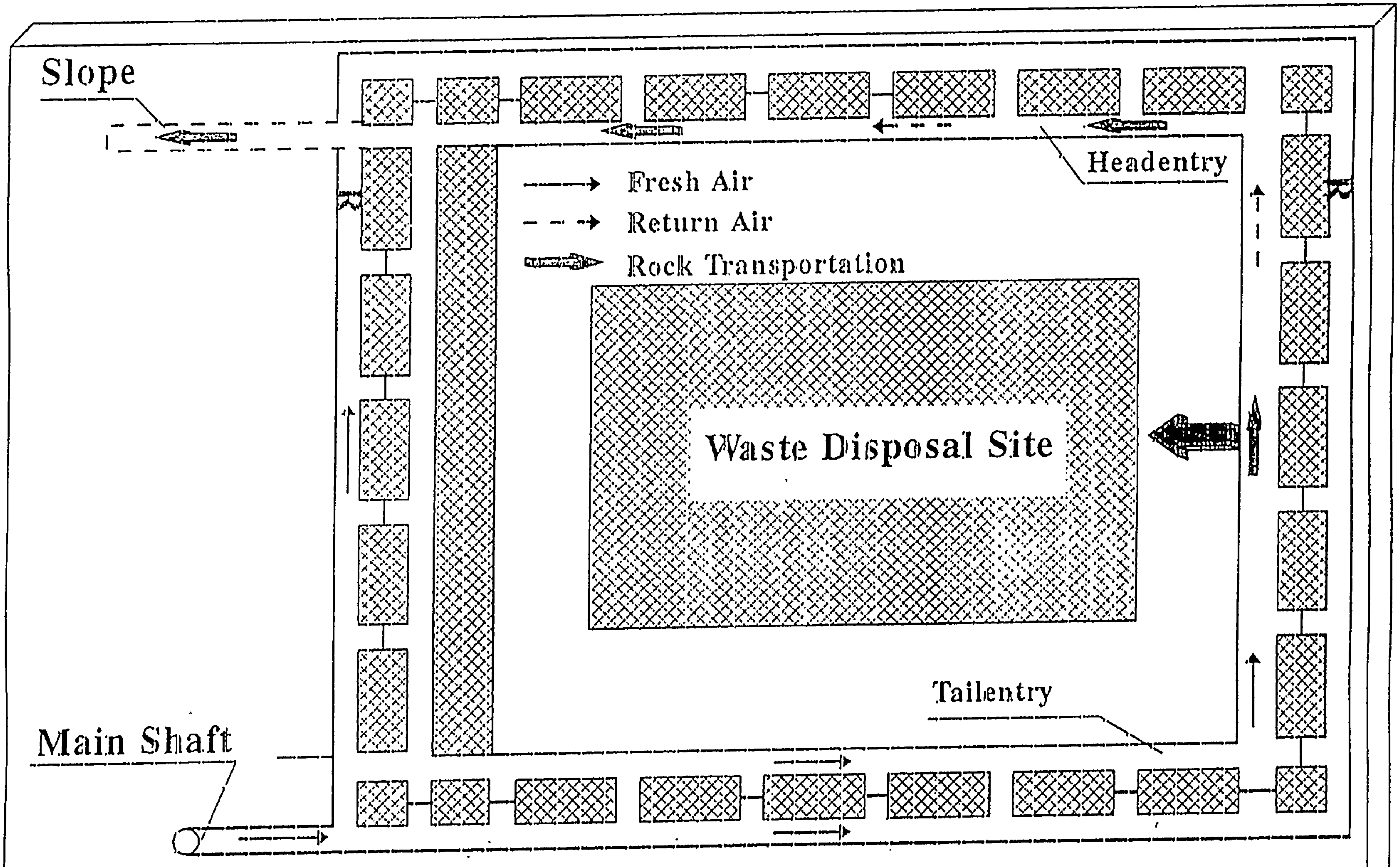


Fig. 1.2 Plane View of Panel Layout

The main items to be considered in shaft design are:

a) the amount of water to be handled in the mining operation,
b) the ventilation requirement,
c) the type of ground the shaft is to be sunk through,
d) the size of the equipment that has to be taken through the shaft.

The shaft wall support should be designed depending on the ground condition and the life span. Shaft can be driven by a fullface boring machine or by the conventional drill and blast technique.

Slopes driven for mine development are divided into three size classifications:

a) Small: less than 100 $ft^2$ in cross section. If dimensions are less, then men could not walk freely when cables or equipment are also present.
b) Medium: between 100 and 250 $ft^2$ in cross section. This size range covers most of the conveying and haulage slopes used in underground mining work. The proposed dimensions of the slope for this project are 15 ft wide and 7 ft high. So, the project's slope falls into this category.
c) Large: between 250 and 450 $ft^2$. Slopes in this size range are used when the passageway must be large enough to permit the use of large capacity rubber tired haulage units.

On the mine level a two-entry system is proposed. In this system two parallel entries are driven side by side separating by a row of chain pillars and connected to each other at fixed interval by a crosscut. The two entry system rather than the single entry system is proposed because a single entry is too crowded for all the necessary equipment and man and supply transportation resulting in much slower advance rate and less safe environments. Entries can be driven either by a roadheader or a continuous miner. Table 1.1 shows a typical performance figures for a roadheader.

**Table 1.1**
**Typical Performance Figures for a Roadheader**

| Application | Compressive Strength p.s.i. | Peak Cutting Rate Tons/hr | Average Cutting Rate Tons/hr. |
|---|---|---|---|
| Coal | 5000 | 448 | 280 |
| Bauxite | 6000 | 336 | 246 |
| Iron Ore | 10000 | 280 | 200 |
| Potash | 4000 | 392 | 280 |
| Salt | 9000 | 280 | 224 |
| Borate | Variable | 168 | 134 |

### 1.2.2 VENTILATION DURING CONSTRUCTION OF THE SLOPE/ENTRY

The primary purpose of ventilation during construction is to supply fresh air to the workmen. The volume of fresh air required is governed by the following:

a) The biological needs of the men working underground. A safe level of supply is 200 cfm per man.

b) Dilution and removal of natural gases of an explosive or poisonous nature. The requirement depends upon the concentration and composition of the gas encountered.

### 1.2.3 SUPPORT SYSTEM FOR THE SLOPE

There are two general support systems used:

a) Steel rib support: steel rib sets are commonly fabricated in two pieces with the side leg and half of the arch in each piece. The two identical pieces are stood up and bolted together at a butt joint in the crown. The size of the steel required will depend upon the nature of the rock and the pressure being exerted by the ground. Table 1.2 shows slope size, steel rib size and spacing.

**Table 1.2**
**Slope support specifications**

| Slope | Steel Rib size | Spacing |
|---|---|---|
| small | 4-5 in | 1.5-4 ft |
| medium | 5-6 in | 1.5-4 ft |
| large | 6-8 in | 2-5 ft |

b) Rock bolting: rockbolts must be installed with careful consideration for the joint pattern of the rock. Average spacing of the rockbolts, throughout the roof of the slope will vary from a minimum of about 12 $ft^2$ of rock per bolt to a maximum of 25 $ft^2$ or more. Selection of the slope support system will depend on the type of the rock.

## 1.3 EQUIPMENT

Shaft sinking is usually done by drilling, blasting and muck removal. Shaft boring is the latest technology. It is simple, fast but more costly.

Slope/entry can also be driven either by drilling, blasting and muck removal or by using a tunnel boring machine or a roadheader or a continuous miner. The disadvantages of the first method are that the process is slow and labor intensive. The second method has a high capital cost. If the rock's compressive strength is not exceeding 15,000 psi, the roadheader is recommended in order to achieve rapid progress and low cost per unit length of excavation. If the rocks are stronger than that indicated above, conventional drill-and-blast methods are usually used. Entries and the longwall face as shown in Figure 1.2 can be developed by a roadheader or a continuous miner. Shaft and slope development will be done by an experienced contracting firm using their own equipment. The type of equipment used is standard once the firm is selected, based on cost and conditions.

## 1.4 EVALUATION

An inclined entry from the surface to the underground workings guarantees the continuity of transportation of the mined materials from underground to surface and increases the efficiency of the underground operation. U.S mining law requires two openings to the surface for ventilation purposes. In this project the slope can also be used for ventilation as well as material and equipment transportation. **Therefore, a shaft and a slope will be recommended for this project.**

Two entries on each side of the panel will provide greater safety and ease of equipment movement. The proposed longwall face should have a certain degree of inclination being up dip in the mining direction to provide adequate drainage of the water used for dust suppression when the shearer is cutting. From the longwall equipments' point of view, the dip angle of the inclined panel can reach as high as 8 to 10 degrees without taking any special measures during the mining process. The operation of the liner placement also imposes a limitation on the dip angle of a longwall panel in this case. It is believed that a dip angle of larger than 8 degrees will not guarantee the quality of the liner after placement. Therefore the dip angle of the longwall panel should be less than 8 degrees.

## 1.5 RECOMMENDATIONS

### 1.5.1 PANEL LAYOUT

Since the detailed information about waste storage sites and geological conditions are not available so far, the face width and length will be assumed to be 500 and 600 ft respectively. Two entries with a dimension of (6-7) x 15 ft are to be developed around the panel. The two entry system is essential for safety reasons. Since the rock strength is usually greater than that for coal, the rock pillar width for each entry could be smaller (30-40 ft). In order to decrease the number of crosscuts, the length of development entry pillars is designed as 75-85 ft. The width of the barrier pillar at the end and start of the panel will range from 50 to 60 ft depending on the in situ rock strength. The maximum permissible inclination of the slope for material transportation is 16 degrees which will be the dip angle of the slope. The length of the slope will be 1088 ft for a vertical depth of 300 ft.

### 1.5.2 SUPPORT SYSTEM FOR SHAFT, SLOPE AND ENTRY

Shaft lining: Several different permanent lining systems can be applied according to the shaft design and environmental conditions. Monolithic concrete lining has the advantage of decreased labor intensity and costs. It is the most popular shaft lining and has the possibility of complete mechanization of the construction process. So, **monolithic concrete lining is recommended for this project.**

Roof support for slope and entries: Selection of the support is dependent on the technology of the slope construction, size of its cross-sectional area, and utilization of the slope. **Steel rib support is recommended for the slope support and rock bolts are recommended for the roof support of the entries.**

# 2.0 LONGWALL ROCK CUTTING SYSTEM

## 2.1 SCOPE AND ROLE

In order to create a space for liner placement, a layer of rock beneath the waste site must be taken. Longwall mining is the most efficient and safest method to accomplish this task. This process is defined as rock cutting at a longwall face. Generally, the major equipment employed in a longwall face include powered supports (for roof support), a shearer (for rock cutting), a face conveyor (for rock transportation), a stage loader, and an entry belt. Among them, powered support and shearer must be selected based on the geological conditions and mechanical properties of the rock strata while the other three types of transportation equipment can be selected by considering only the maximum shearer's cutting capacity. This chapter will concentrate on the determination of rock cutting parameters and the shearer selection as well as sumping and cutting methods for this project.

### 2.1.1 ALTERNATIVES AND PROCEDURES

#### 2.1.1.1 REQUIREMENTS FOR ROCK STRATA AND THE SHEARERS

Most of the nuclear waste storage sites are situated in sedimentary rocks. The compressive strength of the sedimentary rock varies from several thousand psi to twenty or even thirty thousand psi. The selected shearer should have the ability to accommodate the various rock cutting conditions. Since the extraction is undertaken beneath a hazardous waste site, the shearer should be highly automated, highly reliable, easy to modify for systematic remote control or programming control, and also easy for maintenance.

#### 2.1.1.2 CUTTING AND SUMPING METHODS OF THE SHEARER

*Cutting Methods:*
There are two cutting methods in longwall mining: unidirectional and bidirectional. In the unidirectional cutting method, the shearer cuts the coal or rock in one direction only and the return trip is usually for loading and cleaning the floor coal or traveling empty. Therefore, a complete mining cycle requires one sumping in a round trip.

For the bidirectional cutting method, a complete mining cycle can be finished in a single trip. The shearer's sumping will be performed at both ends of the face. Therefore, there will be a high percentage of machine utilization and shorter exposure time of the unsupported roof area.

*Sumping methods*:
Each time the shearer completes a web cut along the whole face, the faceline moves forward a distance equivalent to a cutting web. Before starting the next cut, the drum of the shearer must first cut into the coal or rock face. The process of making the drum cut into the coal or rock face is called sumping. Each method of sumping requires a certain

length of time and travel distance. Thus, sumping is a major factor affecting the operational efficiency of the shearer. There are three types of sumping methods: half face, full face and modified half face. The most efficient and popular method is the full face sumping. In full face sumping, the shearer cuts gradually into the coal or rock face, following the snaked section of the conveyor. When the double-ended ranging-drum is used, no niching is required at either end of the face. The operating procedures for the full face sumping are shown in Figure 2.1.

Generally, the sumping length is twice the shearer's body length and the sumping time at the coal face is about 10 - 15 minutes. Twenty minutes of sumping time is assumed for the rock face.

## 2.2 EQUIPMENT

A shearer, armored flexible conveyor, stage loader, crusher and belt conveyors.

## 2.3 EVALUATION

Table 2.1 shows the impact of the two cutting methods on controlling several critical parameters at a longwall face. **The bidirectional cutting method with full face sumping is clearly superior and will be recommended for this project.**

Table 2.1 Evaluation of Cutting Methods

| Cutting Method | Percentage of Machine Utilization | Exposure Time of the Unsupported Area | Control of Weak Roof | Cleaning of the Face | Control Floor Level |
|---|---|---|---|---|---|
| Uni-directional cutting | low | long | not good | good | good |
| Bi-directional cutting | high | short | good | not good | not good |

*Shearer selection*:
Generally, JOY-4LS is designed for medium thick seams while JOY-6LS is designed for thick seams. Considering the characteristics of rock cutting, the designed cutting parameters for this project and the basic parameters of JOY-4LS and JOY-6LS are listed in Table 2.2. The structure

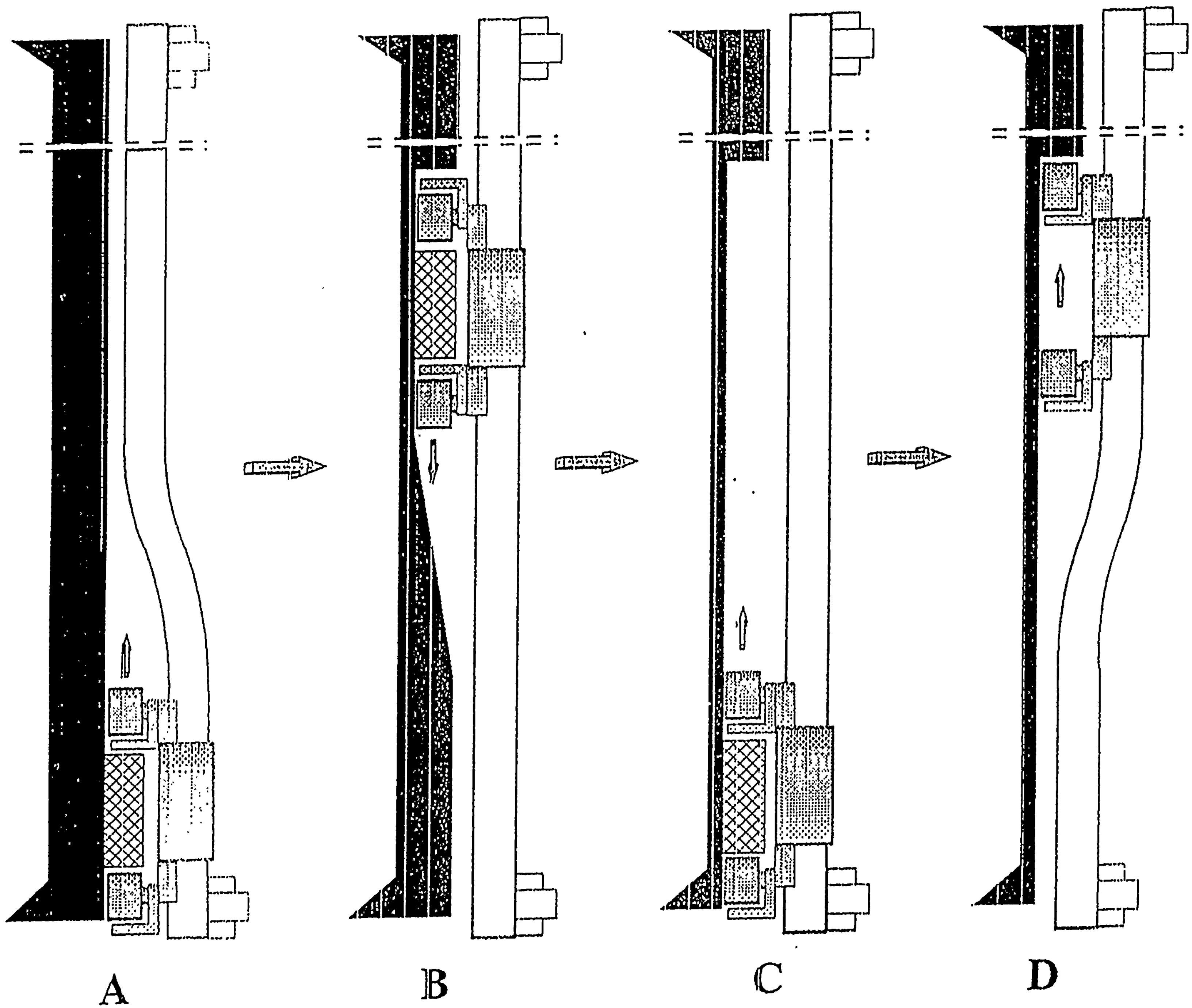


Figure 2.1 Full Face Sumping

of a typical shearer employed at a longwall face is illustrated in Figure 2.2.

Among the conventional shearers employed at longwall faces, JOY-6LS is the most powerful shearer that can be used to cut hard coal and coal/rock conditions. Joy shearers have now been widely used in the U.S., Canada, Australia, South Africa, Poland, Italy and China demonstrating Joy's ability to cut a variety of hard coal and coal/rock conditions.

**Table 2.2 Designed and Joy Shearers's Cutting Parameters**

| Items | Designed | JOY-4LS | JOY-6LS |
|---|---|---|---|
| Web width (in.) | 18 | 27 - 40 | 30 - 40 |
| Drum speed (rpm) | 60 | 45* | 30* |
| Haulage speed(fpm) | 15 | 0 - 65 | 0 - 70 |
| Machine height( in.) | | 42 - 52 | 59 - 85 |
| Machine length (ft.) | | 38.6 | 43.7 |
| Machine thickness (in.) | | 21 | 26 |
| Mining height (in.) | 72 - 84 | 56 - 132 | 72 - 192 |
| Drum diameter (in.) | | 56 - 72 | 72 - 96 |

Note: * means standard speed.

The haulage speed ($V_h$ in fpm) of a shearer can be determined by the rotational speed of the drum ($\omega$ in rpm), the allowable cutting depth ($b$ in in.) and the number of bits ($N$) in each axial cross section. If we assume that $b = 1.5$ in., $N = 2$, $\omega = 60$ rpm, then the maximum haulage speed can be obtained is

$$V_h = \frac{N\omega b}{12} = 15 \quad fpm \tag{1}$$

The cutting time needed for shearer's cutting from one end to the other end of the face can be expressed as

$$T_c = \frac{(L - l)}{V_h} + T_{sp} \tag{2}$$

where $T_c$ is the cutting time for completing a web cut from one end to the other end of the face, in min., $l$ is the sumping length at the end of the face (about 100 ft.), in ft., and $T_{sp}$ is the sumping time needed for sumping operation at the end of the face.

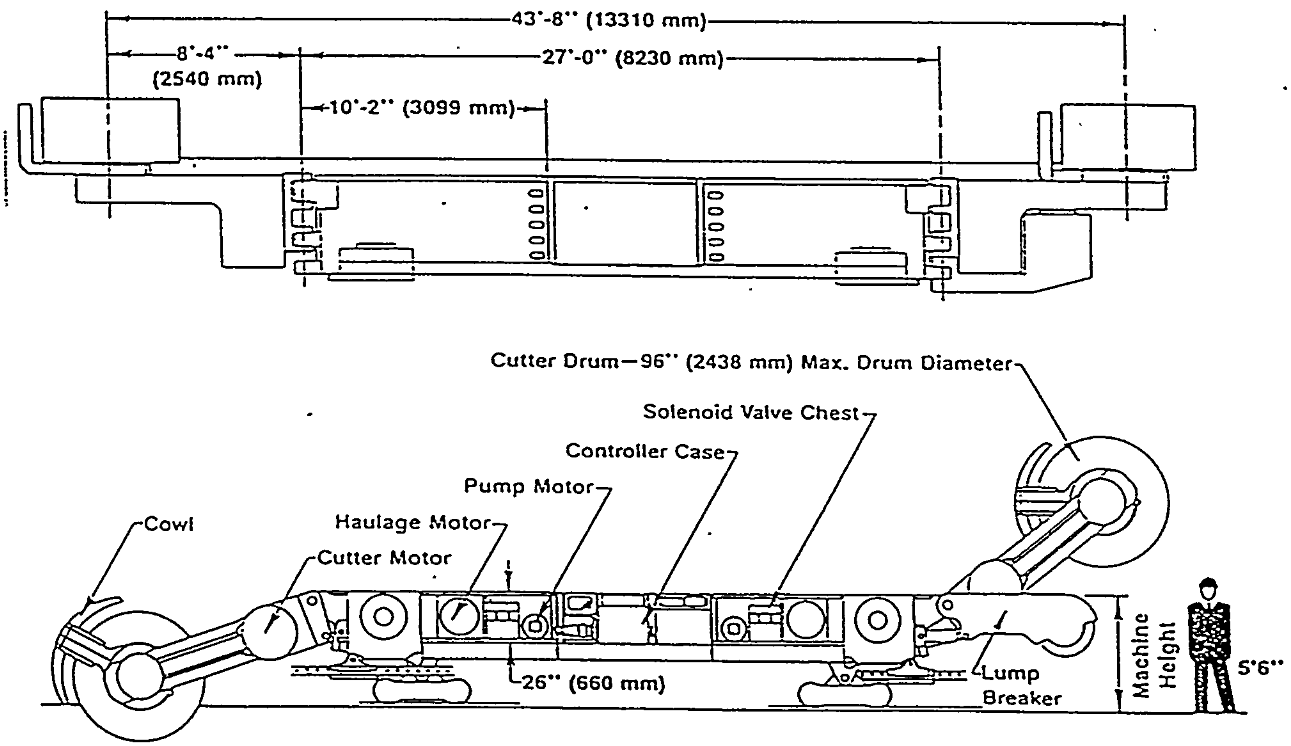


Figure 2.2 The general arrangement of a typical shearer

If it is assumed that the sumping time is 20 minutes for the rock face (10 - 15 min. for the coal faces), then the cutting time for a web cut is about 47 min. (a face length of 500 ft. and a bidirectional cutting are assumed). If the working time for each shift is 8 hours, 70% of the working time is available for the shearer's cutting (considering travel time, machine inspection at the beginning of the shift, down time for the whole system, and etc.), and a 18 in. (or 1.5 ft.) of web cut is assumed, then the face advance rate per shift is

$$R_s = \frac{(0.7\times8\times60)}{47}\times1.5 = 10.72 \quad ft/shift \qquad (3)$$

A 10.5 ft. (or 7 cuts) per shift of face advance rate can be expected for this project. If two operating shifts and one maintenance shift are scheduled, the face advance rate is 21 ft. per day. In this cutting rate, about 29 days are needed for cutting from one end to the other end of the panel (a panel length of 600 ft. is assumed). But for each 36 in. of face advance, the liner placement and backfilling should be sequentially performed. Therefore, the actual advance rate should be less than 10.5 ft. per shift.

## 2.4 RECOMMENDATION

Based upon the special requirements for this project, JOY-6LS is recommended for this project. Its estimated face advance is approximately 10.5 ft. per shift.

# 3.0 LONGWALL ROOF SUPPORTING SYSTEM

## 3.1 SCOPE AND ROLE

In order to protect the working area of the longwall face, the powered supports must be employed. The emphasis in this chapter will be on the arrangement of a longwall sealing system and the determinations of support type, size, and capacity.

## 3.2 ALTERNATIVES AND PROCEDURES

Compared with the longwall mining system in the coal industry, the longwall sealing system requires special activities (i.e. liner placement and backfilling) in the gob side. Therefore, the powered support must be designed in such a way that they can provide protection not only for the face side but also the gob side. Figure 3.1 shows the commercially available powered support, developed by Westfalia Becorit in Germany, for backfilling the gob and controlling surface subsidence. This is a 4-leg chock support with an independent sealing unit for the stowed area. The sealing unit consists of a supporting frame, a sealing wall (or rubber curtain), and a pipe. The sealing unit is advanced by a horizontal-double-acting ram, which is directly connected to the roof support. Hydraulic height adjustment for the stowing pipe (or tube) is employed. All parts of the sealing unit are accessible and the stowing pipe (or tube) is protected behind the sealing wall. The stowing height ranges from 1,400 mm (or 4.6 ft.) to 2,800 mm (or 9.2 ft.).

## 3.3 EQUIPMENT

Emulsion pump station and hydraulic powered supports.

## 3.4 EVALUATION

The advantage of this system is the accessibility to the stowing unit and easier for maintenance of the sealing unit. The disadvantages of this system are: (1) the sealing unit is not integrated with the roof support and needs to be advanced by the horizontal ram for every cutting cycle, (2) the sealing wall (or the rubber curtain) is used to prevent the stowing materials from entering the protected working area and hence a lot of efforts are needed to maintain the rubber curtains in good conditions.

## 3.5 RECOMMENDATION

In the system, the stowing direction is parallel to the faceline and the stowing materials are stowed immediately underneath the canopy and takes up the whole area. The control gear can be either hydraulic or electronic and consists of two control boxes (one for roof supports and one for stowing unit).

Since in this project it requires the installation of the LP (or liner placement) machine in that area, a new sealing system must be developed to accommodate the installation and operations of

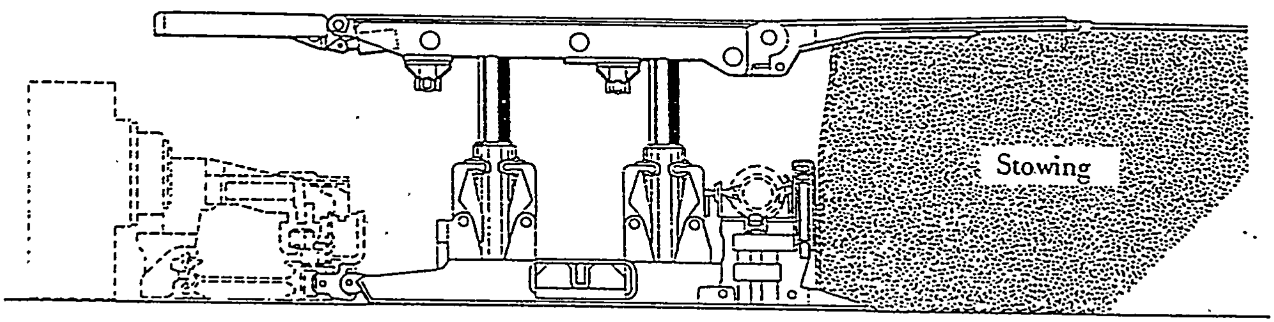


Fig. 3.1 The Commercially Available Powered Support for Backfilling

the liner placement. The proposed longwall sealing system, as shown in Figure 3.2, consists of rock cutting (a shearer), rock transportation ( a face conveyor), roof supporting (4-leg chock supports), liner placement (LP machine), and stowing (pipes, nozzles and supporting parts) subsystems. The LP machine can be advanced by the horizontal-double-acting rams connected between the conveyor-like supporting track for the LP machine and roof supports. The stowing unit is comprised of a pipe and a nozzle while the supporting part includes a sliding unit integrated with the canopy, and vertical and horizontal hydraulic jacks. The height adjustment for the stowing pipe can be implemented by the vertical hydraulic jack connected between the sliding part and the stowing pipe while the horizontal movement of the stowing pipe can be controlled by the horizontal hydraulic jack and the sliding part. The stowing direction in the proposed stowing system is perpendicular to the faceline. In this way, the possibility of the backfilling materials' entering the work area could be dramatically decreased. In order to protect the stowing pipe and the activity of the liner placement, a rubber curtain should be installed at the canopy tip on the gob side.

Figure 3.3 shows the plane view of the proposed longwall sealing system. The pipeline, 12-in. in diameter will carry a solid-air mixture with a water content of 7 to 10 percent from the main shaft through the tailside to the face for pneumatic stowing. The stowing materials are discharged into the gob area by a side discharge unit (or nozzle). The discharge units are spaced every 5.25 m (or 17.2 ft) along the faceline (one discharge unit for every three support's width). The telescopic sections of the pipeline in the tailentry permit the pipeline to be advanced continuously with the longwall face.

Since the chock cannot effectively prevent roof caving in the unsupported area, a medium stable roof is preferred.

### 3.5.1 DETERMINATION OF SUPPORT SIZE

A canopy width of 65 in. (or 1650 mm) and center to center distance of two neighboring supports of 69 in. (or 1750 mm) are recommended. The support length can be determined by:

$$L_s = l_1 + l_2 + l_3 \qquad (1)$$

where $l_1$ is the length of the face canopy ( 69 in. or 1750 mm), $l_2$ is the length of the middle canopy (80 in. or 2030 mm), and $l_3$ is the length of the gob canopy (84 in. or 2130 mm), depending on the number of layers of materials to be placed on the floor (assuming a total of 3 layers of materials in this case). The total length of the support is 233 in. (or 5915 mm).

### 3.5.2 DETERMINATION OF SUPPORT CAPACITY

For the gob caving method, the setting load of the powered support is determined in terms of the strata weight of 4 to 8 times the mining height plus that associated with the

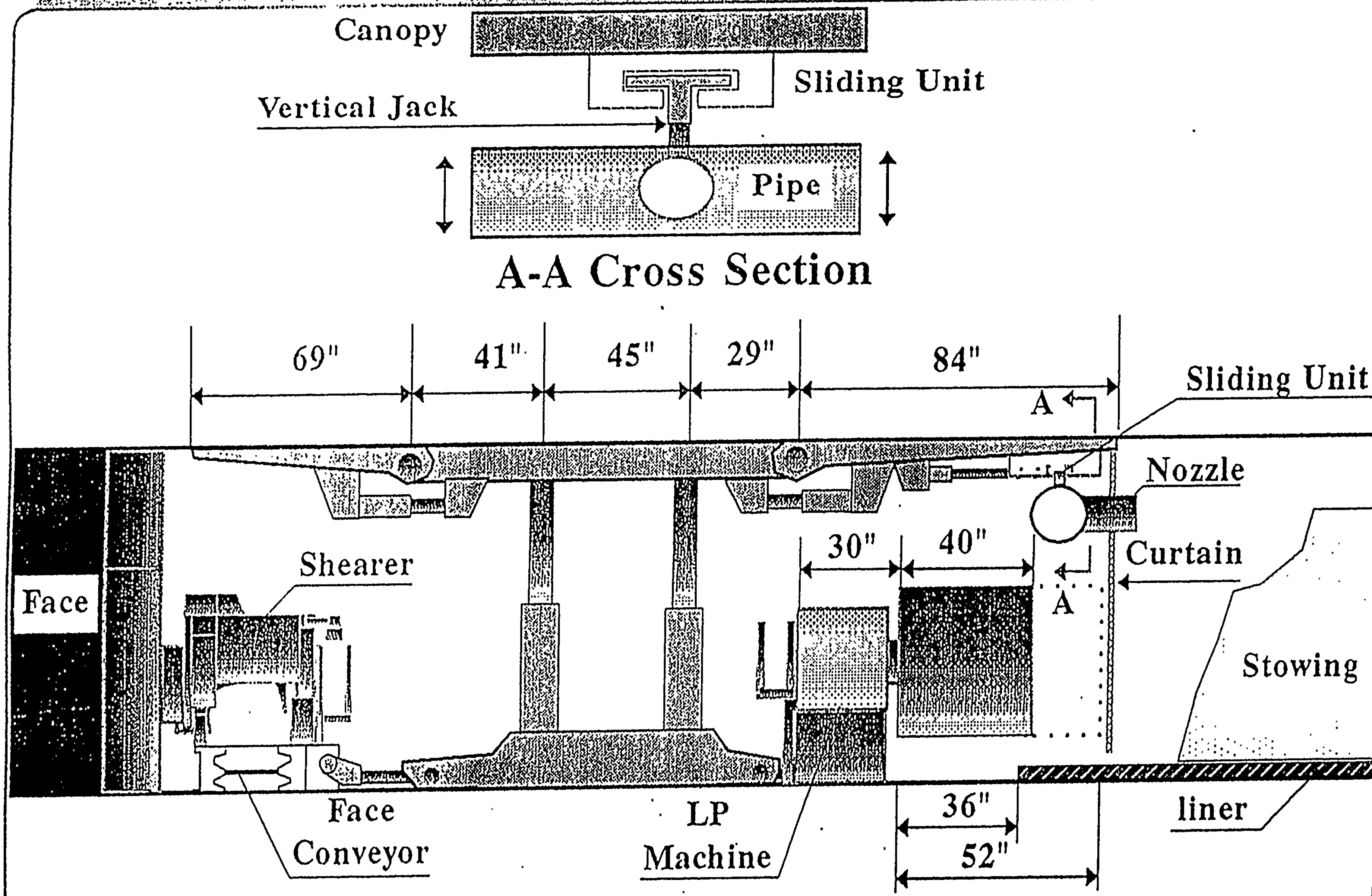


Figure 3.2 Side View of the Longwall Sealing System

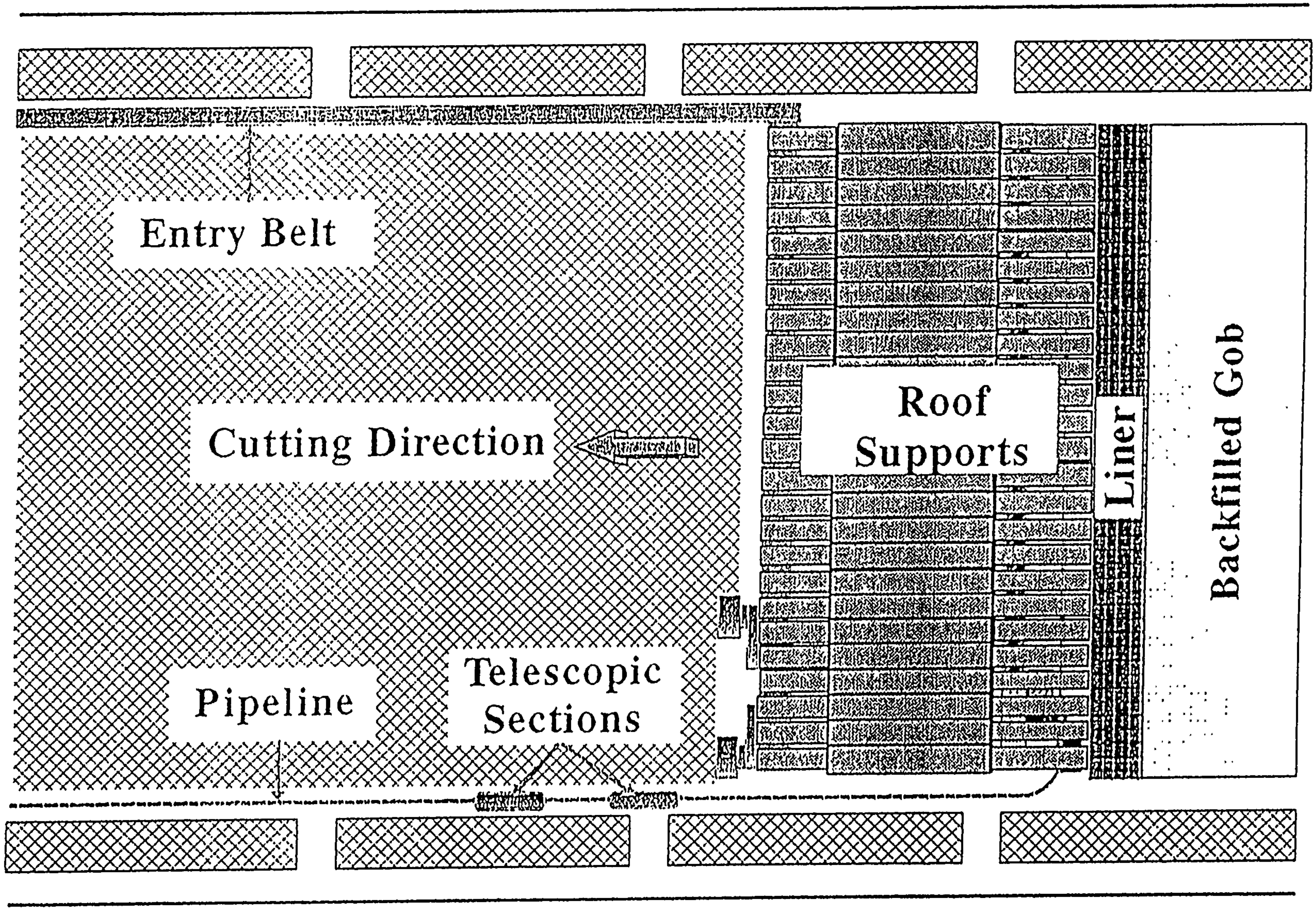


Figure 3.3 Plan View of Proposed Longwall Sealing System

weighing effect of the main roof if the ratio of the immediate roof and mining height is less than 4. The weight of the immediate roof can be calculated by:

$$W_i = \frac{(4\sim8)mLW_c\gamma}{2000} \tag{2}$$

where $m$ is the mining height for the gob caving method. For the backfilling method, if the backfilling materials can fill up to 70% of the mining height, $m$ in Equation 2 should be equal to 0.3 times the actual mining height. Therefore, $m = 0.3 \times 6 = 1.8$ ft. $L$ is the maximum length of the immediate roof that needs to be controlled by a powered support during the mining process, which includes the web width (1.5 ft.), the unsupported distance between canopy tip and face (1.5 - 2 ft.), the total length of the support, and the overhang distance of the immediate roof behind the support (here a 10 ft. overhang is assumed). Therefore, $L = 1.5 + 2 + 19.4 + 10 = 32.9$ ft. $W_c$ is the center to center distance of the two neighboring support (5.75 ft.), and $\gamma$ is the unit weight of the immediate roof, in lb/ft$^3$ (162 lb/ft$^3$ is assumed). Then the weight of the immediate roof can be estimated as

$$W_i = \frac{8\times1.8\times32.9\times5.75\times162}{2000} = 221 \quad tons \tag{3}$$

The setting load of the powered support can be determined by considering the weight of the immediate roof and a safety factor of 1.5.

$$P_s \doteq n\times W_i = 1.5\times221 = 332 \quad tons \tag{4}$$

If the setting load is 70% of the yield load, the yield load ( or support capacity) should be designed as 474 tons.

Based upon the discussion above, a powered support with a setting load of 350 tons and a yield load of 500 tons will be recommended for this stage. The final decision cannot be made until the detail geological conditions are available.

### 3.5.3 OPERATING PROCEDURES OF THE LONGWALL SEALING SYSTEM

Figure 3.2 shows the relationship among rock cutting, roof supporting, liner placement, and backfilling subsystems. Both the face conveyor and the track for liner machine are flexible and advanced by the double-acting-advancing rams connected to the hydraulic powered supports. The extendable face side or gob side piston could be set at 18 in. equivalent to the web width. For each web cut, the support advances 18 in. and the liner placement machine also moves forward 18 in. For every two web cuts, the operation of liner placement will be performed once followed by the backfilling operations.

# 4.0 LINER PLACEMENT SYSTEM

One of the key elements of the remote containment system is the installation of an impermeable membrane and leachate collection system in the excavation. The membrane requirements and design are discussed in detail in Volume 2 of this report. The membrane will consist of High Density Polyethylene (HDPE) sheets with a coating of bentonite clay to form the seal between layers. Typically, the liner material comes in rolls 4 feet wide and several hundred feet long. These dimensions can be adjusted by the manufacturer if needed to better accommodate the width of the excavation face or other constraining elements of the system. In this chapter, we present the basic functions and objectives of the liner placement system, introduce key technical issues, develop alternative concepts, and conduct preliminary evaluation of the concepts.

## 4.1 SYSTEM FUNCTION

As the longwall face moves forward, the liner placement system must function within the confines of the gob-side canopy, because of the configuration of longwall equipment for roof support and cutting. It was decided that all leachate containment and collection materials should exist in rolled form as to simplify and standardize placement operations. With each advance of the longwall face, the liner and leachate collection system (LLCS) components will place materials on the mine floor in a prescribed manner. The LLCS will be built up from several layers of materials, carefully installed in overlapping layers and shown in Figure 4.1. Each layer will be transported to the site and into the excavation in roll form. The layer must be unrolled while maintaining a minimum overlap between layers and avoiding bends or buckling along the seams.

In light of the general function described above, the major tasks for liner placement are to 1) prepare a relatively smooth and dry application surface, 2) place the multilayer elements of the containment system onto the floor, 3) control the quality of the horizontal alignment and maintain minimum overlap between layers, and 4) perform monitoring and quality assurance. There are also some secondary requirements, such as being well coordinated with the movements of the equipment at the mining face (e.g. movements of chocks).

To fulfill the liner placement tasks, the LLCS should have the following basic components:

1) A liner carrier which carries and unrolls liner materials along the face,

2) A mechanism for lateral mobility for advancing with the face and adjusting overlaps between layers,

3) A mechanism for lateral mobility for maintaining an overlap among subsequent layers of rolled materials,

4) A means of anchoring or fastening the starting-ends of rolls to facilitate unrolling motion and to maintain liner orientation throughout placement, and

5) A system of sensors to detect liner alignment, liner overlap, moisture, subgrade strength,

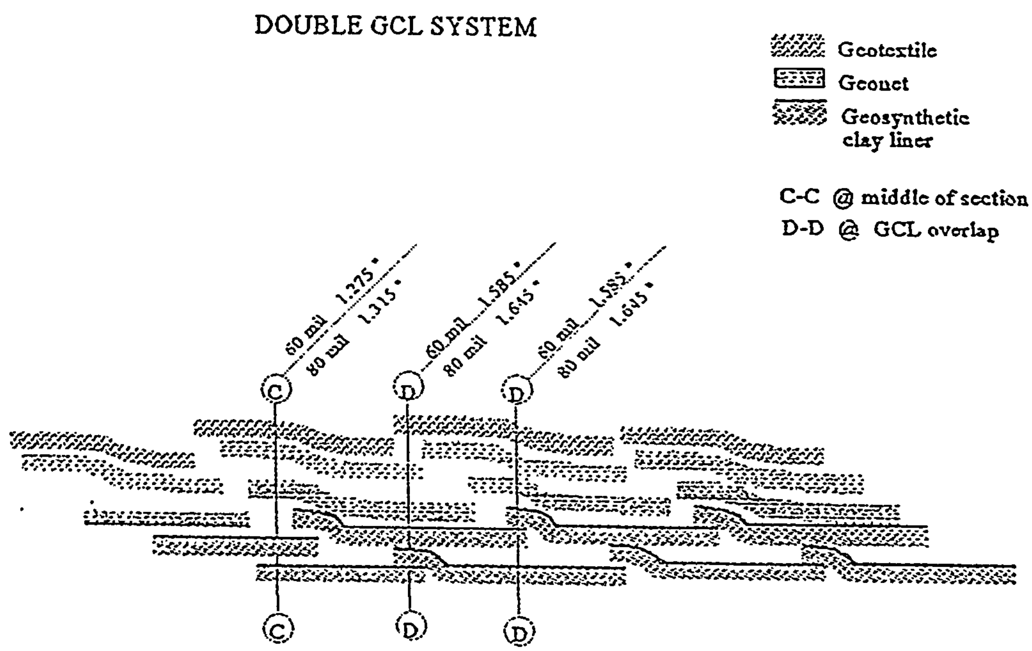


Figure 4.1 Double GCL Layer System

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surface texture, and other important parameters necessary to conduct remote operations.

## 4.2 LINER PLACEMENT TECHNICAL ISSUES

The development of a system that realizes the liner placement functions described in Section 4.1 leads to numerous technical concerns. In order to establish technical feasibility for the remote longwall containment technology, the technical concerns of liner placement must be adequately addressed. The first task was to identify a set of inherent technical issues. This identification led to the formulation of four liner placement alternative technologies. Next, additional issues were identified based on characteristics specific to each technology. Finally, a preliminary evaluation of the alternative liner placement technologies is presented.

The following are considered to be the key technical issues surrounding liner placement operations:

### 4.2.1 COORDINATION WITH MINING SYSTEM

The liner placement system must be well coordinated with the rock cutting, roof support, and backfilling sequences. This coordination will require additional controls, but liner placement will likely operate on its own system of controls.

### 4.2.2 FLOOR PREPARATION

To protect the liner from being damaged, the floor should be as smooth as possible. While smooth floor surfaces are not common within typical longwall mines, longwall mining equipment can be operated in a manner that yields a relatively smooth surface. In a remote containment application, the rate of production is not an issue, therefore the equipment can be operated in a manner where a smooth surface is likely. On the other hand, in conventional operations, longwall equipment is almost always operating at maximum rates which gives rise to rather rough floor surface conditions. The methods of providing a smooth floor include the following: reduction of bit spacing during the rock cutting, incorporattion of surface preparation into liner placement, and modification of the bottom layer of the leachate collection system.

Sensors and/or vision systems are likely to be employed in the detection of the conditions of the mining floor. It is found that detecting the strength of the mining floor and enforcing the subgrade can be rather difficult. The estimated conditions and designed alternatives are as Table 4.1.

**Table 4.1**
**Mining Floor Preparation**

| Conditions | Alternatives |
|---|---|
| 1. falling small rocks (high possibility) | 1. air blowing forward;<br>2. vacuum; |
| 2. remained bigger rocks | 1. mechanically push forward or sideways; |
| 3. soft subgrade (<1000 psi) (low possibility, because of uniform limestone assumed) | 1. no action, waiting for the protection from the backfilling;<br>2. local enforcement by filling materials; |
| 4. holes (very low possibility) | 1. local enforcement by filling materials; |
| 5. wet floor | 1. drying<br>2. pumping water out |

### 4.2.3 ALIGNMENT CONTROL

Each layer will be transported to the site and into the excavation in roll form. The layers must be unrolled in a manner that maintains a fairly precise overlap between layers and avoids bends or buckling along the seams. This allows for a more effective seal between the bentonite backing of one liner and the HDPE of the layer just beneath. Laboratory tests in Phase II will determine exactly how precise the alignment should be. Also, it is possible that the compression force from the backfill will negate any effects from misalignments and buckling. However, adequate alignment control should be achieved by the liner placement equipment.

### 4.2.4 TENSILE STRESS CONTROL

In order to keep the liner straight and smooth, a constant tensile stress is necessary at one end of the liner roll. One possible unrolling scheme is shown in Figure 4.2. According to this scheme, a constant reference speed is given to Motor 2, while variably setting the speed of Motor 1.

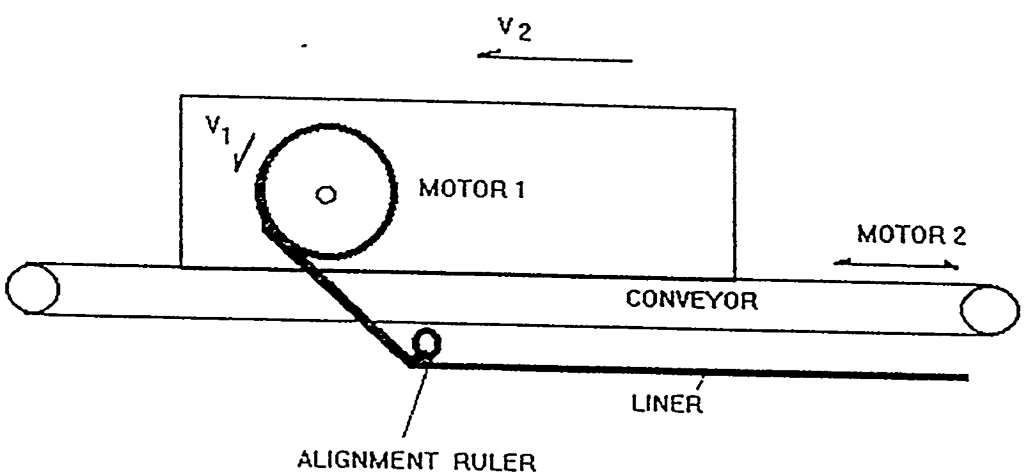



Figure 4.2  Tensile Stress Control

#### 4.2.5 TRANSPORTATION AND LOADING OF LINER ROLLS

It is desired that rolls of materials be brought from the surface to the excavation area and ultimately loaded onto the liner placement equipment with minimum human involvement. An understanding of the physical features and properties of the liner materials is important in establishing the performance constraints and specifications for liner handling and transportation. The interim report for this phase outlined the key parameters for the liner materials and identified commercially available equipment currently used in the paper industry as possible options for roll handling technology.

#### 4.2.6 LEVEL OF AUTOMATION

The intent of the Remote Longwall Containment technology is to provide in-situ isolation of contaminants with a minimum of human labor. There is a spectrum of degrees of automation from conventional longwall operations to full automation. Currently, "shearer-initiation" systems exist for longwall mining, where minimum human labor is required. These systems rarely operate in initiation mode. However, this is not because shearer initiation is technically infeasible, but rather because the rate of production is higher in the conventional mode. In our application, there is little concern for the speed of operations, thus high automation through shearer-initiation is feasible. Furthermore, the most difficult element of shearer-initiation is to keep the shearer in the boundary of the irregularly shaped coal seam. In our application, the shearer need only guide itself through a level cut rather than an irregular cut. Therefore, automation of longwall operations is more favorable in our application than in conventional mining.

#### 4.2.7 MONITORING AND QUALITY CHECKING

A system of remote cameras and sensors should be installed as part of the liner placement system such that the quality of coverage and seams can be monitored continuously. It may also be necessary to install a system of sensors to detect certain contaminates, dust, moisture, temperature and other important parameters.

## 4.3 ALTERNATIVE LINER PLACEMENT TECHNOLOGIES

There are three basic types technologies of liner placement: conveyor-based, vehicle-based, and winch-based. In general, the difference between these technologies is that a conveyor-based system is coupled to the roof supports and the vehicle-based and winch-based systems are decoupled from the roof supports. From these, four alternatives are generated: 1) rigid conveyor, 2) flexible conveyor, 3) automated/remote vehicles, and 5) winch as shown in Figure 4.3.

### 4.3.1 OVERVIEW OF CONVEYOR-BASED LINER PLACEMENT

#### 4.3.1.1 DESCRIPTION

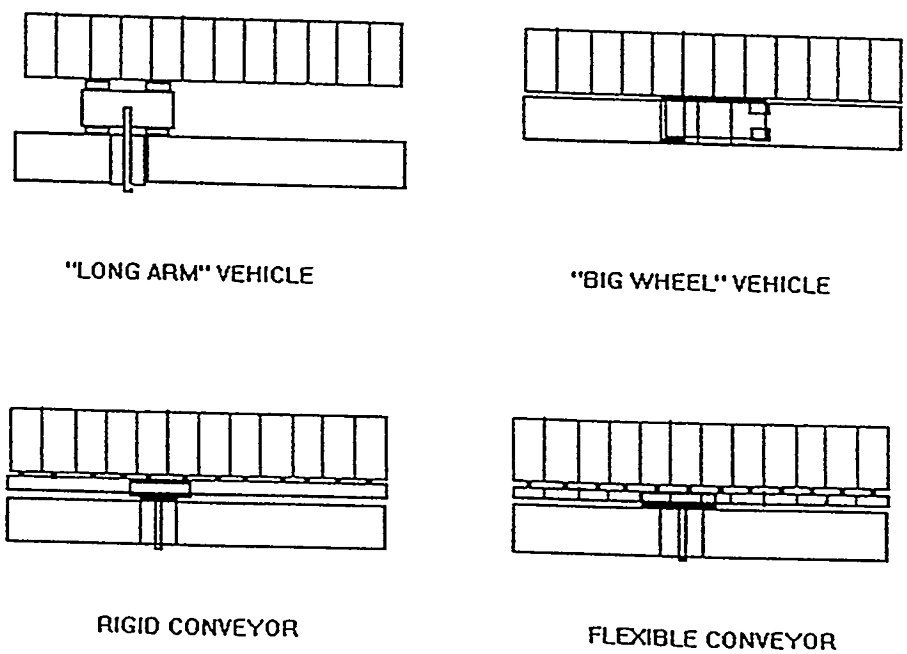



Figure 4.3 Liner placement systems

The idea of using a conveyor-based liner placement system stems from the configuration of a longwall coal cutting system. In a coal cutting system, a longwall shearer rides on a flexible face conveyor placed along the entire face line and cuts the coal wall from one end of a face to the other. The conveyor is advanced one step forward with hydraulic rams connected to the roof supports when one cutting trip is completed. In a conveyor-based liner placement system, a liner placement machine will be designed to ride on a track and place liner sheets from one end of a face to the other under the rear canopy of roof supports. The conveyor is also connected to the base of the roof supports by advancing/retracting hydraulic rams.

### 4.3.1.2 PRIMARY ADVANTAGES AND DISADVANTAGES

In comparison with a vehicle-based liner placement system, the primary advantages and disadvantages of a conveyor-based are as follows:

Advantages:

* No bearing or shear stress on the placed liner
* Conducive to automatic operation and control
* Easy to coordinate with face advancing operations

Disadvantages:

* Requires a track which occupies additional canopy space
* Transfer and loading of liner rolls can be difficult
* Spindle must be extendable in order to provide for overlapping of liner sheets

### 4.3.1.3 MECHANISM OF LOADING LINER ROLLS

Liner rolls are to be transported from the surface to the intersection of the tailgate or headgate and the longwall face by a special designed vehicle. The liner rolls are seated in the gates behind the face. The liner placement machine is required to travel to the end of the face and should be able to turn the spindle system 90° and load liner rolls without any assistance. This can be implemented by building the spindle system on a rotating table.

### 4.3.1.4 MECHANISM OF UNROLLING

To unroll a liner roll once loaded on a spindle, the liner placement machine travels to the designated end of the face and mounts the exposed end of liner sheet at the end of the face. The spindle can rotate freely around an extendable shaft. When the liner placement machine travels on the track, the liner roll automatically unrolls and lies on the floor. The tension of a liner sheet can be controlled by increasing or decreasing the friction between the spindle and the shaft.

### 4.3.1.5 PROVISION FOR OVERLAPPING

In order to have the provision for overlapping of liner sheets, the shaft on which a liner roll is loaded should be extendable. Three alternative techniques of extending shaft mechanism are as follows: hydraulic mechanism, thread mechanism, and sliding mechanism. The contact surfaces between shaft and frame are subjected to a high pressure. A sliding shaft can better carry the pressure without affecting the function of extension/retraction. To eliminate the requirement of a linkage system, a hydraulic sliding shaft is apt to be best. The hydraulic cylinder extends/retracts the shaft and the sliding block carries the load.

### 4.3.1.6 PREVENTION OF MACHINE ROLLOVER

When a liner placement machine carries a heavy liner roll with an extended shaft, the machine may loose its stability and rollover. To prevent rollover, the body of the machine should have sufficient weight. Assuming that the gravity center of a liner roll is 4 feet from the wheel on the gob side when the shaft is fully extended and the gravity center of the machine body is 1.5 feet from the wheel, the weight of the body should be more than 2.7 times of the weight of the liner roll. If the machine does not have a enough weight, a special connection between the liner placement machine and the track is required to increase the stability.

There are two alternative conveyer-based technologies considered: flexible conveyor and rigid conveyor. The flexible conveyor alternative is a design where a conventional mining conveyor is linked to the gob side of each roof support along the mining face, Figures 4.4 and Figure 4.5. A liner placement spindle travels on this conveyor parallel to the mining face. The primary advantage of this design is that it largely consists of commercially available and proven technology. The primary disadvantage of this design is the conveyor is coupled to the roof supports which causes the alignment of the liner placement spindle to be determined by the alignment of the roof supports. It is therefore likely that more sophisticated alignment control for the roof supports will have to be developed.

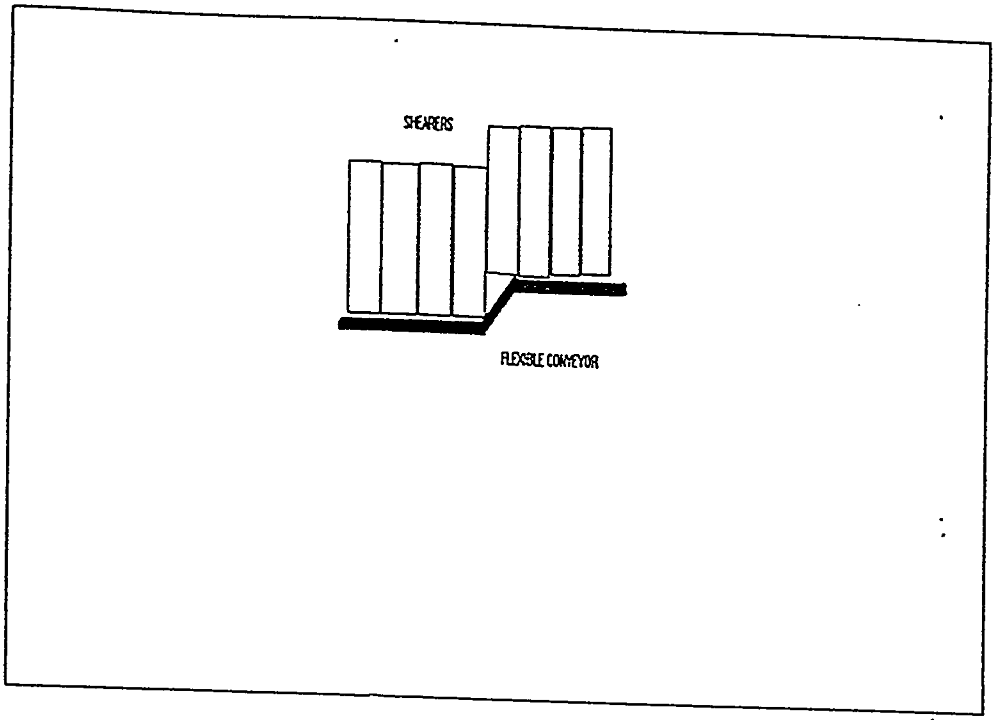



Figure 4.4 Flexible conveyor (state 1)

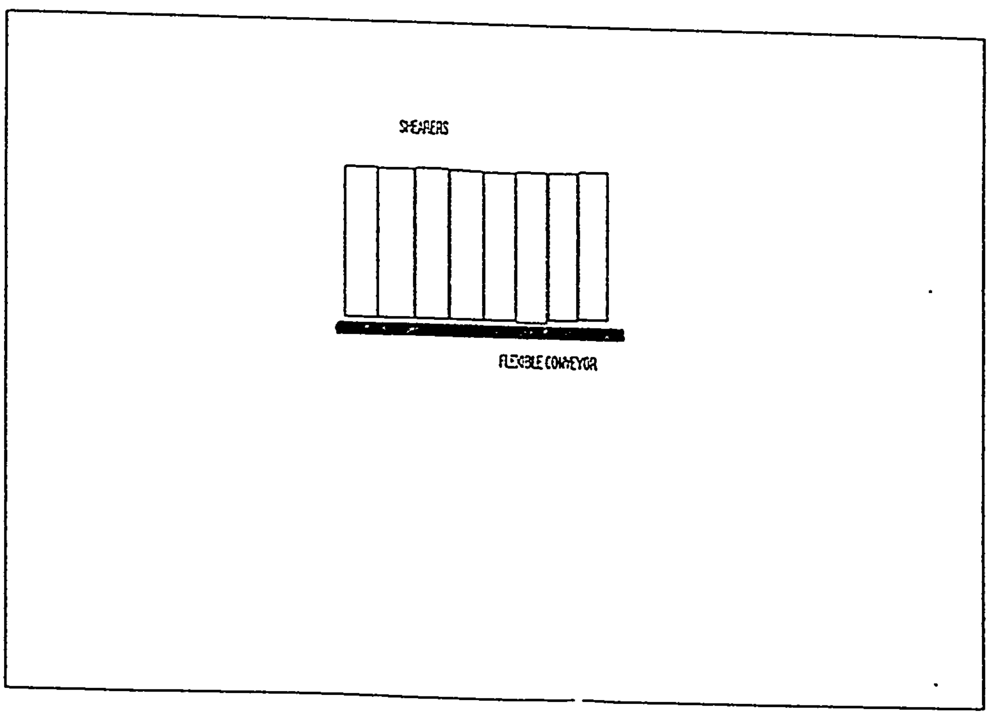



Figure 4.5 Flexible conveyor (state 2)

The rigid conveyor alternative was conceived to reduce the degrees of freedom in the alignment of the conveyor. As such, the alignment for liner placement is not as dependent on the alignment of the roof supports. The primary advantage therefore, is that it is more likely to preserve the liner alignment. The primary disadvantage is that it would require modifications not only to shield control but also to conveyor design. It is also likely that such a conveyor may be technically infeasible.

## 4.3.2 OVERVIEW OF VEHICLE-BASED LINER PLACEMENT

### 4.3.2.1 MOTIVATION

There are some key complications with the conveyor-based design. In order for a conveyor-based system to accommodate overlapping of the layers, the spindle would also be required to telescope by at least 4.5 feet while supporting the full weight of a roll of liner material. Furthermore, the spindle would be required to simultaneously translate along the rail, unroll the liner, and telescope quickly and accurately to correct for misalignments among the shields. The mounting system connecting the spindle to the guide rail would need to be extremely rigid to counteract the significant moments generated by the liner roll while the spindle is extended. At the same time, the mounting system must be able to cope with misalignments in the guide rail due to shield positioning errors. Furthermore, some provision must be made for allowing the spindle to swivel approximately 90 degrees to its normal operating position to accommodate loading of the rolls of the liner materials in the cramped space behind the shields.

These requirements represent a formidable design challenge. In light of this, the vehicle-based option was conceived. The alternative involves the use of robotic vehicles which will act both as transport vehicles and as the liner placement equipment. A rough sketch of the concept is shown in Figure 4.6. The rubber tired vehicle would carry the liner roll on a double spindle on one end of the machine. The double spindles could be spread slightly to accomplish loading of the rolls at the roll storage area near the material supply shaft. The loaded machine would then proceed along the entry tunnel to the face area. A special shield on each end of the roof support system would allow the vehicle to pass between its cylinders to the liner placement area. Note that the requirement for a special "access" shield would be present for the spindle system also, as the liner rolls would still need to be delivered to the gob side of the shield line.

Figure 4.7 shows how the vehicle(s) could circulate around the block of uncut rock in the longwall panel to pick up and place rolls of LLCS materials. Once behind the line of shields, the end of the liner roll would be unfastened, probably by a human although robotic means will be investigated. The liner end would be secured in place against the end of the face area and the vehicle would proceed down the face unrolling the liner as it goes. Each

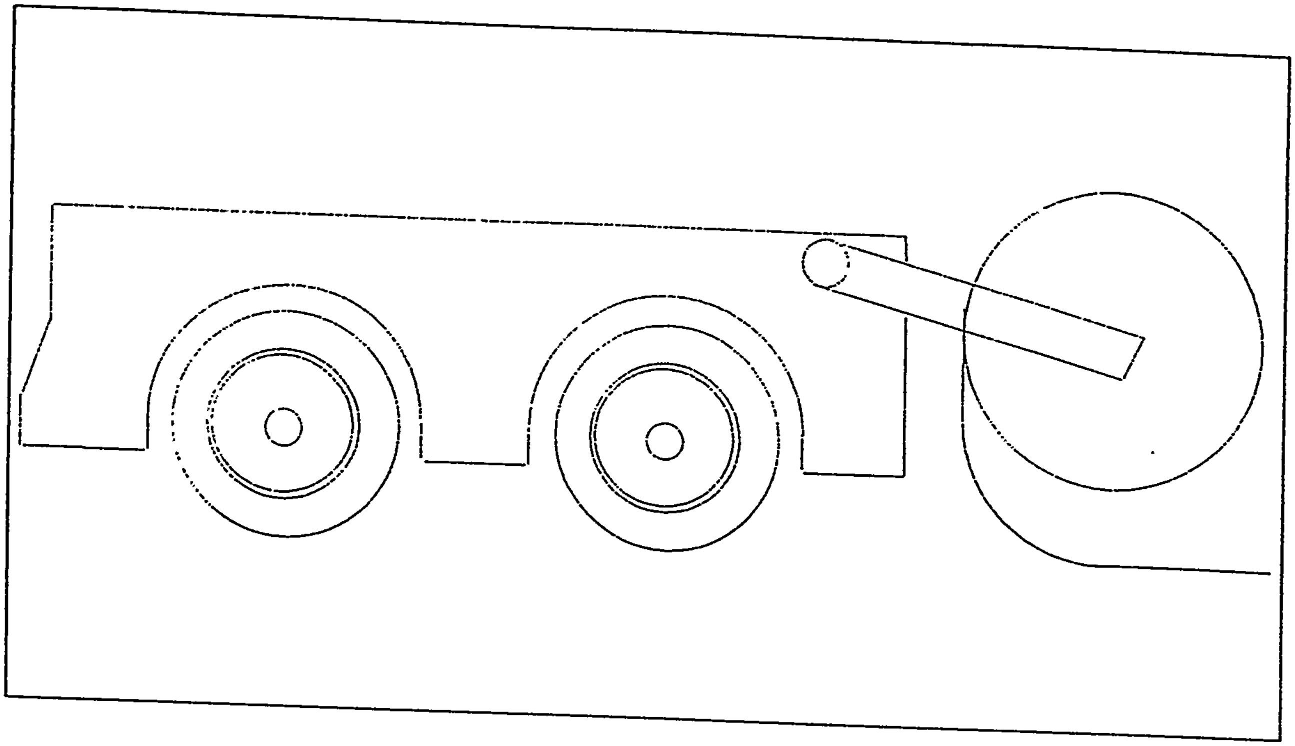


Figure 4.6 Rough Sketch of Vehicle-Based Liner Placement Concept

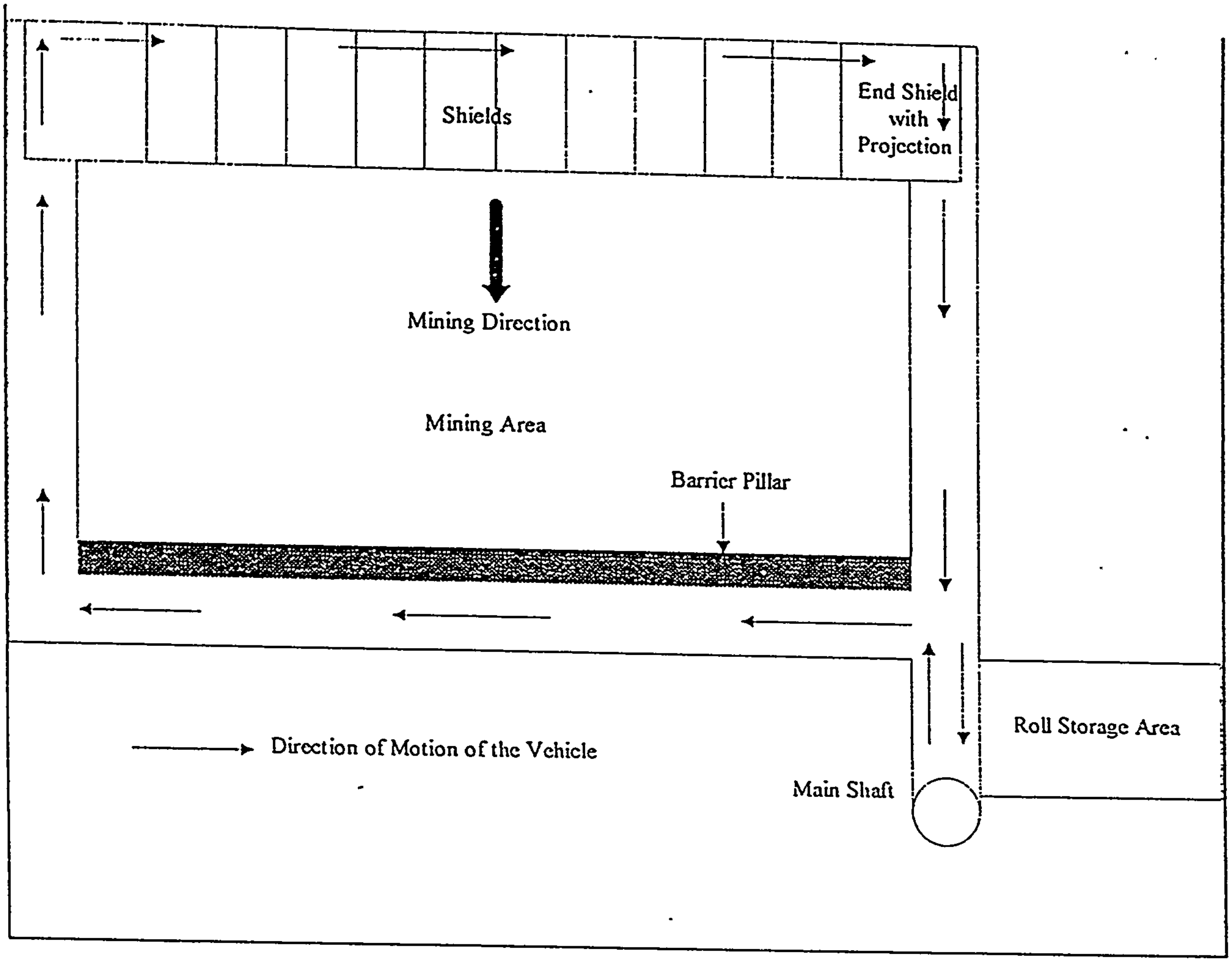



Figure 4.7 Diagram showing the path of motion of the liner laying vehicle

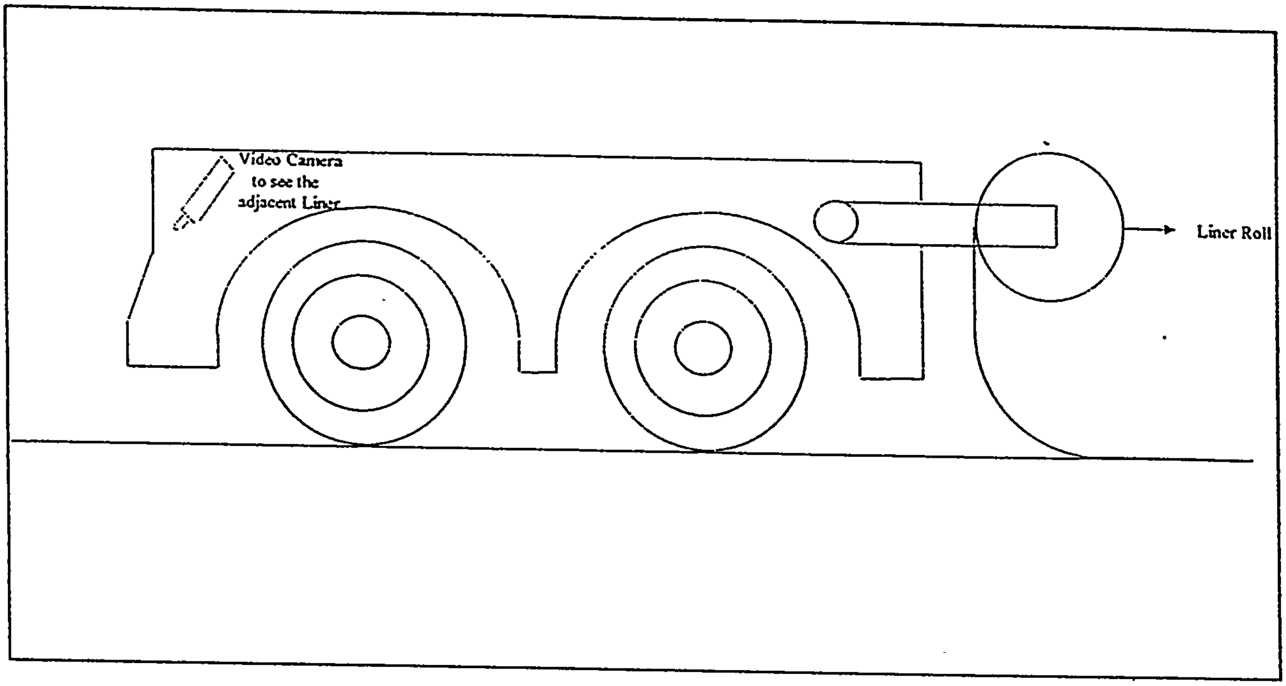



Figure 4.8 Sensor Guided Vehicle

vehicle would carry a vision system or some means of detecting the edge of the previously unrolled liner layers to insure that the correct liner overlap is maintained. Such an edge detection system would also be required for the spindle system, and does not pose a significant technical barrier to develop. The vehicle would proceed to the other end of the line of shields and stop to allow the end of the liner to be cut to the proper length. The vehicle would then turn and proceed through the access shield to the entry tunnel, and forward along the tunnel to the end of the longwall panel. At the end of the panel it would turn and pass through the end tunnel to the loading area where it would pick up a new roll for placement.

One drawback to the vehicle-based system is that all vehicles following the lead one would have to drive over the already emplaced liner layer. Ongoing investigations are being conducted to determine if the tire loading will displace or destroy the bentonite sealing material coating the HDPE barrier. It will be necessary to be certain that the floor is as smooth and free of debris as possible to avoid puncture of the liner by the vehicle tires. Alternatively, a vehicle could precede the liner vehicle and put down a layer of sand, geotextile or other cushioning material before the first liner layer was installed. We are investigating the option of having the second and subsequent vehicles in the train unroll their burden ahead of the vehicle.to better distribute the tire loads through multiple liner layers. In any case, vehicle weight must be kept to a minimum and large tires must be used to reduce point loading on the liner.

### 4.3.2.2 PATH DEFINITION

The initial step involved in setting up the vehicle-based liner placement system would be to define the path of motion of the vehicle. The tasks that the vehicle must accomplish are to pick up the liner rolls from the storage area and carry them to the gob side of the shield. Once it reaches this point, the vehicle has to align itself to give the required overlap with the previously laid liner and then lays the roll down to the floor. Special access shields would be setup at each end of the roof support system. These shields would also have the ability to hold the free end of the roll that the vehicle carries. Once the roll is lowered and the free end is held by the end shield, the vehicle moves along the face of the shield on the gob side unrolling the liner. The vehicle then comes back to the roll storage area to pick up the next roll.

Referring to Figure 4.7, the motion of the vehicle has to be in such a way that the liner achieves the required overlap. In order to achieve this, laser sensors would be attached to the vehicle to sense a color pattern marked in the liner. This can be seen from the sketch of the proposed vehicle shown in Figure 4.8.

The "long-arm" vehicle configuration is one of the vehicle-based technologies. A principle behind this design is that the liner carrier can be independent from the movements of chocks. A sideways arm ("long-arm") is used for unrolling the liner. The omnidirectional wheels allow the vehicle to move sideways and turn around on any given origin. The sensors are used to guide the vehicle's direction and travel speed. The primary advantages of this design are as follows: 1) there are no wheels on the liner, 2) it is relatively easy to install and maintain because of the mobility of the vehicle, and 3) following the movement of the roof supports is straight-forward because of the sideways movement of the omnidiractional wheels. The disadvantages of this design are as follows:1) the center of gravity is biased and is possibly unstable, 2) it occupies more (wider) workspace (width of vehicle + width of a liner), and 3) it is relatively difficult to control the placement quality because of the dependency of the mining floor.

The "big-wheel" type technology is also a vehicle-based design. In this system, light weight big wheels are used to support and move the vehicle. The liner is unrolled below the vehicle. The advantages of this design are as follows: 1) less workspace (one liner wide and 2) easy to maintain and set up. A possible disadvantage of this design is wheels-on-liner so that it may damage the liner although the big wheels are designed to reduce the stress on the liner.

#### 4.3.2.3 ANALYSIS REQUIRED

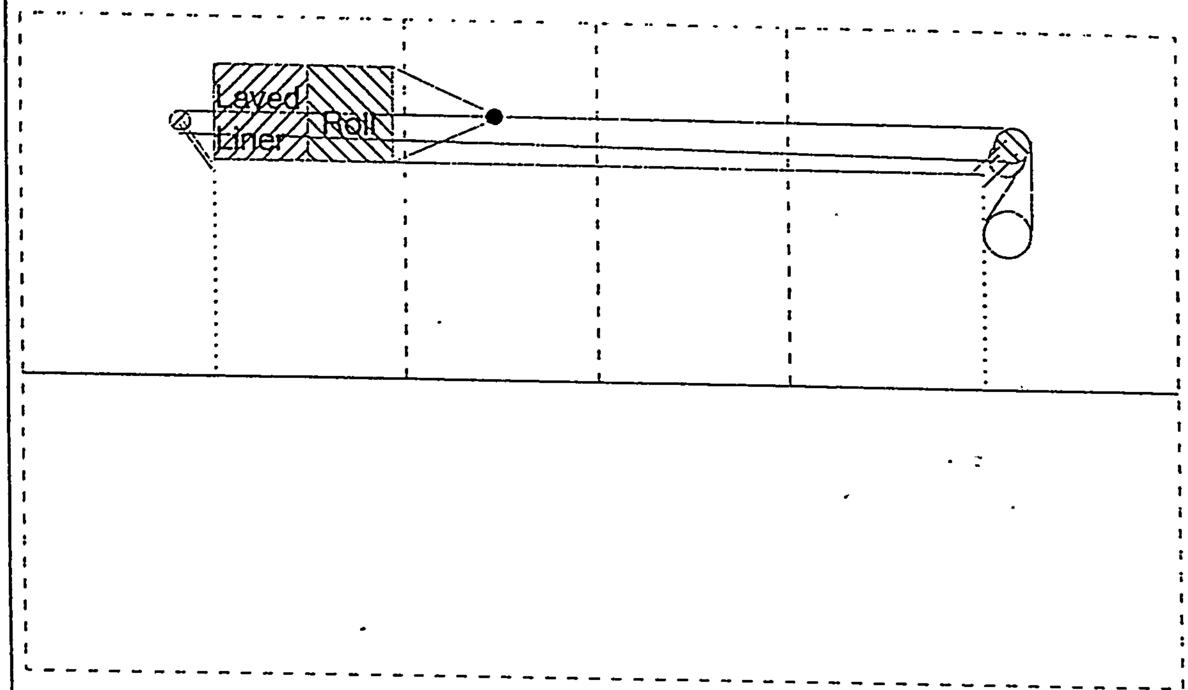
The strength of the liner material to bear the load of the vehicle is a key requirement. Based on this, the weight of the vehicle and the shape of the tires have to be designed to achieve this requirement. The concept of automation of the vehicle to accomplish the different tasks required have to be analyzed. Proximity sensors that could be used to guide the vehicle along its path have to analyzed. A detailed design of the vehicle arm used to hold the roll has to be performed in order to hold the liner roll at different positions as the requirement of the task being performed. The final evaluation would incorporate the engine and power requirements of the vehicle.

### 4.3.3 OVERVIEW OF WINCH-BASED LINER PLACEMENT

A fifth liner placement technology is the winch or yoke system which is relatively simple in concept. It involves an automated winch which picks up the liner roll from one end of the excavation shield and pulls it to the other end, unrolling the liner in the process. The winch then comes back to unroll the next liner roll. In order to have the required overlap, it is necessary to have an actuator that can laterally shift the winch position. This will likely require a sensor package which may include a number of infrared or optical sensors to detect the overlap that has been achieved with the previously laid liner. The winch has a microcontroller chip set in it. This chip will acquire the sensor data and steer the winch according the required alignment. The sketch of the proposed winch control is shown in Figure 4.9.

## 4.4 PRELIMIINARY EVALUATION OF LINER PLACEMENT ALTERNATIVES

Table 4.2 is a summary of the relative merits of the alternative technologies with respect to several criteria. The columns represent each of the five technologies while the rows represent design criteria. From the table, it appears that a vehicle-based technology most adequately satisfies the design criteria. The most influential criteria in the preliminary evaluation is the required innovation. -51-




Plan View of the Winch Based Liner Laying System

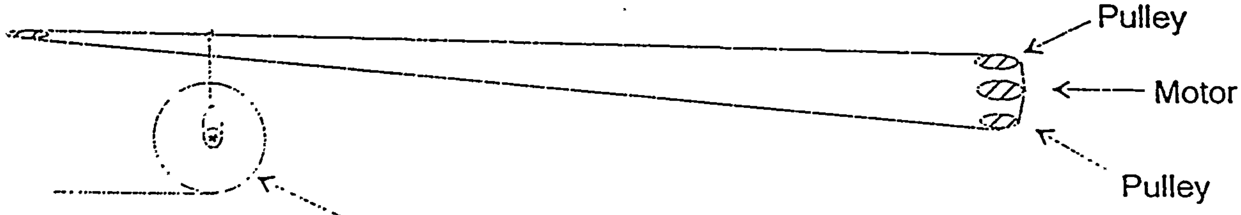



Figure 4.9 Proposed Winch Control

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**Table 4.2**
**Evaluation Table for Selecting the Configuration of a Liner Placement System**

| | Flexible Conveyor | Rigid Conveyor | "Big-Wheel" Vehicle | Winch System | "Long-Arm" Vehicle |
|---|---|---|---|---|---|
| Wheel-on-Liner | No | No | Yes | No | No |
| Required Workspace | Liner width + conveyor width | Liner width + conveyor width | Liner width only | Liner width only | Liner width + vehicle width |
| Alignment Preservation | Moderate: but advanced shield control required | Moderate: but redesign of conveyor required | High: can be done with vehicle controls | Moderate | High: can be done with vehicle controls |
| Motion Control | Directly linked to conveyors | Complex controller needed | Independent motion control | Independent motion control | Independent motion control |
| Coordination with Shearer Movement | Exclusively in-turn movements | May work simultaneously | May work simultaneously | Exclusively in-turn movements | May work simultaneously |
| Innovation Required | High | High | Low | Moderate | Low |
| System Setup | As traditional conveyor | As traditional conveyor | Flexible | Moderately Flexible | Flexible |
| Maintenance | High/Complex | High/Complex | Moderate | Moderate | Moderate |
| Sensors | Few | Few | Moderate | Few | Moderate |
| Extra Haul Forces | Yew | Yes | No | Yes | No |

While a conveyor-based system employs some commercially available mining equipment, there are several components that would require substantial design and fabrication. On the other hand, automated vehicles have been successfully developed for a number of field applications including mining and hazardous waste exploration. Therefore, at this stage, we believe that the vehicle-based alternatives have significant advantages over the conveyor-based system and would be an attractive alternative. A more detailed design of such a vehicle is required in either case for transportation of the liner rolls. This motivates research in developing a vehicle that would be as shown in Figure 4.8.

The vehicle-based alternative can be a vehicle which has the capability of carrying the liner from the headgate to behind the shield and laying the liner. A number of these vehicles can be used in series for the liner laying process. The fixed link mechanism can have variable length arms attached to the rear end of the shield. The liner rolls are attached to these arms and then the arms move along the face like the shearer and lay the liner. Each of these systems have their advantages and disadvantages.

The fixed mechanism requires a separate roll handling component that can bring the liner from the headgate and load it onto the arms. This requires a mobile vehicle and hence the design of a fixed mechanism would require designing both types of mechanisms. The mobile mechanism requires only the design of the vehicle that can pull the roll (in a manner that unrolls it) from the headgate to the gob side of the shield. The fixed mechanism would be attached to the shield and misalignment in the shield would affect the alignment of the liners.

Though the same type of vehicle that is designed for the fixed mechanism cannot be used for the mobile mechanism, an improved version of the same could be used. The modifications required in the vehicle would be additional sensing features required by the vehicle-based system. It should have the capability to sense its position and location, and perform the sequential tasks like placing the liner, laying it, and returning back to fetch the next roll, and so on. The primary disadvantage of a vehicle-based system is that part of the vehicle's wheels would run over the liner that has already been laid. A solution for this would be to design a wheel that has a distributed loading and hence not damaging the liner. Yet another method of solving this problem is by finding the weight bearing capacity of the liner materials and then design the weight of the mechanism to be below this limit. In order to do this a finite element analysis has to be performed on the liner material and the stress concentration due to a applied load has to be studied in order to design the weight of the vehicle that is to be used. The number of sensors would be increased to have the required sensing capability and the controls system in the vehicle should have the programming capability to perform the series of tasks it need to perform.

From the discussion above we can see that a decision has to be made on the liner laying mechanism as to which type is going to be used. Then the required design factors have to be analyzed. Certain key design parameters were listed above. Further consideration would be given to this problem and a mechanism would be selected to be used in this project.

**Table 4.3**
**Discussion of Mobile vs. Stationary Liner Placement Equipment**

| | Method 1 | Method 2 |
|---|---|---|
| Description | Liner placement machine carries liner rolls, travels from one end of a face to the other end, unrolls liner rolls and places liner sheets on the floor. | Liner rolls sit at the headgate. A machine picks up an end of liner sheets, pulls/drives it from headgate to tail gate, and thus places it on the floor. |
| Advantages | The liner sheets are not subjected to any dragging action and it is easy to ensure the quality of placement. | Machine does not have to carry the liner rolls. It is stable. The design of the machine is very simple. |
| Disadvantages | Need to design a complicated machine which has an extendable universal arm to load liner rolls, to change the position of liner rolls, and to unroll liner rolls. Runs over laid liner. | Drag liner sheets on the floor. It may be very hard to pull it when the area that a liner sheet covers is getting greater. It is hard to ensure the quality of liner placement. |

The advantages of a vehicle-based system over the conveyor-based system prompted an analysis of the vehicle system. The vehicle-based liner placement system involves a vehicle which could be automated to a degree to perform the tasks of transportation and laying of the liner with all the required specifications.

The initial step involved in setting up the mobile liner placement system would be to define the path of motion of the vehicle. The path of motion of the vehicle is shown in Figure 4.7. The tasks that the vehicle must accomplish are to pick up the liner roll from the storage area and carry it to the gob side of the shield. Once it reaches this point, the vehicle has to align itself to give the required overlap with the previously laid liner and then drops the roll down to the floor. As mentioned in the previous report, special access shields would be setup at each end of the roof support system. These shields would also have the ability to hold the free end of the roll that the vehicle carries. Once the roll is lowered, and the free end is held by the end shield the vehicle moves along the face of the shield in the gob side unrolling the liner. The vehicle then comes back to the roll storage area to pick up the next roll. The motion of the vehicle has to be in such a way that the liner achieves the required overlap. In order to achieve this, laser sensors would be attached to the vehicle to sense a color pattern marked in the liner.

Figure 4.8 shows a possible vehicle shape that could be used. The major disadvantage of this system would be that the vehicle runs over the laid liner and hence has the possibility of spoiling them. This means that we have to design tire pressures of less than 5 psi which becomes near impossibility with the loads being discussed. This leads to a further analysis of the winch based system. The working principle of the winch system is shown in Figure 4.9.

It can be seen from the figure that the roll is fixed to the winch and is then dragged along the face. The system components are also shown in the figure. The need for a dual pulley system is due to the fact that the bentonite layer has to be unrolled inside down. If this can be done by rolling the roll conventionally, we can do with a single pulley system.

## 4.5 RECOMMENDATION

From all the discussions so far it can be seen that Phase I analysis of the liner placement system leaves us with a task of selecting the system to be used from the above mentioned options. In the initial part of the Phase II analysis of all these systems would be made to identify their advantages and disadvantages. The result of this analysis would be identification of the liner placement mechanism.

# 5.0 BACKFILLING SYSTEM

## 5.1 SCOPE AND ROLE

Following the strata excavation and containment system installation, the void between the top layer of the containment system and the immediate roof is to be filled with specific materials to form a stowed bed. The stowed bed plays the following three basic roles:

### 5.1.1 SUPPORT ROOF STRATA AND PREVENT ROOF FROM CAVING

In conventional longwall mining, backfilling is seldom utilized. Roof strata are left to cave after a layer of stratum is excavated. A weak roof caves immediately after the support is removed while a strong roof remains hanging over the gob up to a substantial area and then collapses. Both cases are not desirable in this project. The cave of a weak roof near the face threatens the liner placement activities, damages installed liners, and reduces the stability of roof strata above the face. The cave of a large area of a strong roof could destroy a whole longwall face. Backfilling aims at providing solutions to the problems.

### 5.1.2 PROTECT UNDERLYING CONTAINMENT SYSTEM

If the backfilling does not completely eliminate roof caving, the filled bed will protect the liner from being damaged due to falling rock. It also prevents the containment system from any other impacts.

### 5.1.3 REDUCE THE MAGNITUDE OF OVERLAYING STRATA MOVEMENT AND PREVENT SURFACE SUBSIDENCE

Without backfilling, after roof strata cave, overlying strata successively move downwards. Fractures are developed from the roof to the surface during the strata movement. Severe overlying strata movement and surface subsidence may damage the original package of the waste. As a result, the waste leaks through the fractures, intersecting with the water bearing strata, and forming contaminated underground floods during the excavation and liner placement operations. The overlying strata movement also extends laterally far beyond the boundary of a panel. Lateral extension of strata movement will disturbs and damage the vertical containment wall if it is installed prior to the horizontal layers of the containment system.

The three basic roles of backfilling determine the requirements for backfilling operation and backfilling materials. In order to prevent roof from caving, filling operation must be carried out as soon as possible and the distance of non-support roof should be minimized. To minimize the overlying strata movement and prevent surface subsidence, a high packing efficiency and a high packing density are required. The packing efficiency is defined as the ratio of the packing height to the height of the void. The packing density significantly depends on the size of filling materials. Small sized material tends to yield a higher packing density and well grade materials work better than uniformly sized materials. Under the overburden pressure, the filled bed will experience a significant shrinkage. The contents of clay and moisture have a significant effect on the amount of shrinkage and they should be well controlled. To protect the underlying leachate collection system, backfilling materials shall consist of clean, washed, non-angular material conforming to a specific gradation range. The containment system also requires that the backfilling materials to provide adequate drainage.

Based on the above requirements, a number of criteria for backfilling operation and backfilling materials are established as follows:

*Criteria for backfilling operation*

Do not damage the underlying layers of the containment system
Packing efficiency: 80 - 90%
Maximize packing density
Minimize the non-support area and time delay
Maximize level of automation and remote control
Minimize labor work
Safe and reliable

*Criteria for backfilling materials*

Particle gradations: No.4 mesh to 2 inches
Particle condition: clean, non-angular particles
Materials do not change their chemical properties after exposure to the leachate
Filled bed does not fail under the overburden pressure
Moisture content: 7-10%
Clay content: < 10%
Permeability > $10^{-3}$ darcy

## 5.2 PROCEDURES AND ALTERNATIVES

To minimize non-support area of roof and minimize the time delay of backfilling, backfilling will be carried out immediately after a sheet of liner is placed. The longwall operation follows a cyclic procedure of excavation/face-advancing/liner-placement/backfilling. The face advances 3 to 4 feet each cycle. Backfilling procedure basically includes three step: material preparation, material transportation, and filling operation.

### 5.2.1 MATERIAL PREPARATION

Backfilling materials must be selected and tested based on the requirements for the mechanical and chemical properties. Mine refuse is usually an ideal choice in coal mines. However, because of the contamination of waste and the restrictive requirements of the containment system, the choice of excavated materials may be rejected. Sand with gravel or washed debris can be considered as a good choice in this project. After the materials are selected, the coarse materials are obtained and then subjected to crushing, size classification and wet classification. The prepared materials are stored in surface facility and are ready to use.

### 5.2.2 MATERIAL TRANSPORTATION

To minimize the transportation distance, backfilling materials are usually transported from the surface to underground through a borehole which is drilled near the panel to be filled. Backfilling materials can be transported to the working face in a number of means, depending on backfilling methods.

### 5.2.3 FILLING OPERATION

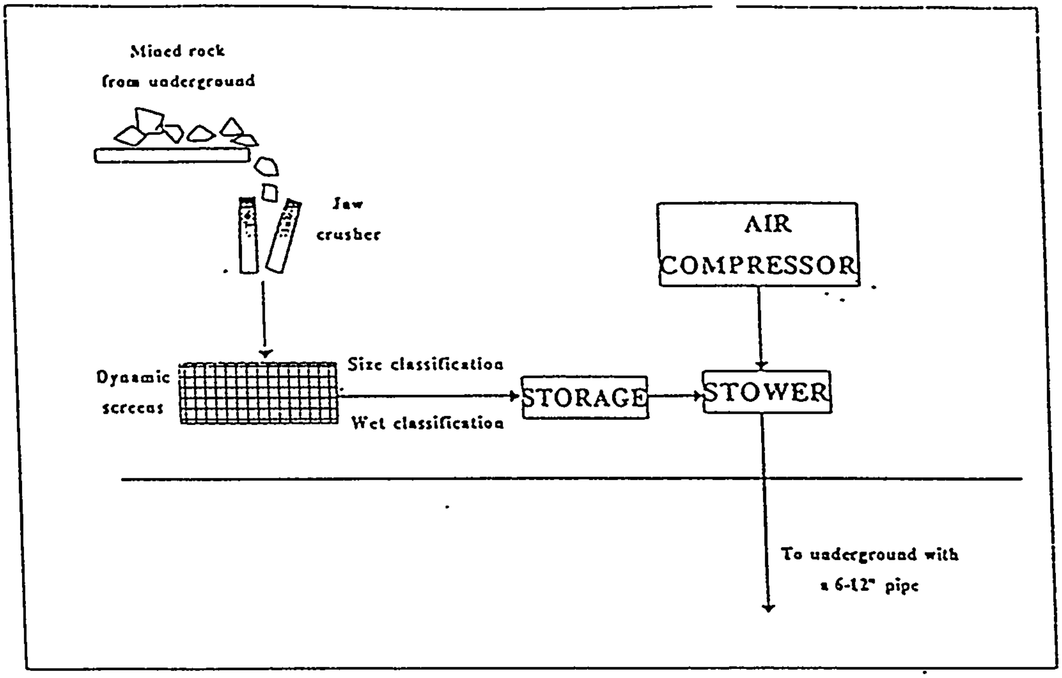
The filling operation includes preparing the face for filling and discharging the materials from the transportation line to stowage area. It also varies with backfilling methods.

*Alternatives*
Three backfilling methods have been studied for this project. They are mechanical, pneumatic, and hydraulic backfilling methods.

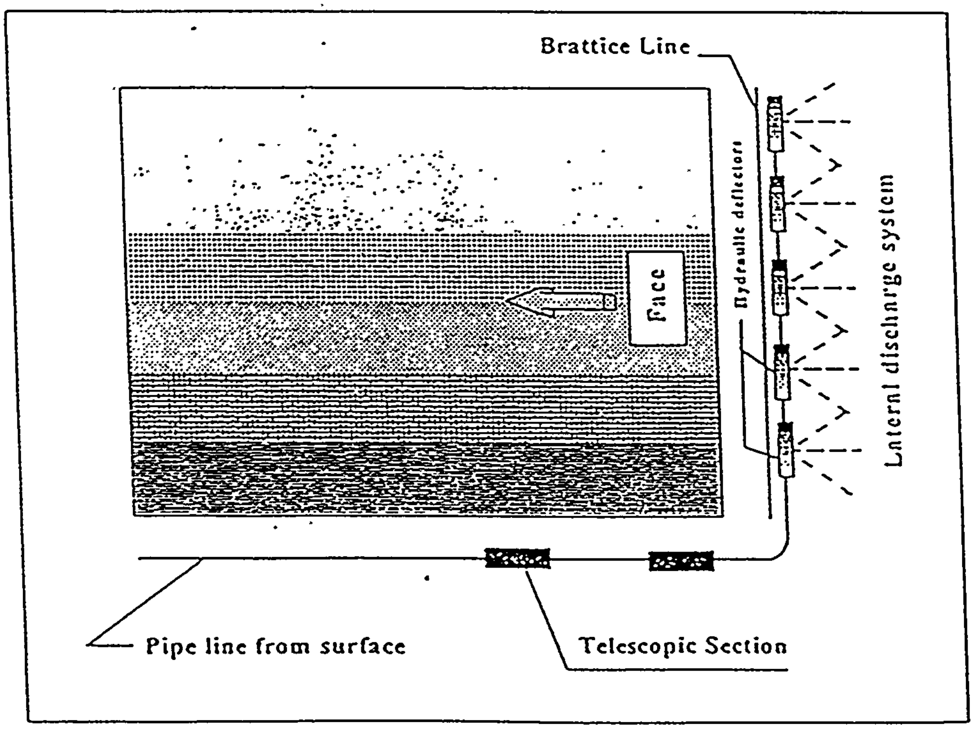
*Alternative 1 - mechanical backfilling*
In a mechanical backfilling system, materials are dropped from the surface to underground through a borehole. A conveyor or a track locomotive transportation system delivers the materials to the intersection of a panel entry and the longwall face, where the materials are discharged to stowage area in certain mechanical means or due to gravity. Mechanical backfilling is the cheapest method in backfilling operation. But it is seldom used because it requires intensive labor work and is also time consuming. Obviously, this method can not meet the requirements of this project and shall not be considered as a good choice.

*Alternative 2 - Pneumatic backfilling*
A typical pneumatic backfilling system is shown in Figure 5.1, where compressed air imparts a high velocity of compaction which is further aided by volume expansion. A stower feeds the backfilling materials into the compressed air flow. The compressed air propels the materials through a pipe line to the working face for filling operation. Before filling, a heavy rubber belt guard is attached to the rear portion of supports along the whole face length to protect the excavation and liner placement sections. A number of filling procedures have been attempted in the last decades. Lateral discharge procedure represents the most advanced procedure and it is a highly mechanized discharging system. The lateral discharge system consists of a face pipe and evenly spaced side discharge unites. The materials are discharged laterally into the stowage area having been deflected from the pipe via the side discharge units as shown in Figure 5.1b. The discharge units can rapidly be opened and closed hydraulically without interruption of the material delivery. The stowage area is filled progressively along the face by first opening the furthermost deflector, and simultaneously opening the next. The face pipe is flexibly hung on the tip of rear canopy of the chocks so that it will be advanced with longwall face without breaking the pipe. The telescopic sections in the tailgate permit the system to be advanced continuously with the longwall face.

Figure 5.1 Diagram of a Pneumatic Backfilling System




a) Material preparation and transportation at the surface




b) Lateral discharge system at the working face

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In each operational cycle, the air compressor is turned on first and the regulator is adjusted to give the predetermined air pressure and air flow rate. Then, the stower is started to feed the solid materials. In closing down, the stower is stopped first and the air compressor last, thus leaving the system a clean pipe line.

*Alternative 3 - hydraulic backfilling*
The procedure of a hydraulic backfilling system is similar to that of a pneumatic backfilling. However, unlike a pneumatic system, a hydraulic system utilized a water flow to transport materials to the working face through a pipe line. In a classical hydraulic backfilling operation, the water are drained and collected in a sink after filling. The collected water is then pumped back to the surface for reuse. The drainage of water had many undesirable impacts on the environments of a longwall face. The problem was overcome by cemented hydraulic backfilling. When cements are added to water-solid mixture, it solidifies to form a concrete bed. It usually takes a quite long period of time to complete solidification. Recently, a new cemented hydraulic backfilling material has been developed. This material has a volume ratio of 90% water to 10% cement. The water-cement mixture completes solidification in 5 to 30 minutes after adding catalyst and obtains the full strength of 5-8 Mpa in 5 to 7 days.

## 5.3 EVALUATIONS

Both pneumatic and hydraulic backfilling systems are extensively used in overseas. The procedures of the two methods are similar. They are highly mechanized and easy for remote control. Dust problem is the most serious problem associated with pneumatic backfilling and water drainage problem with hydraulic backfilling. Though cemented hydraulic backfilling eliminate the water drainage problem, it is still difficult to retain the water-solid mixture in the stowage area before it completes solidification. In order to choose a backfilling system which best meets the requirement in this project, pneumatic backfilling and hydraulic backfilling are compared in details in Table 5.1.

**Table 5.1**
**Comparison between pneumatic backfilling and hydraulic backfilling**

| | Pneumatic Backfilling | Hydraulic Backfilling |
|---|---|---|
| Facilities | Air compressor, stower, pipe line, discharge system. | Water pumps, mixer, pipe line, discharge system |
| Materials | Prepared solid materials | Cement, and prepared solid materials |
| Transportation medium and power | Compressed air | Water with pump or gravity |
| Horizontal distance distributed | 600-3000 ft, depending on the air pressure, air quantity, and head loss along pipe line | 300-600 ft per 100 gravity head |
| Permeability | Good | Poor |
| Moisture content | Can be controlled | Hard to control |
| Packing efficiency | High | Low |
| Packing density | Low | High |
| Application | Any conditions | Good for 10-30° dips |
| Automation level | High | High |
| Problems | Dusty | Weaken the roof and floor because of water<br><br>Hard to protect face from water |

## 5.4 RECOMMENDATION

Based on the criteria for the backfilling operation and the comparison between a hydraulic backfilling method and a pneumatic backfilling method, it is found that pneumatic backfilling basically meets the requirements of this project. It is a highly mechanized system and easy for remote control. It has a high packing efficiency and provides a high permeability for the leachate collection system. The discharge system is hung on the canopy of the chocks, thus, the underlying containment system will not be damaged due to filling operation. Though the hydraulic backfilling method has some advantage over the pneumatic method in terms of dust problem, it is hard to retain the water-solid mixture in the stowage area before it completes solidification. Besides, the water may mess up the underlying containment system.

# 6.0 MATERIALS HANDLING AND TRANSPORTATION

## 6.1 LINER HANDLING AND TRANSPORTATION

### 6.1.1 SCOPE AND ROLE

The primary task of the liner handling and transportation system is to transport the liner (in form of rolls) from a storage to the liner placement equipment. In this Chapter, we discuss the requirements of the system and the conceptual design and configuration of the related equipment.

**Parameters of Liner Rolls**

An understanding of the physical features and properties of the liner materials is important in establishing the performance constraints and specifications for liner handling and transportation. A typical liner roll is shown as Figure 6.1. For design of the liner handling and unrolling systems, and understanding of the following parameters is necessary.

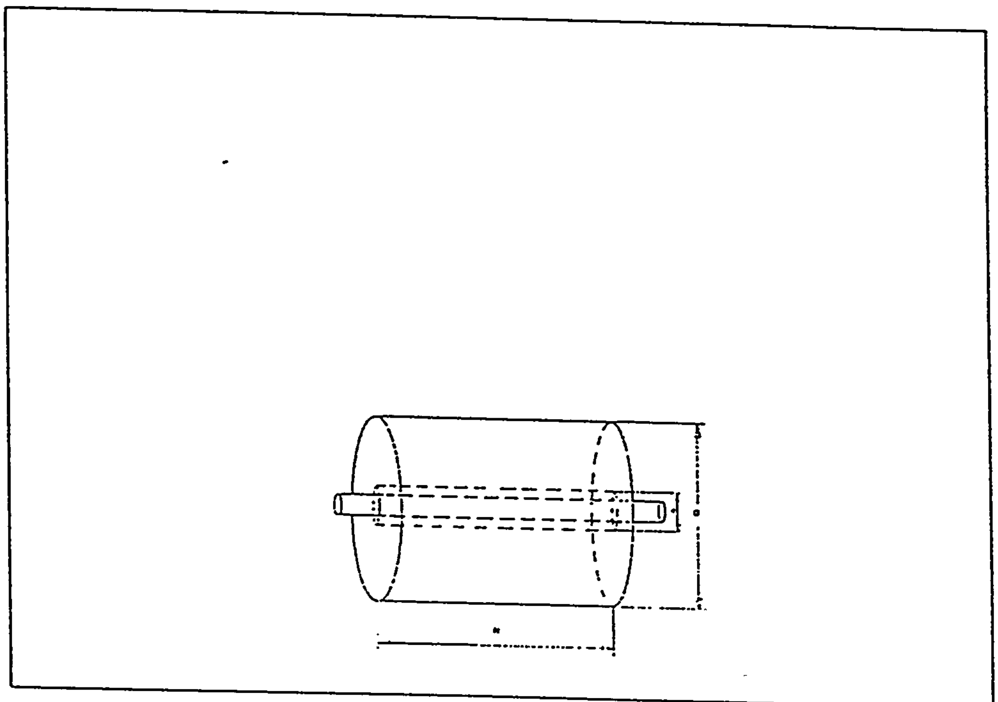


FIGURE 6-1 LINER ROLL

L - length of a roll of liner;
W - weight of a roll of liner;
d - diameter of the bearing of a roll;
D - diameter of a liner roll (e.g. 1 m);
B - width of a roll of liner (e.g. 22 ft);
n - number of layers around a liner roll;

t - thickness of the liner;
$G_0$ - unit weight of liner;
$W_d$- weight of the bearing of a liner roll;

The coverage length of the liner for each roll can be estimated by:

$$N \approx \frac{D - D}{2T}$$

The weight of a liner roll can be estimated by:

$$L = \pi \sum_{i=1}^{n} [D + \pi(2i - 1)]$$

$$W = L * B * G_0 + W_d$$

## Turning Constraints for Liner Transport

Due to the space limitations that will likely exist during the mining/containment operations, turning constraints should be considered for any liner placement equipment.

Assuming the planar outline of the transits is a rectangle and it can move along the wall of the supply entry; the turning constraint for this case is,

$$D = \sqrt{2}E - \frac{B}{2}$$

Where, D - width of a transit;
B - length of transit and liner roll;
E - width of mining entries;

For example, for E = 20 ft, B = 22 ft, the maximum D = 17 ft.

Furthermore, we may consider the vehicle turning characteristics so that more precise constraints for D, B and E may be obtained.

### 6.1.2 Procedure

The procedure of transporting liner rolls are according to the following sequence: 1) moving rolls from ground to the main entry, 2) moving rolls from mains to the mining face according to the path and the order shown in Figure 6.2, where the direction of the longwall system is towards the top of the figure, and 3) feeding the liner rolls onto the lining machine.

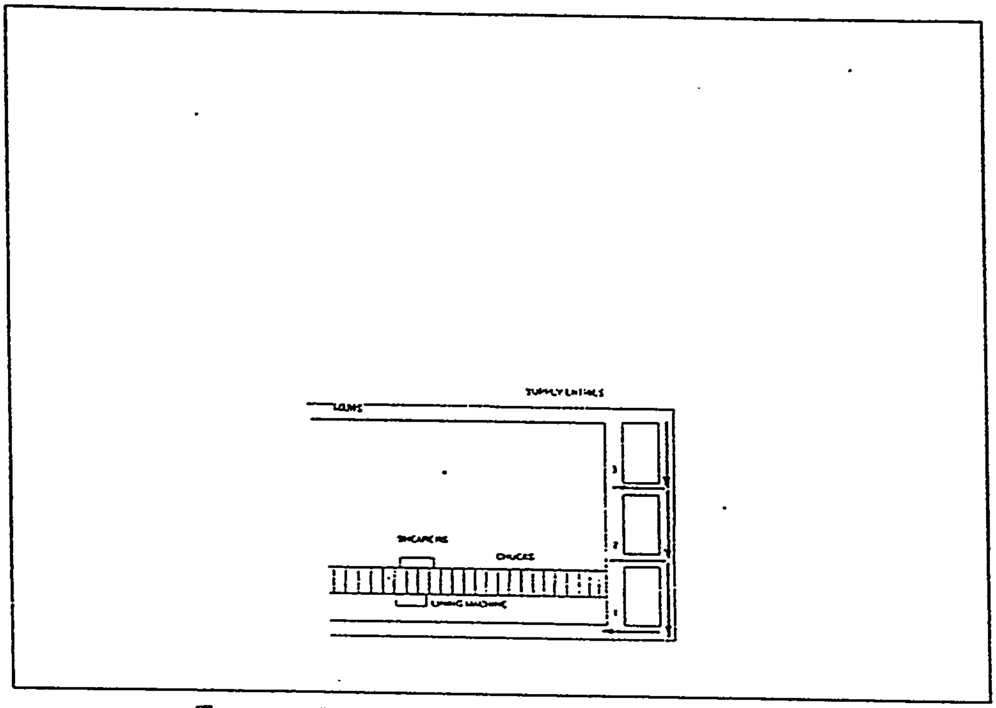


FIGURE 6.2 LINER TRANSPORTATION PATHS

### 6.1.3 Equipment.

Figure 6.3 shows four products from the mining and paper industries which perform functions that are quite analogous to the nature of liner transport operations: 1) conveyor, 2) rail shuttle, 3) 90 degree rotation clamp, and 4) scooper. The conveyor, rail shuttle and scooper are conventional mining equipment, while the 90 degree rotation clamp is the equipment for paper roll handling, which was manufactured by CASDES Company.

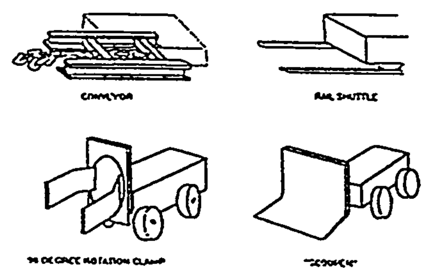


FIGURE 6.3 TRANSIT SYSTEMS

### 6.1.4 Evaluation

Table 6.1 is an evaluation table for comparison these alternatives.

**Table 6.1**
**Comparison Among the Transit Systems**

| | Conveyor | Rail Shuttle | Rotating Clamp | Scooper |
|---|---|---|---|---|
| Heavy Material Handling | feasible | feasible | feasible | feasible |
| pre-installation | needed | needed | no | no |
| roll handling | modification needed | modification needed | well designed for the task | modification need |
| Transferring Roll to Lining Machine | extra equipment needed | extra equipment needed | self-contained | extra equipment needed |
| Original Application | mining | mining | paper roll handling | mining |
| Navigation System | Not Required | Not Required | Required | Required |

As presented in the evaluation table, the 90 degree rotation clamp is recommended to be the mode of transit for the liner rolls primarily due to its ability to handle rolls in an efficient and reliable manner, without any ancillary equipment. The roll handling procedure for the clamp is shown as Figure 6.4. Where, (a) is the original clamp position; (b) the clamp grasps a roll and carries it to the face; (c) the clamp rotates 90 degree and moves the roll forward to the lining machine; (d) the roll handling arm of the lining machine grasps the roll and then the clamp withdraws.

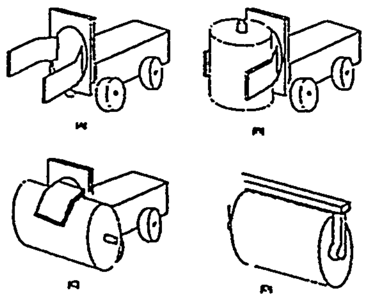


FIGURE 6.4 LINER HANDLING BY CLAMP

### 6.1.5 Recommendation

It is concluded that the 90 degree rotate clamp is feasible to handling and transfer the liner rolls. Comparing to other transits, this design need not extra roll handling equipment as well as large turning space. Also it is commercially available.

## 6.2 UNGROUND TRANSPORTATION SYSTEMS

### Scope and Roles

Underground transportation systems include vertical shafts, slopes, main underground gateways, panel gateways, and the working areas. The basic roles of an underground transportation system includes:

1. <u>Transport equipments and deliver materials to underground working areas</u>:
Entry development, strata excavation, liner placement, backfilling, and all other activities require various equipment and materials. Underground transportation systems must deliver all supplies and materials to the working areas. In recovery, all equipments and useful materials have to be transported back to the surface.

2. <u>Provide access for human operators</u>:
Underground workers are transported through an intake shaft or slope, an intake gateway, and dropped near the working areas and take opposite direction in return trips.

3. Transport excavated material and other waste out to the surface:
This includes the material excavated in longwall operations and entry developments.

The three basic roles of underground transportation systems require that the systems should meet the following requirements:

1. Provide a high accessibility:
Underground activities spreads to every corner. Various vehicular modes may be required to get through different underground openings, especially the low, narrow openings.

2. The transportation systems should have a sufficient capacity:
Most underground equipments, such as longwall shearers, hydraulic powered supports, and face conveyors, are very heavy. The modes selected for equipment transportation should be able to accommodate the size and the weight of the largest equipment employed in the mining/containment operation. The excavated material transportation system should have a sufficient capacity to take the materials discharged from the longwall face.

3. The vehicles must be compact and safe:
Underground transportation systems are operated in a limited space The vehicles should be compact and protect riders from surrounding objects.

4. Maximum level of automation and high reliability:
Some transportation systems, such as excavated material transportation, run continuously throughout mining operations. In such cases, it desirable to have a reliable computerized control system.

5. Minimum maintenance:
Maintenance requires human labor or additional automated equipment which may have implications on the technical and safety feasibility of the operation. Therefore, transportation system options should minimize the required maintenance.

6. High durability:
Underground transportation facilities and vehicles are subjected to severe adverse conditions, such as ground water, moisture, and rough floor surfaces. Therefore, they should resist wear and breakdown prone under such conditions.

Alternatives, procedure, and evaluation

Existing automatic hoist system in a shaft, locomotive transportation system in gateways, and scoop/shuttle car in the working areas can basically meet the requirements of equipment transportation, material delivery, and manriding.

For excavated material transportation, a continuous conveyor system has been used for many decades in longwall mining. With a slope providing an access from the surface to underground, a conveyor system can transport excavated material from a longwall face to the surface without mode transferring. As shown in Figure 6.5, the system consists of an armored face conveyor laid along

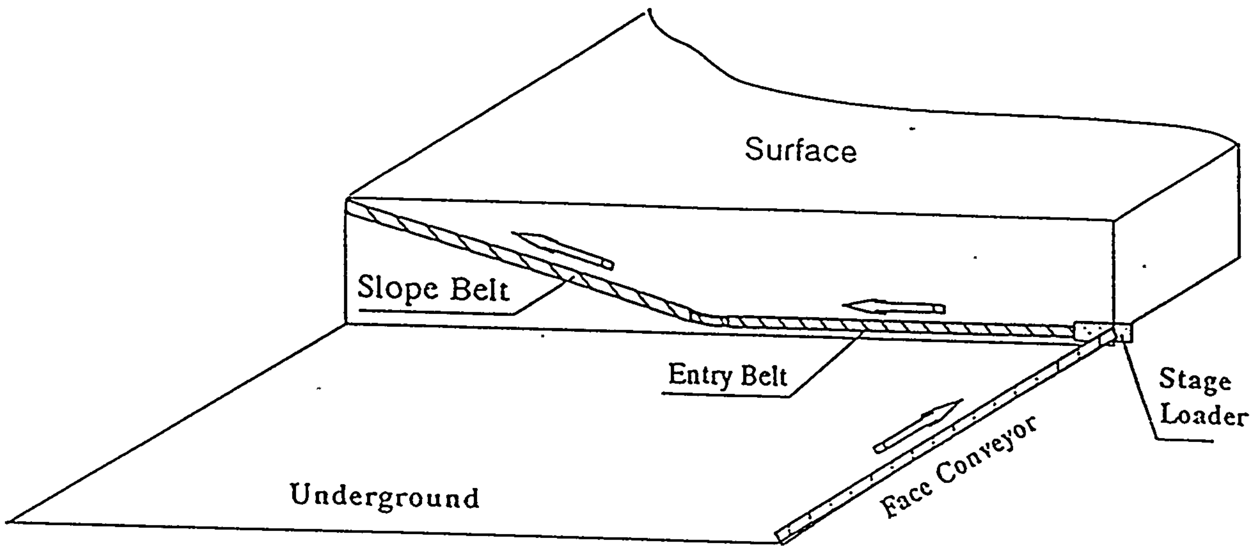



Figure 6.5 Continuous conveyor transportation system for excavated material

the full face length, a secondary belt conveyor in a panel entry, and a main belt conveyor in the slope. Mined rock is loaded to the face conveyor by a longwall shearer during its cutting operation. A stage loader, at the T-intersection of the entry and the face, transfers the rock from the face conveyor to the belt conveyor. The entry conveyor discharges the rock onto the main conveyor which takes the rock out to the surface.

The armored face conveyor consists of a drive head, various pans, link chains, scraper bars, and a tail unit, as shown in Figure 6.6. Electrical motors in the drive head drive the endless link chain to which the scraper bars are tied, carrying the rock on the line pans toward the entry conveyor. The face conveyor are flexible and advanced by double-acting-advancing-rams connected to hydraulic powered supports.

A typical entry belt conveyor is shown in Figure 6.7. It consists essentially of a drive unit, a belt, supporting frames, a belt tension unit, and a belt storage unit. The belt conveyor is also driven by electrical motors in the drive unit. The length of a belt conveyor should be adjusted as a longwall face advances. To shorten a belt conveyor, some support frames have to be removed and the tail unit is moved toward the drive unit. Belt length adjustment is implemented section by section.

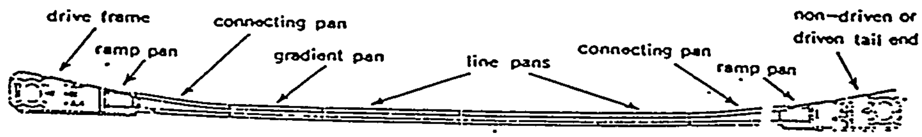
Figure 6.8 shows a typical stage loader which transfers material from a face conveyor to the a belt conveyor. It consists of a level section, an inclined section, an overhanged bridge, and a drive head. A line pan in the level section of the stage loader are connected to the drive unit of the face conveyor. The drive head of the stage loader is trapped on the sliding rails on the tail end of the belt conveyor. As the longwall advances, the stage loader is pushed forwards and the skid slides on the supporting frame of the belt conveyor.

The construction and operation of the main belt conveyor is similar to the entry belt conveyor. But it is fixed in length and does not need a belt storage unit. For effective conveyor operation, the slope should not be greater than 17° and a slope of 15° is selected.

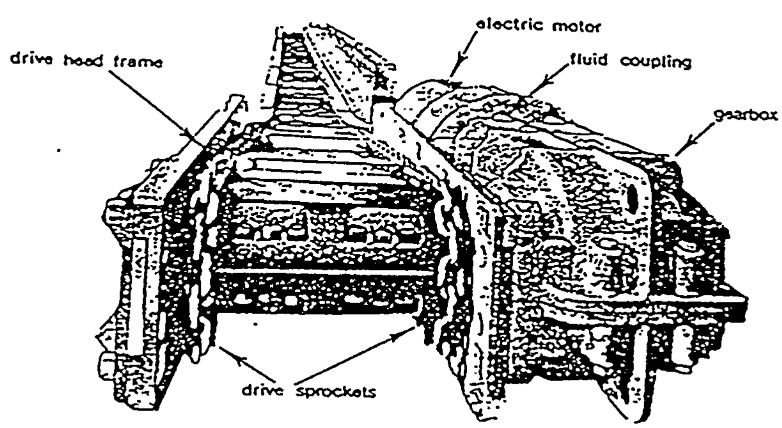
The operation of conveyor system is computerized. A computer program provides the sequential control and belt protection. In order to prevent piling up of material on to a conveyor. It is essential that the main conveyor should be started before the entry conveyor and the entry conveyor before the face conveyor. It is also necessary, for the same reason, that a feeding conveyor stops before a receiving conveyor. Further, the program makes it impossible to start a feeding conveyor unless the receiving conveyor is running. The system is equipped with motor temperature, belt/chain tension, and overload monitors. If any monitor detects undesirable conditions. the computer will shutdown the system.

## Conclusions

Existing underground transportation technology is adequate to provide transportation for underground equipments, supplies, workers, and excavated materials. Main transportation systems, such as hoist systems, track locomotive systems, and conveyor systems are operated by computers and they are reliable. Operator controlled vehicles, such as scoop, are necessary to provide access to the low, narrow, and remote working areas. The capacity of transportation systems and the




a) Major Components of a face conveyor




b) The drive head of a face conveyor

Figure 6.6 A typical armored face conveyor

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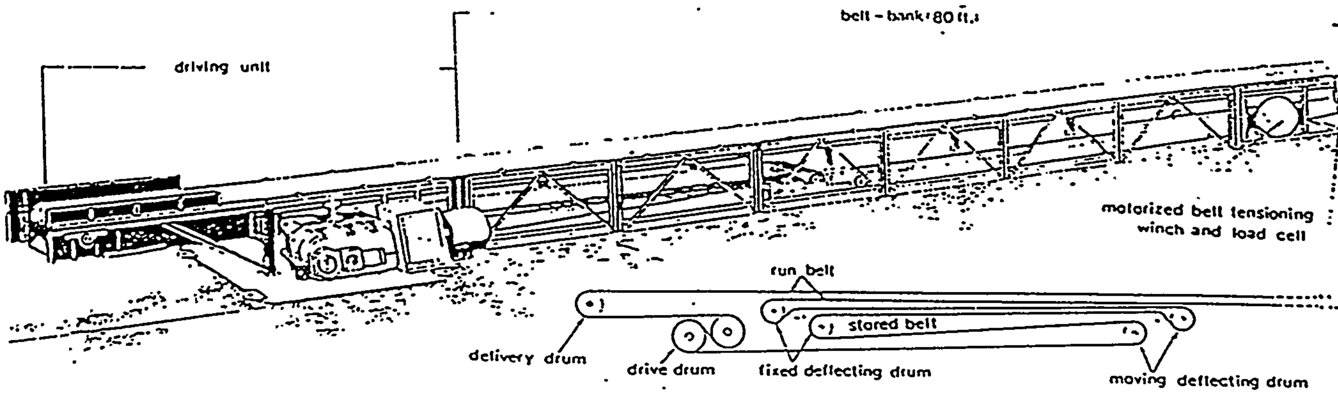


Figure 6.7 Typical structures of a belt conveyor

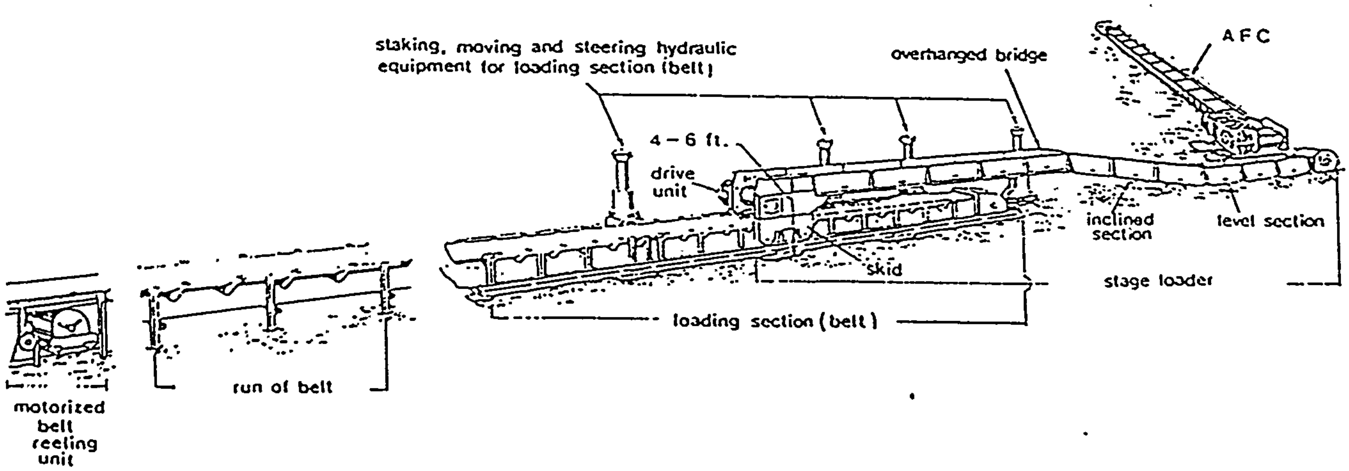


Figure 6.8 Transfer section between a face conveyor and a belt conveyor

selection of vehicles can be determined for a given site.

# 7.0 FACE ALIGNMENT AND SHIELD CONTROL SYSTEM

## 7.1 SCOPE AND ROLE OF THE SUBSYSTEM

The purpose of the Face Alignment and Shield Control System (FASCS) is to sense and control the movements of the roof support shields to maintain proper alignment between the shields and straightness of the mining face as the longwall moves forward.

In conventional mining, it is desirable to keep the face as straight as possible, but precise alignment of the shields is not critical and so is not measured. If significant bowing of the face occurs, the headgate and shield operators generally deal with it by manually instituting a series of short shearer passes across the "high" spots to straighten the face back out. In the proposed application the alignment of the shields will be much more critical. The liner system being laid down behind the shields is made of rolled sheets of materials which are not extremely flexible. Details of the liner system and its critical parameters are given in Volume 2 of this report. The sheets must be placed fairly precisely in order to maintain the proper overlap and to prevent any gaps between the sheets. Any bowing of the face or shield misalignment may cause the edges of the liner material to buckle up, creating unacceptable gaps between layers. Buckling of the liner may be created either by longitudinal or angular misalignments of the shields. Figure 7.1 illustrates these two types of alignment problems.

The sensing systems currently employed by commercial shield controllers are capable of measuring only the extension of the hydraulic drag cylinder connecting the shield and the conveyor. This measurement does not afford sufficient information to accurately calculate the shield's position and orientation. In addition, control using only the single drag cylinder between the shield and the conveyor will not be flexible enough to correct angular position errors in shield placement. The following section presents an overview of the recommended shield control modifications necessary to provide adequate shield control.

## 7.2 ENHANCED FACE ALIGNMENT AND CONTROL SYSTEM

### 7.2.1 BACKGROUND

The progress of the longwall mining operation is controlled by interaction between the roof support system and the pan conveyor/shearer system. The conveyor which transports cut material from the face to the belt entry is semi-flexible. It is generally constructed in sections the same width as the shields--approximately five feet. Individual sections of conveyor are joined by a "dogbone": a dumbbell-shaped link which allows small angular misalignments between conveyor sections while still keeping the sections held together longitudinally.

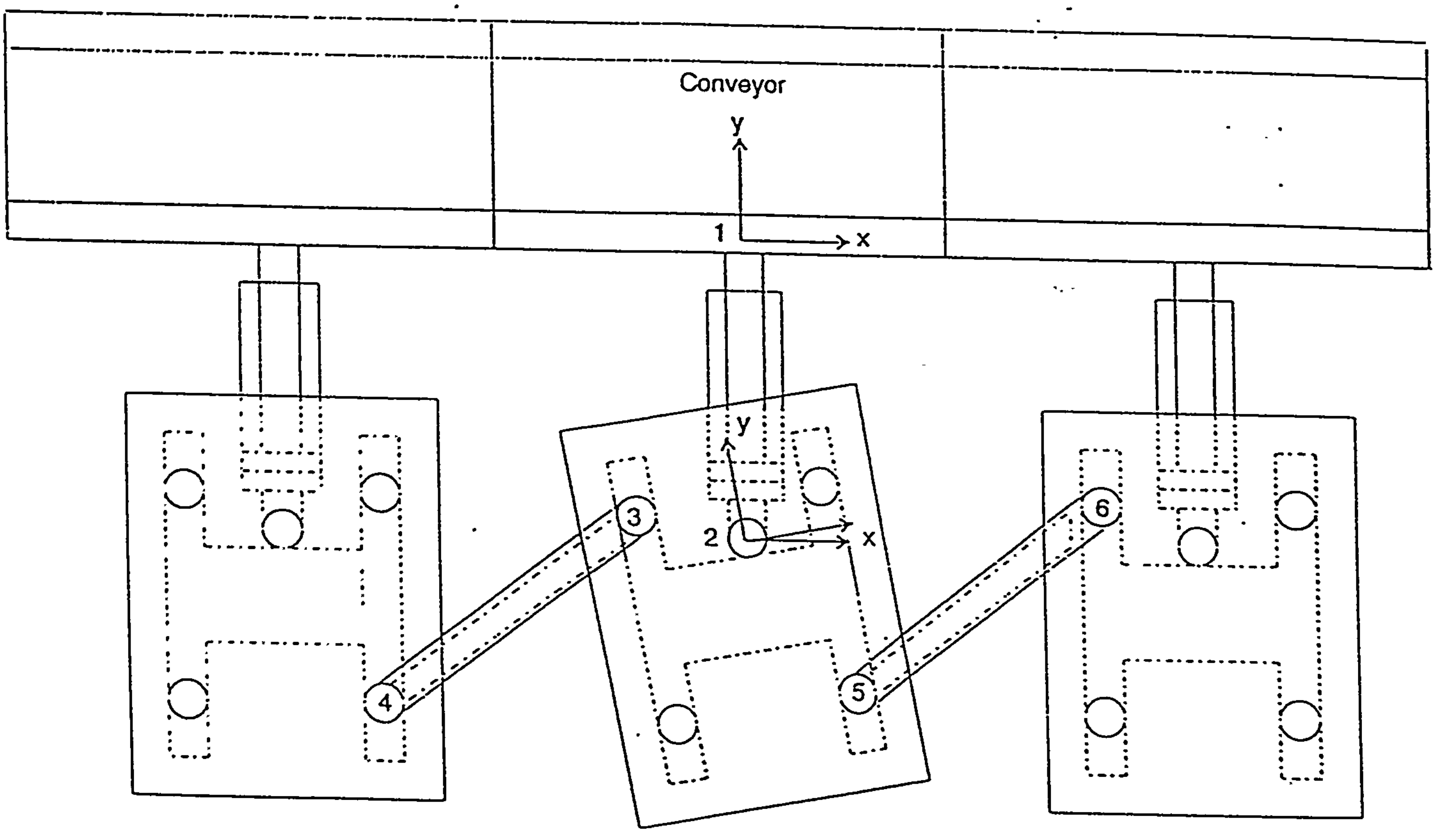


Figure 7.1: Sketch of the conveyor section and associated shields. Coordinate frames for the center conveyor section and shield are shown illustrating angular misalignment.

As the shearer cuts rock from the face, first the conveyor and then the shields must be moved forward into the space won by the shearing operation. This is accomplished by first pushing the conveyor forward and then dragging the shields behind it in a process commonly called "snaking". The process is illustrated in Figures 7.2a-7.2c. The process begins by extending the hydraulic cylinders connected from the roof supports to the conveyor, pushing the conveyor forward. This must be done in a coordinated and gradual fashion, due to the limited flexibility of the conveyor. It is accomplished by maintaining pressure on the roof with the shields and extending the forward cylinders of each of the shields in a timed and sequenced fashion. The friction between the shields and the mine roof immobilizes the shields, providing a firm base for the conveyor moving operation.

Following this step, the shields must be moved forward to support the roof above the newly mined section. At the same time, roof support must be maintained above the existing work area. To accomplish this, shields are moved forward in a staggered fashion as illustrated in Figure 7.2a-7.2c. The shield to be moved is lowered, removing the frictional contact with the roof and reducing the friction at the floor to that caused by the weight of the shield. The shields to either side of the one being moved retain their roof pressure, supporting the roof and also holding the conveyor firmly in place. The hydraulic cylinder connecting the moving shield to the conveyor is then retracted, pulling the shield forward. This process is repeated in a wave-like fashion down the face as the shearer moves along the face cutting rock.

It should be noted that the above description is a gross simplification of the actual sequence, since movement of the semi-rigid conveyor must take place gradually, thus each shield/conveyor segment may actually be repositioned several times in the process of "snaking" the conveyor. However, the description above summarizes the salient points of the operation, i.e. the conveyor segments and shields move in a push/drag sequence controlled by double acting hydraulic cylinders.

### 7.2.2 ALIGNMENT CONTROL

The process of moving the face involves hundreds of individual shield and conveyor segments over the length of the face, and requires a high degree of coordination between the shearer, the shields and the conveyor. The automatic control of this process is commonly done using a computerized controller placed at the headgate operator's station. The computer monitors the position of the shearer and orchestrates the complex series of shield/conveyor movements which keep the amount of unsupported roof in the working area to a minimum and which move the face forward smoothly and efficiently.

For the hazardous waste application, control of the face and shield alignment is much more critical than for the typical longwall. It is necessary to control the progress of the mining process in three dimensions. Control of the x and y directions (ref Figure 7.1) keeps the excavation under the contamination site, while control of the vertical or z direction will be necessary to maintain the proper floor flatness and slope required for drainage of the leachate

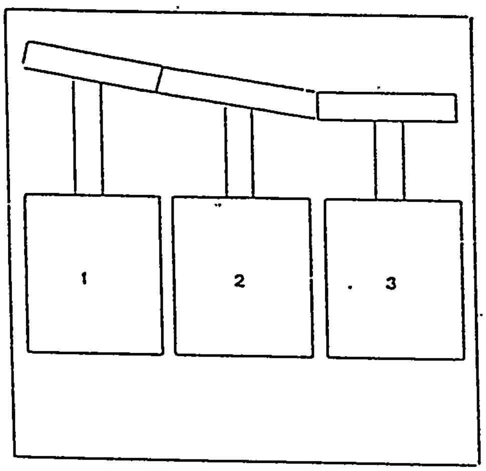


Figure 7.2a: The conveyor advances. All shields hold roof pressure.

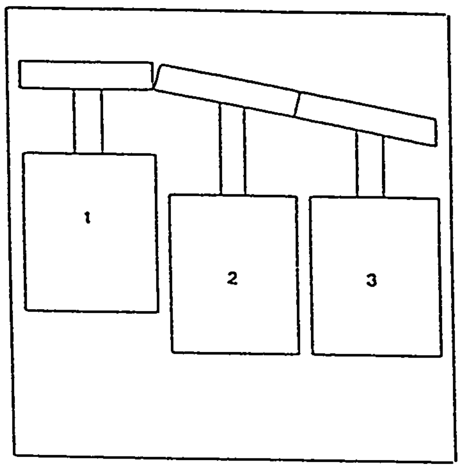


Figure 7.2b: Shield 1 is lowered, releasing roof pressure. Shields 2 and 3 maintain roof pressure. Shield 1 advances by dragging itself. It is then raised again reestablishing roof support and friction.

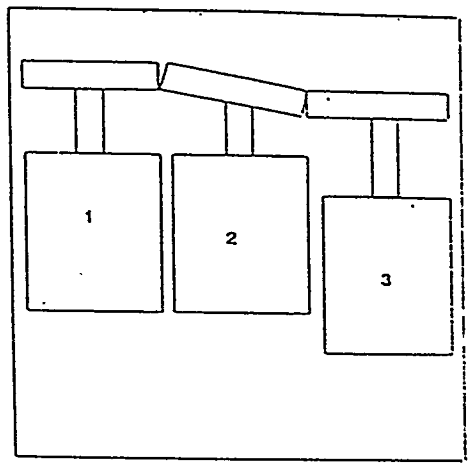


Figure 7.2c: Shield 2 is lowered, releasing roof pressure. Shields 1 and 3 maintain roof pressure. Shield 2 advances by draggir itself. It is then raised again reestablishing roof support and friction.

into the leachate collection sump.

In conventional mining, x and y control are effected by the mining of the entry passages along the sides and ends of the longwall section. These passages form lateral boundaries for the longwall operation, as well as an indicator of the seam location at the ends of the longwall. Along the face, the vertical mining dimension is dictated by the location of the coal seam. The arms of the shearer are raised or lowered by the shearer operators to keep the cutting drums in the coal seam, which may vary in thickness and undulate across the face. If a seam has a significant tilt, the longwall is generally set up to run uphill, allowing water to drain back into the gob and away from the face. Strict control of the floor flatness and slope is not required for coal mining, however. Considerable bowing of the face in both the y and z directions is common in a coal mine. If bowing in the y direction becomes severe, it can be manually corrected by making several short passes across the "high" spots, bringing the face back to the required degree of straightness.

For the hazardous waste application, the entry passages will also be used for lateral (x direction) mining control. Much more stringent control of the y and z directions will be required than for coal mining, however. To maintain the required alignment, it will be necessary to monitor and control the position of every conveyor segment and shield individually. It will also be necessary to control two degrees of freedom of each shield: its front-to-back position (y direction) and its orientation or angle with the face ($\theta$ position). In current mining systems, the $\theta$ position is not measured or controlled. Modifications to standard mining equipment will be required and are discussed in Section 7.3. The general procedures for maintaining face and shield alignment are outlined here.

As in all mining operations, a "global" coordinate system will be established for the panel, and accurate survey points will be established along the entry passages leading down either side of the longwall section. As the longwall moves forward, periodic surveys will also be taken of the face, by sighting down the pan line with laser-based surveying equipment called theodolites. The theodolite will record the position of a reflective target which will be attached to the shearer, and correlated with the position of the shearer along the face, which is known using standard instrumentation found in longwall equipment. Dust and vibration will preclude performing the alignment with the shearer and conveyor running. Therefore a special calibration pass of the shearer will be made periodically. In this procedure, the target will be attached to the shearer and it will be run down the face, stopping at locations which place the theodolite target at the reference point(s) of the reference conveyor sections. Since the conveyor is rigid except at the joints, it is unlikely that each individual conveyor section will need to be surveyed unless a serious misalignment problem were to occur.

This alignment traverse will establish the location of the reference point for each conveyor segment along the face. From this data, the straightness and elevation of the face can be monitored and corrected as required. Undulations in the y direction can be corrected by adjusting the extension of the push/drag hydraulic cylinder for key roof support shields. Errors in the elevation (z) direction will be corrected by adjustment of the shearer arm position on subsequent cutting passes, or perhaps by the execution of an immediate trimming pass to restore flatness and proper pitch.

Once the locations of the conveyor sections are known, the position and orientation of each shield can be calculated based on the extension and orientation of the hydraulic cylinders connecting the shields to the conveyor and to each other. A detailed analysis of the conveyor-cylinder-shield kinematics has been performed, and is presented in the appendices to this report. That analysis serves as the basis for the recommendations for equipment modification recommendations presented below, and for the shield alignment control procedures outlined in the appendices.

The requirement for accurate alignment of the shields and the face will require a number of extra steps beyond what would normally be used in a coal mining situation. However, since the liner placement process can not be done during active cutting, we propose that the face/shield alignment procedure and the liner placement procedure can be accomplished simultaneously, thus reducing the amount of dead time in the shearing cycle. There is no way to assess analytically how much vibration and dust will be generated by the liner placement process, and whether either or both would disturb the surveying procedures. If possible, alignment and liner placement will be scheduled to operate simultaneously.

## 7.3 EQUIPMENT

To adequately control both the position (x,y) and attitude (θ) of the shield, additional actuators and sensors must be installed on the shield and incorporated in the control scheme. The hydraulic cylinder connecting the shield and conveyor can control only the forward (y direction) motion of the shield. In order to control θ, one additional actuator/sensor system must be added to each shield. A double-acting hydraulic cylinder could be connected parallel to the existing one between the shield and the conveyor, as shown in Figure 7.3a. Alternatively, the cylinder could be connected laterally between adjacent shields, as shown in Figure 7.3b. By coordinating the actuation of both cylinders, both the y and θ positions of the shield can be adjusted. Fortunately, one of the options on the shields manufactured by Westfalia Mining Progress is a set of lateral hydraulic cylinders which can be used to interconnect adjacent shields. This system is commonly used in European mines, and would require only minor modifications for adaptation to the hazardous waste application. The adaptations consist of the addition of cylinder angle sensors and additional control logic, described below.

In addition to measuring the extension of the cylinders, the orientation of the cylinders with respect to the shield must be measured. The cylinder extension measurement is standard equipment. The cylinder orientation measurement can be effected by the addition of encoders, resolvers or precision potentiometers to the shield system. Retrofit of standard shields would not be difficult, although care will need to be used in the design to insure ruggedness of the system and wiring. It may also be necessary to replace the solenoids for control of the hydraulic fluid flow to the lateral cylinders with proportional flow valves. This is necessary to accommodate the additional constraints placed on the conveyor-cylinder-shield kinematics by the lateral cylinders.

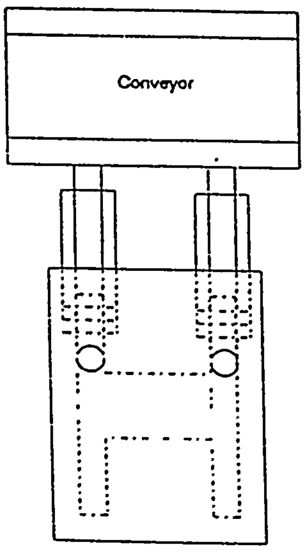


Figure 7.3a: Shield control
Using two drag cylinders

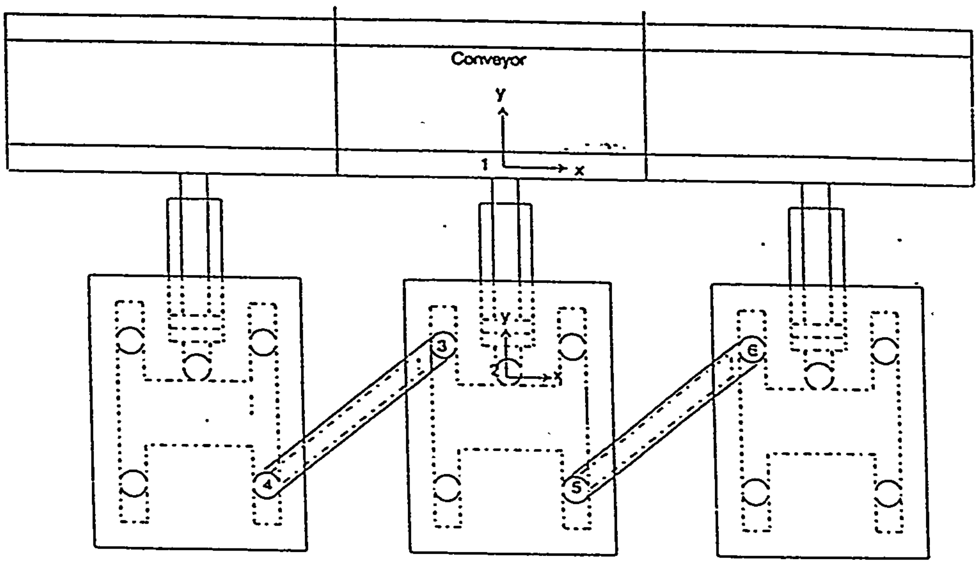


Figure 7.3b: Shield control using drag cylinder and lateral cylinders

Automatic control of the shield position will require the modification of some of the control logic now used for shield positioning in the headgate computer. Two of the industrial partners in this project supply equipment for control of the shearer and shield system: Joy Manufacturing and Westfalia Mining Progress. A number of other companies also manufacture similar control systems. Any of these systems will require modification of the standard software for the control of the shearer/shield systems in the hazardous waste application. A study of the control logic required to effect adequate positioning accuracy has been instituted. This study constituted the MS Thesis of Mr. Murali Parthasarathy, one of the graduate students working on this project. Pertinent sections of that document are included in the appendices. The thrust of the work was to develop a control scheme for maintaining shield alignment which is computationally simple enough to implement on existing longwall control equipment. Mr. Parthasarathy developed a controller based on fuzzy logic which we are confident can be implemented on existing control hardware.

## 7.4 EVALUATION AND ANALYSIS

Two options for implementing shield attitude control were presented in Section 7.3, however only one of them is under serious consideration at this time. The configuration of Figure 7.3a was rejected because it is non-standard and because it would place too much torsional stress on the conveyor system in the process of correcting shield attitude. We recommend the use of a shield system which includes lateral linkage between shields as shown in Figure 7.3b. This configuration distributes torsional stresses between the pan line and the adjacent shields, and is available as standard equipment from Westfalia Mining Progress, one of the industrial partners in this project. If this equipment is used, only relatively simple modifications to the shield hardware will be required. These modifications consist of adding angle sensors and proportional flow control valves to the hydraulic positioning cylinders. Neither of these measures constitutes a major technical hurdle.

Modification of the headgate and shield control computer systems will require more effort. As was noted, standard control systems are not set up to monitor or control the angle of the hydraulic cylinders with respect to the shield, as will be required in the proposed system. The addition of two angle sensors per shield will increase the data load for the control systems to monitor and act upon. The control logic for the shield alignment will also be more complex than is currently required for coal mining. However, an effective but computationally simple control scheme has been developed as part of this research which holds promise as a means of expanding the functionality of existing commercially available control systems without overtaxing its processing power. Modest modifications of existing hardware may be necessary to handle the increased sensing and control functions, but no radical changes in the equipment are expected.

Finally, the proposed alignment calibration system is based on standard surveying equipment with some modifications to the mining procedure only. We do not believe that insurmountable obstacles will be encountered in implementing this system, either.

## 7.5 SUMMARY AND CONCLUSIONS

The conceptual design of a system for maintaining accurate control of the mining geometry and alignment of the roof support shields has been presented. The system is designed around commercially available equipment to which relatively minor modifications would be required. The most significant development effort will involve the modification of face control software for the control of shield position and attitude. A second major effort will involve the refinement and testing of alignment calibration procedures outlined in this report, and the development of software to automate them. This process does not constitute a technological hurdle, but will consume some resources as a development effort.

# 8.0 COMMUNICATIONS SUBSYSTEM

## 8.1 SCOPE AND ROLE

The role of the communications subsystem will be to move information between a myriad of sensors, computers, actuators, and people. There will be three distinct types of information transmittal: data, voice and video.

The data network will comprise the largest and most vital network in the system. The data network will be multi-tiered, consisting at the lowest level of sensors and actuators and at the highest level of humans observing a computer video output screen or entering commands through an input device. The data network will also consist of two subsystems, one of which will service "stationary" equipment such as the shields, shearer and ancillary equipment at the mining face, and a second system which will service mobile robotic devices, such as the material transport devices which will carry supplies and personnel between the face and the access shafts. Figure 8.1 shows a preliminary block diagram of the data communications subsystem. The role of this subsystem is to collect and process information from sensors on virtually all of the machinery, interpret and display that information to human monitor/operators, and transmit control signals and other messages back down the chain to the actuators. The only difference between the stationary and mobile data networks is in the existence of a radio modem link in the mobile network, and in the fact that the stationary network is several times larger and more complex than is the mobile network.

The video communications network is primarily a surveillance system for facilitation of remote monitoring and teleoperation of the system. It is a reasonably simple network, consisting of multiple cameras, camera controls, displays and appropriate switching equipment. Figure 8.2 is a preliminary block diagram of the video communications subsystem. This system contains both analog video signals and digital control and data signals as shown.

The Voice Communications Subsystem will be important as both a safety feature and a productivity enhancement. Since one of the goals of the project is to minimize the number of humans in the mining area, they will necessarily be outside the range of visual or unaided voice contact at times. The geographically dispersed operation and high noise levels mandate that any human in the mining area have constant communications ability with other workers both underground and on the surface. The voice communications network will meet the need for connecting people underground with each other and with those at the control center on the surface via a convenient voice link. The network contains both physical and radio transmission links in order to allow the miners maximum mobility while preserving continuous access to communications. Each miner will carry a compact transceiver containing a radio frequency voice link to the network through repeaters and an antenna system. A block diagram of the voice communications subsystem is shown in Figure 8.3.

## 8.2 INSTALLATION AND OPERATION

Operation of the communications subsystems will largely be a background activity, completely transparent to the user. No human activity other than maintenance/repair should be required of the data and video systems.

## 8.3 EQUIPMENT

### 8.3.1 DATA COMMUNICATIONS SUBSYSTEM

#### 8.3.1.1 STATIONARY DATA COMMUNICATIONS SUBSYSTEM (SDCS)

The Stationary Data Communications Subsystem will be the largest and most complex portion of the communications network, due to the number and variety of sensors, actuators and computing nodes in the mining operation. The backbone of the SDCS will be the headgate computer and shield control system found in a typical longwall mine. The headgate computer and its operator will comprise the highest underground level in the hierarchical structure as shown in Figure 8.1. Communications between the headgate computer and the lower levels will be done via daisy-chained serial lines running between each of the shield control units as in a typical longwall. Virtually all of the equipment required for the SDCS is available commercially, and is supplied by Westfalia Mining Progress, one of the industrial partners in this project. These units have already been certified for use in underground mining environments and will require only minimal development work to configure them for service in the hazardous waste application.

#### 8.3.1.2 Mobile Data Communications Subsystem (MDCS)

The MDCS will be smaller but similar to the SDCS, due to the smaller number of nodes in the system. Each node will be a robotic vehicle of some sort, e.g. liner transport vehicle, personnel transport, scoop, etc. The main controller of the vehicle will be the counterpart of the shield control computer, and a dispatching and traffic control computer will be the counterpart of the headgate computer. The primary difference between the MDCS and the SDCS will be the presence of a radio data link in the mobile system which connects the individual robots to the dispatcher. A number of options have been studied for the radio data link. The two most promising candidates are the "leaky feeder" system and the repeater/transceiver system. Each of these is described below.

Leaky feeder antenna systems have been used in mines in the past with some success. A leaky feeder system is a large-diameter coaxial cable with slots cut into the shield layer, causing radio frequency energy to "leak" out of or into the center conductor. The feeder constitutes a long antenna through which radio messages can be transmitted or received for short distances from anywhere along its length. The feeder would be deployed along the development tunnel walls to provide access to the robots at any point in the entry. A similar antenna would be run along the gob side of the shields for communications in the liner placement and backstowing areas.

A second option is to use a series of radio transceivers and direct broadcast to the radio modem links on the robots. The system would be similar to the repeater network used widely by amateur radio operators throughout the world. This system would eliminate the long feeder antenna and may increase the range from the robots to the transceivers, reduce sensitivity to directional effects and increase bandwidth. At least one company, RIMtech, manufactures such equipment specifically for mining operations. If this project is continued into the development stage, other vendors would be sought out as well. In the RIMtech equipment, all components are housed in explosion-proof enclosures and are intrinsically safe for the mining environment. The RIMtech equipment is capable of using power lines as carriers where regular data lines are unavailable or inconvenient. The basic structure of this system would be the same as for the leaky feeder network; only the particular communications medium would be different.

Of the two technologies, we prefer the use of the repeater-based system as simpler in installation and probably less prone to damage from shield movement. Experiments must be carried out however to determine if the system will have sufficient range in the highly confined and metallic environment near the face. Such experiments would be conducted in Phase II of the program.

### 8.3.2 VIDEO COMMUNICATIONS SUBSYSTEM (VCS)

The VCS consists of a series of video cameras placed at strategic locations throughout the mine, and connected by a network of cables, amplifiers, video transmitters, switches, control units and monitors. All of the equipment required is commercially available, however development work may be necessary to obtain mine safety certification for some of it. Wherever possible, fixed installation methods consisting of amplifiers and coaxial cable will be used to connect surveillance cameras to switching centers, since this technology is mature and well-proven. In some cases, it may be necessary to create wireless connections between a camera and the network. Specific examples include cameras attached to the shearer and to the liner placement equipment. However small transmitters are readily available for this purpose. These will be used to create an analog radio data link between the camera and the hardwire network. Such links will be confined to relatively short range, due to the line-of-sight nature of the radio signals at high frequencies, and to the large amount of metal equipment surrounding the mining area.

Persons in both the headgate operator's station and in the main control center above ground will be able to view several channels simultaneously, to choose among cameras to view, and to control camera and peripheral equipment settings such as lighting, focus, and where necessary the orientation of the camera. All of the switching and control systems for the remote monitoring task are readily available as mature technology.

### 8.3.3 VOICE COMMUNICATIONS SUBSYSTEM (VOCS)

The VOCS will contain both physical and radio transmission links to allow miners the maximum degree of mobility in the cluttered environment. Each miner will wear a headset with an earpiece and microphone connected to a transceiver on the belt. The same problems mentioned with the video and mobile data communications will be experienced by the VOCS. During normal operations, there will be no people in the face area except for operators at the headgate. However, during maintenance or repair activities, people will be required in the conveyor area and/or in the liner placement area. These areas are very confined and extremely noisy during mining or backfilling operations.

The basic communication problem is no different from those for the video and data networks described above, and can be handled using commercially available equipment. However there are some additional constraints for the voice systems which merit mentioning here. In general, people should not be in the face area during operations; however it is necessary to have a communications system which can function properly if a miner should be forced into the situation of working near the shearer or backstowing systems while they are operating. High noise and dust levels generated by the machinery will require that special measures be taken. We recommend the use of microphones which strap to the miner's throat and pick up vocal signals directly from the larynx. This system would avoid the inconvenience of a standard headset mike in front of the miner's mouth, which could be a nuisance when working in confined spaces. The throat mike would also allow the miner to maintain communications while wearing a filter mask or self-contained breathing apparatus (SCBA). In addition, the system should be equipped with noise cancellation circuitry for filtering out background noise. Such equipment has been developed for military use and could be adapted to this application.

## 8.4 ANALYSIS AND EVALUATION

We do not believe that the development of adequate communications systems for the applications described above will constitute any major technological hurdles. As noted in Section 8.3, most of the communications tasks required by this application are already commercially available, at least in part. We believe that a significant development effort will be required to modify, adapt, and test some of the components of that equipment for use in the harsh and critical environment. However, we foresee no requirement for technological breakthroughs in the communications area.

In the Data Communications Subsystem, the basis for the system will be equipment already available for longwall mining, perhaps supplemented by networking equipment developed for factory floor usage. Due to the increased number of sensors and controls required by the target application, questions of processing power requirements will need to be resolved once more details of the sensor and control algorithm complexities are resolved. However, given the rapid and relentless advances in microprocessor technology, it is inconceivable that adequate processing speed will not be available if upgrades are in fact even required.

In the Video Communications Subsystem area, the situation is similar. Remote surveillance, teleoperation and transmission of video information over considerable distances is a very mature technology. Surveillance cameras are routinely used in a wide variety of hostile environments ranging from mines to pipes and boreholes to steel mills. Surveillance cameras are routinely hardened against extreme heat, shock, vibration, moisture and corrosive agents. Again, some development work will be required to insure reliability, convenience and data integrity, but no major technological barriers are foreseen at this juncture.

Finally, the Voice Communications Subsystem may present the greatest need for developmental work and experimentation, but again we see no insurmountable obstacles. Hands-free headsets are commonplace technology, even in fast food restaurants. Headsets in helicopters and other noisy environments have been developed with noise cancellation circuitry to filter out even extreme levels of background noise. Cellular communications technologies have vastly improved the sophistication and reduced the size and weight of mobile communications equipment in recent years. Dozens of examples of reliable voice communications systems can be found already in existence. A fruitful area for research may be to investigate the enhancement of the VOCS by adding additional functionality to it. For example a locating beacon for a miner who was trapped, or lost might be incorporated as part of the system. However these ideas are enhancements, and not critical to the development of the basic VOCS.

## 8.5 SUMMARY AND CONCLUSIONS

This chapter has addressed the fundamental strategies for the multi-functional communications system. Final designs for these systems will be developed in Phase II. However, the requirements and available technology issues have been investigated in sufficient detail to draw some conclusions about the scope of the detailed design.

The communications system for the remote mining environment will actually consist of three distinct subsystems. A Voice Communications Subsystem will provide voice communications for all persons underground with each other and with the control center on the surface. This is a basic and critical safety feature. The Video Communications Subsystem will link the headgate operator and personnel in the surface control center with a network of surveillance cameras that can be used for monitoring, teleoperation or diagnostic purposes. This system will be instrumental in providing intelligence about the situation underground without the need for human presence in the dangerous mining area. The largest and most complex system will be the Data Communications Subsystem. This system will consist of multiple levels and will be the primary data acquisition and control network for the mining, materials handling, and liner placement/backfill operations. It will be based on existing longwall control system strategies with enhancements for the increased number of sensors and control actuators required by the barrier placement operations.

The vast majority of the equipment and software for all three of these systems is commercially available, well-proven equipment. The major work to develop the communications system will be to integrate the equipment and control software together, to customize items to fit the exact requirements for the proposed application and perhaps to enclose some equipment in explosion-proof enclosures. We foresee no significant technical hurdles in establishing a reliable communications system as described in this report.

# APPENDIX A

# Fuzzy Logic Controller for Variable Four-Bar Mechanism

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## Abstract

Heavy lifting and construction equipment makes widespread use of hydraulic actuators coupled to rigid links in a variety of configurations. In many cases, the mechanism is a simple prismatic or revolute joint and feedback control is straightforward. However in some cases, multiple hydraulic actuators and interconnected links may be used, creating more difficult control problems. Examples can be found in excavating equipment, cranes, articulated vehicles, and drilling equipment among others. Most of these applications require coordinated control of several actuators to achieve correct position/attitude/orientation of the equipment. At West Virginia University, we are working on an application of longwall mining methods to the problem of hazardous waste containment. This application requires stringent control of the position of each shield, including control of its orientation with respect to the face. The resulting mechanism can be modelled as two coupled four-bar linkages, each of which has two variable-length links. The problem is nonlinear and difficult to solve using conventional control techniques.

We have developed a shield position control system based on the use of Fuzzy Logic which is accurate, flexible and computationally much simpler than an equivalent controller using traditional methods. The controller is of general interest because the mechanism is similar to many other common applications requiring multi-actuator control. The controller was developed by combining a formal kinematic analysis of the mechanism with computer simulation of the closed loop system. This paper describes the problem, the approach taken to the development of the fuzzy rule set and the results of the simulation studies used to test the performance of the controller.

## I. Introduction

The roof support system on a longwall face consists of up to 200 individual shields, whose positions are controlled by programmable logic controllers (PLCs) and hydraulic cylinders linking them to the longwall conveyor system. However, at West Virginia University, we are applying longwall technology to the containment of buried hazardous materials. Details of this application can be found in [1,2]. The application imposes constraints on shield positioning which are considerably more stringent than those imposed by coal mining, leading to the need for an improved position control system for the shields. Specifically, it is necessary to control not only the position but the orientation of each shield, insuring alignment to within approximately one centimeter of translation error and one degree of orientation error.

In Europe, many of the coal seams lie at significant inclines. European roof support systems thus often include hydraulic cylinders coupling adjacent shields as a means of controlling lateral creep during face advance maneuvers [3]. This same configuration can be adapted for control of shield orientation with the development of an enhanced instrumentation and control logic package. This paper describes the development of such a system. We believe that the approach described here is not unique to mining systems but that it can be applied to other mechanisms in which prismatic links constitute part of a closed chain mechanism. Examples would be Stewart platforms, certain robot configurations and heavy construction equipment.

While the performance requirements for the control system are more severe than for conventional mining system controllers, it is desirable to use the same, rather low-tech hardware to effect the control. Most PLCs use 8 or 16-bit microcontrollers running at moderate clock speeds and are not set up for general purpose computing such as would be required by a control system based on the state variable approach. Even for more sophisticated computing systems, the nonlinear plant represented by the shield system would prove a challenging assignment. We have therefore incorporated fuzzy logic as a means of matching the complex plant model to a control strategy which requires minimal floating point computational power. The result is a simple, robust algorithm which is presented below.

## II. Mathematical formulation

The shield can be represented by the four-bar mechanism shown in Figure 1. The base of link 1 will be used as a reference point for the global coordinate system, and point 2 on the shield will be used as the reference point for the shield location. Because of the way the system is constructed, link 1 is constrained to be at an angle of 270° in the global coordinate frame. Thus the shield has only two degrees of freedom: y and $\theta$, where $\theta$ is the angle between the global coordinate frame and the shield coordinate frame. All angles are measured positive in the counterclockwise direction.

Numerous kinematics textbooks, for example [4], treat the problem of the four-bar linkage with one variable-length link. However, we have found no analyses of mechanisms with two or more variable-length links in the literature. We have formulated the kinematic equations in the standard fashion, by taking as the closed chain linkage 1-2-3-4-1. We define $r_i$ as the length of the link connecting point i with point i+1, and angle $\alpha_i$ as the angle between the global positive x axis and link i. For any closed chain, the following must be true:

$$\sum_{j=1}^{n} r_j e^{i\alpha_j} = 0 \qquad (1)$$

Expanding the exponential to sine and cosine terms and separating the x and y components, we obtain:

$$r_2\cos\alpha_2 + r_3\cos\alpha_3 + r_4\cos\alpha_4 = 0 \qquad (2)$$

$$-r_1 + r_2\sin\alpha_2 + r_3\sin\alpha_3 + r_4\sin\alpha_4 = 0 \qquad (3)$$

Equations (2) and (3) reflect the fact that $\alpha_1 = 270°$. We wish to control the position and orientation of the shield using the lengths of links 1 and 3 as the control inputs. Thus it is

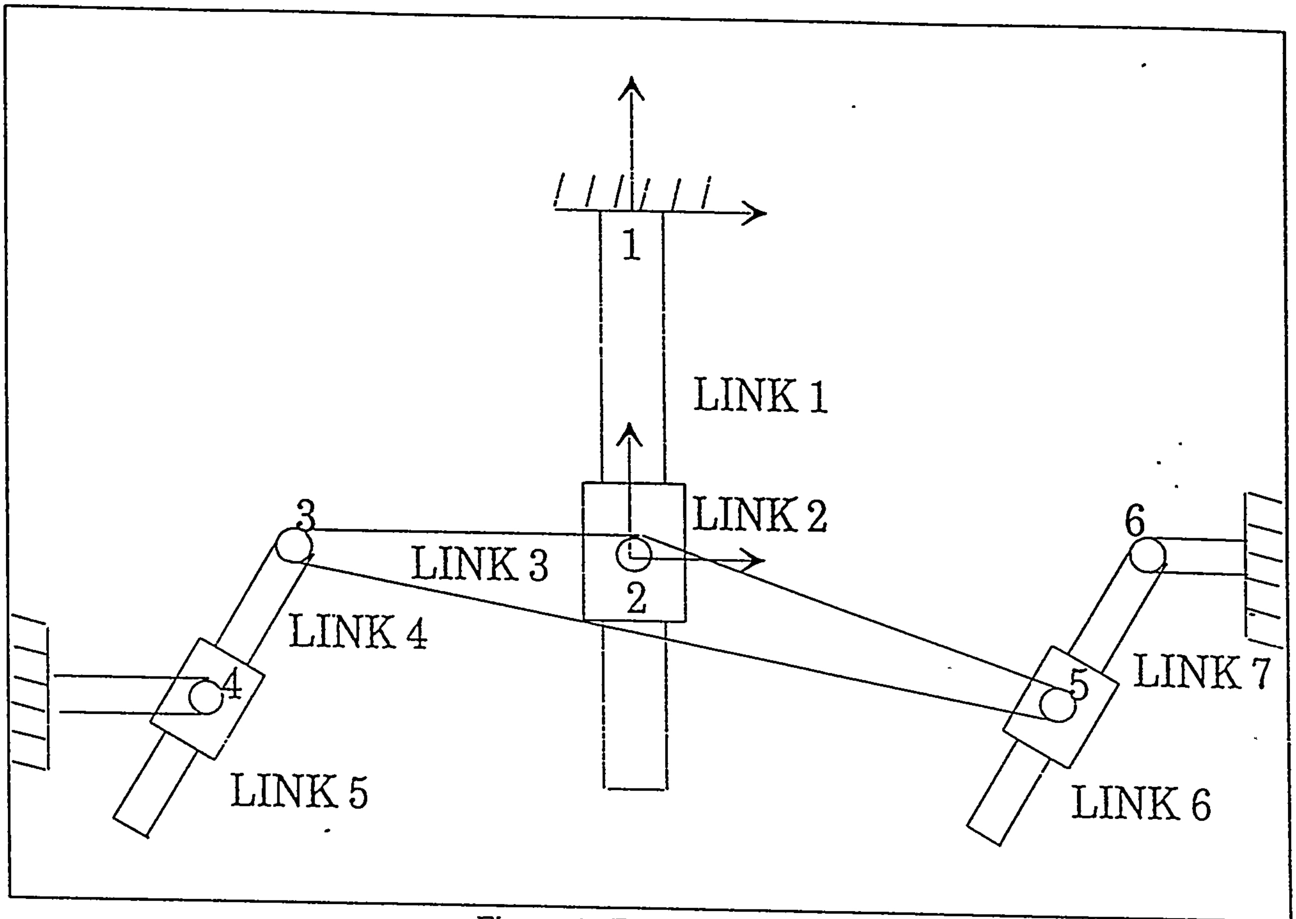


Figure 1: Four-Bar Model

necessary to determine the relationship between the control inputs and the plant outputs, i.e. the transfer function of the system. We generally approach this by attempting to find the differential change in the output resulting from differential inputs, i.e.

$$\Delta y = \frac{\partial y}{\partial r_1}\Delta r_1 + \frac{\partial y}{\partial r_3}\Delta r_3 \qquad (4)$$

$$\Delta \theta = \frac{\partial \theta}{\partial r_1}\Delta r_1 + \frac{\partial \theta}{\partial r_3}\Delta r_3 \qquad (5)$$

By inspection of Figure 1 it is clear that only $r_1$ controls the y position, so equation (4) becomes trivial. However, both $r_1$ and $r_3$ influence the orientation of link 2, i.e. the shield. From Figure 2 it can be seen that the angle $\alpha_3$ is critical in the formation of a control strategy, since as $\alpha_3$ passes through 180° the function relating changes in $r_3$ and changes in $\theta$ becomes singular. Analytical evaluation of equation (5) is intractible. A kinematic simulation of the shield mechanism was constructed and the derivative terms were evaluated numerically over the range of possible mechanism configurations. This information was used to construct the fuzzy rule set as described below.

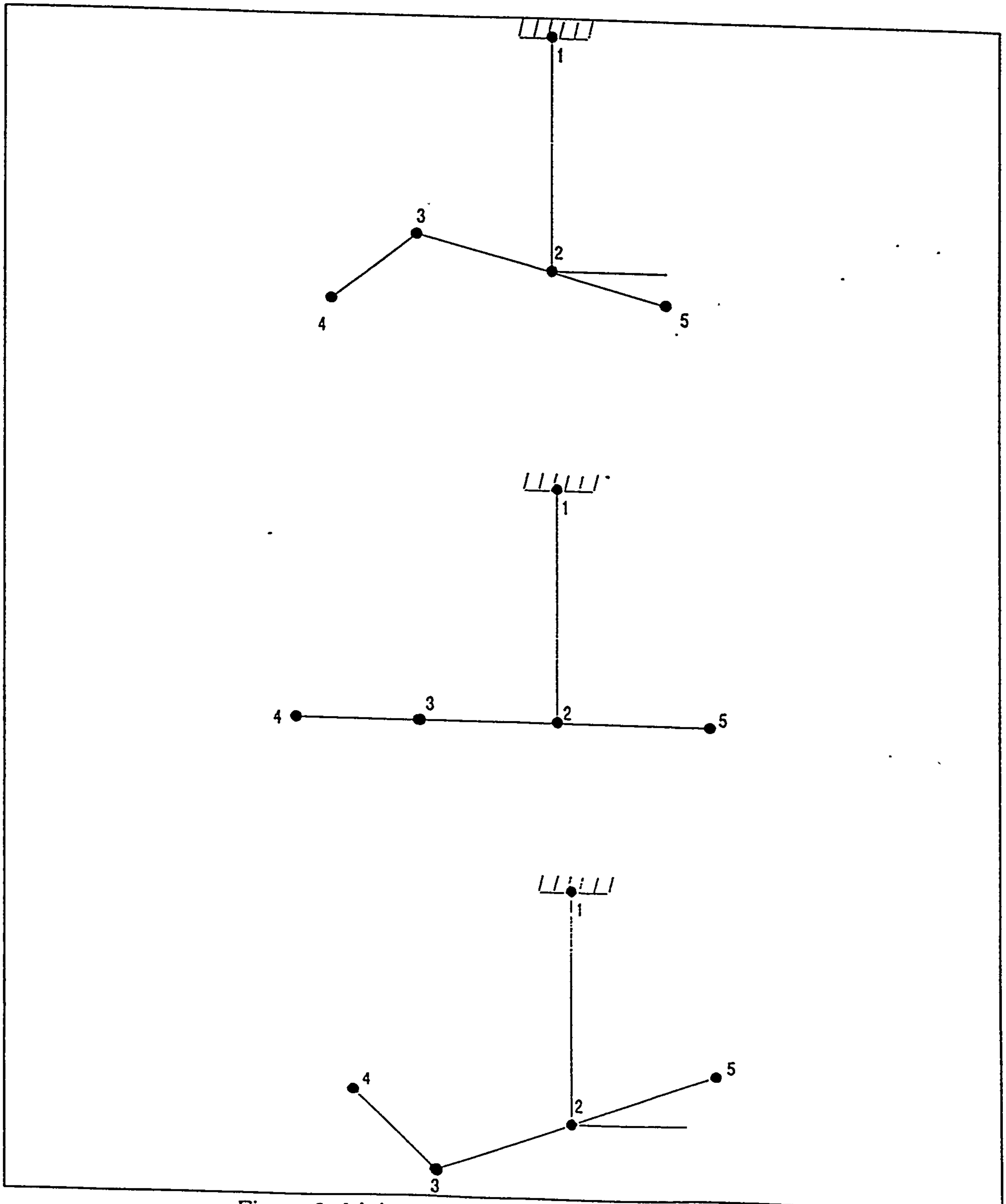


Figure 2: Linkage configurations--singularity in TF

## Fuzzy Controller

Fuzzy logic has been applied to a broad range of control problems involving nonlinear or imperfectly modeled dynamic systems, time-varying systems and noisy sensors. A few examples can be found in [5-8]. All of these conditions are present in the case at hand. As was explained in the introduction, it is also necessary to minimize the computational complexity of the controller. We have therefore chosen a fuzzy logic approach to the control system design.

We can define membership functions for both the input and outputs which transform the distinct sensor and actuator values into degrees of membership in various fuzzy sets. We wish to be able to drive the mechanism to any desired configuration in its range. Therefore we develop a regulator type of control which is driven by the error between the current position and the desired position. A block diagram of the system is shown in Figure 3.

Let us assume that only *reachable* states will be specified by the operator so that checking against hydraulic cylinder range limits is not required. We see then that two logical inputs are the errors $\varepsilon_y$ and $\varepsilon_\Theta$. However, since the plant is nonlinear, the controller must adapt for different locations in the configuration space of the linkage. Adaptation of the system is accomplished in the fuzzy controller by developing an appropriate rule set. The fuzzy rule set accomplishes the same function as gain scheduling or sliding mode control in conventional

| Yaw angle / Y Position | Large Positive | Positive | Zero | Negative | Large Negative |
|---|---|---|---|---|---|
| Large Positive | Large Negative | Negative | Negative | Negative | Large Negative |
| Positive | Large Negative | Negative | Negative | Negative | Large Negative |
| Zero | Large Positive | Positive | Zero | Negative | Large Negative |
| Negative | Large Positive | Positive | Positive | Positive | Large Positive |
| Large Negative | Large Positive | Positive | Positive | Positive | Large Positive |

Table 1 : Rule Set for Yaw Angle Control

control configurations. The rule set for control of the angle error is shown in Table 1.

Development of the membership functions for the input and output variables is straightforward. The error inputs were divided into five classes each: Large negative (LN), Negative (N), Zero (Z), Positive (P); and Large positive (LP). The fuzzy outputs for $dr_1$ and $dr_3$ are divided into the same five regions as the error inputs. The input and output membership functions are shown in Figure 4. Note that in this formulation, the control variables are not the hydraulic link lengths, but the *changes* in the link lengths.

Normally, hydraulic valves are on/off devices, making control of the cylinder motion rather limited. While cylinder speed could be accomplished by the use of proportional control valves on the hydraulic system we assume here a simpler technique. Since the fuzzy controller is not required to have uniform sampling periods, we propose to vary the cylinder motion by simply varying the "on" time for each valve. This system is less elegant than the proportional controller. It precludes the control of the exact trajectory followed by the mechanism in reaching its final state, since the relative speeds of the two cylinders cannot be coordinated. However in this application, trajectory control is not required--only the endpoint is important.

## Simulation

The controller was tested by computer simulation, conducted as follows. The kinematic model shown in Figure 1 was assigned dimensions, allowing the calculation of lengths for the fixed links and angles between the links for any configuration of the linkage. The hydraulic links were assigned maximum and minimum values, thus defining the configuration space of the mechanism. An initial position and a target position were input by the user. From the initial position data, the kinematic equations were solved to find the initial link lengths $r_1$ and $r_3$. The position error vector was also calculated and input to the fuzzy logic controller. The controller then output the desired change in the hydraulic link lengths. The kinematic equations were again invoked to find the new position, and the cycle was repeated until the position error was driven to zero.

## Results

Twenty four different starting positions were tested, corresponding to one in each of twenty four fuzzy regions of the input data. For example, an initial position was chosen which would correspond to the y error being Large Negative and the angle error being Large Positive, etc. All combinations were tested except the trivial case Zero, Zero. In all cases the mechanism was driven to the desired end position. Plots of a few representative cases are shown in Figures 5 and 6. The simulations showed the need for a dead band about zero to prevent oscillations in the angle error trajectory, but with this modification the fuzzy system performed admirably.

## Conclusions and Future Work

A first-generation fuzzy control system has been developed for the control of longwall mining shields which in simulation performs quite well. We are currently working on refinements to this system to improve its response. These refinements include some experimentation with the shapes of the membership functions and alteration of the inputs to determine if direct sensor inputs can be substituted for some of the processed data now used. For example, we currently process encoder inputs and hydraulic extension sensor inputs to calculate the position of the shield for comparison with the desired position. This calculation occurs at each time step. We are now reformulating the problem to calculate the desired endpoint configuration at the outset. We are interested to see if this initial calculation can be used in lieu of repeated floating point calculations to obtain a simpler control algorithm. Results of the evolution of this system will be reported in future publications.

## Acknowledgements

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Appendix II

Remote Mining for In Situ Waste Containment
DE-FC21-92MC29121

# Contents

# Tables

## Tables (Cont.)

## Figures

# Figures (Cont.)

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# 1.0 EXECUTIVE SUMMARY

Innovative liner technology for application to existing unlined hazardous waste facilities is presented. Research conducted to-date includes the investigation of various liner systems and installation considerations. The various components for this innovative hazardous waste containment system are presented and discussed.

A critical aspect in the development of the appropriate liner system for this challenging application is the installability by the remote miner. Qualitative analysis is presented regarding the suitability for application of prefabricated and in-situ formed barrier and leachate removal systems. Placement of natural and synthetic components of the liner system with several options for configuration of the leachate collection and removal system are presented. Perimeter containment strategies for lateral groundwater containment are presented in collaboration with the robotically placed liner system.

A general QA/QC plan for the establishment of performance guidelines for a site-compatible liner system is included. This overview QA/QC plan incorporates several minimum key elements developed for the hazardous waste containment at a robotically mined waste site. Comprehensive technical specifications are developed which stipulate the material and installation requirements for the preferred containment system.

# 2.0 LINER SYSTEM CONFIGURATION

Proposed main components of the hazardous waste containment system for installation by the robotic miner are shown in Figure 2.1. In general, the configuration of these components meet the RCRA requirements for surface installed waste containment systems. Components of the proposed containment system can be described as follows:

1) processed spoil backfill material,

2) leachate collection system and upper liner protective layer,

3) primary hydraulic barrier, and,

4) lower liner protective layer and secondary hydraulic barrier.

Possible configuration of the different component are discussed in more details as follows:

## 2.1 Processed Spoil Backfill Material

This layer of the containment system utilizes previously mined material as a filler medium for the mined seam. The primary purpose of this filler material is to minimize the severity of mine roof collapse and subsequent mine subsidence.

The backfill material will be available through the utilization of previously mined spoil. This mine spoil is transported to the mine surface and processed into specified gradation then transported back for placement by the robotic miner. The processed mine spoil will be evaluated for use as backfill based on the material's physical and engineering characteristics.

## 2.2 Leachate Collection System and Upper Protective Layer

The requirements of this layer are:

1) provide a leachate collection system to function as a high hydraulic conductivity layer, and.

2) protect the primary liner system from damage during installation by the robotic miner.

The leachate collection layer will utilize an engineered material specific for the mined site. Possible leachate collection media include natural inert coarse grained sand or crushed stone materials. and/or high density synthetic geonet drainage layer.

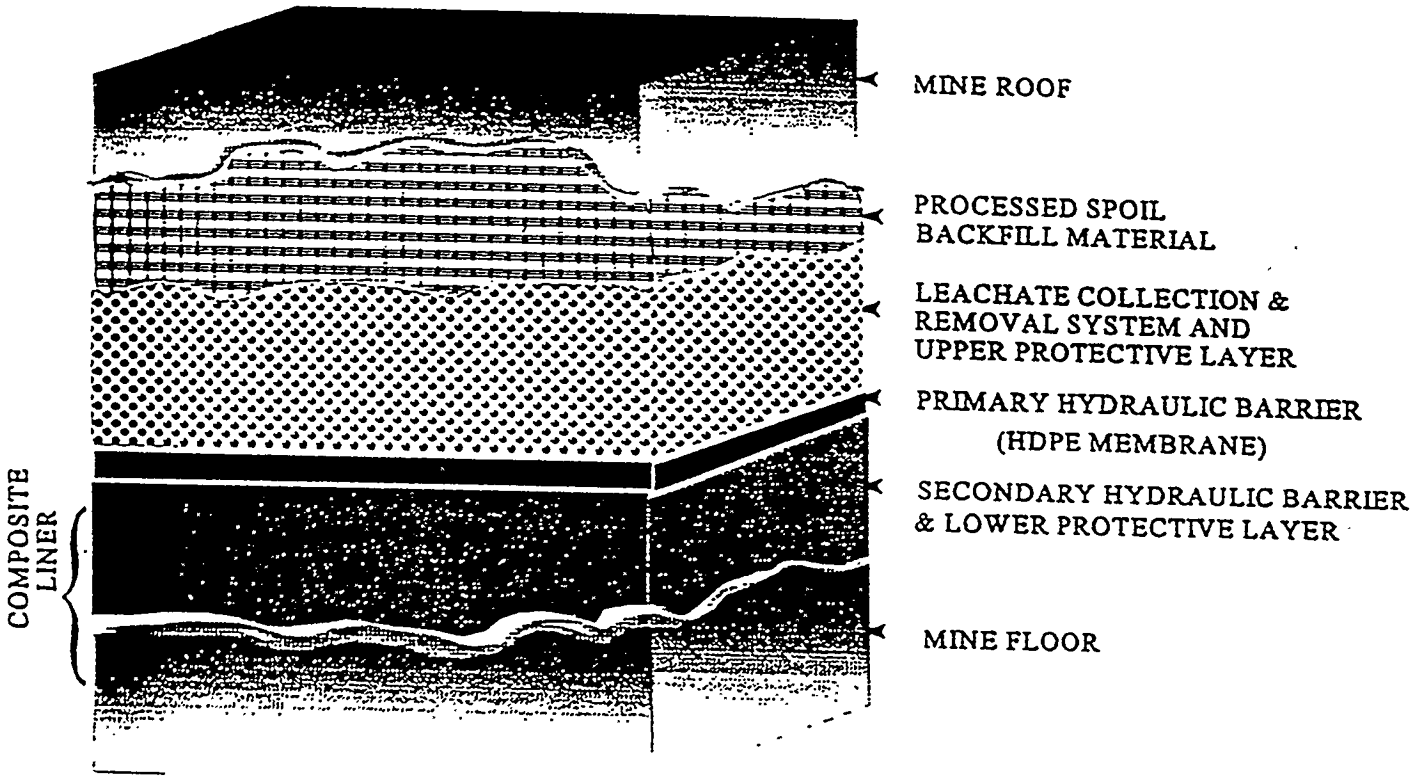



Figure 2.1
Main Components

The secondary function of this layer is to provide protection for the primary hydraulic barrier from damage caused by the mining equipment during placement. In addition, this layer will serve to protect the primary liner from damage that may be caused by mine roof collapse.

2.3 Primary Hydraulic Barrier

The primary hydraulic barrier is singularly the most important component of the waste containment system. There are several possible configuration for the liner component. Most commonly, this liner component is manufactured from high density polyethylene (HDPE) that is placed in individual layers. The HDPE liner is characteristically and virtually chemically impervious and, with no defects or installation damages, provides a low hydraulic conductivity on the order of $1.0 \times 10^{-12}$ cm/s.

2.4 Secondary Hydraulic Barrier and Lower Protective Layer

This component layer serves two functions. The first function is a secondary hydraulic barrier to contaminant transport. This liner acts as backup to the primary layer. The secondary layer retards the migration of contaminants that escapes through the primary liner system. A secondary function of this layer is to protect the primary liner from puncture damage caused by irregularities the mine floor.

Two feasible options for the underground waste containment system utilizing these basic components have been developed and are discussed in further detail in Section 7.0, Selection of Liner types.

# 3.0 EVALUATION OF PREFABRICATED SYNTHETIC LINER SYSTEMS

## 3.1 GEOSYNTHETIC LINER COMPONENTS

The main components of the liner system are the hydraulic barrier and the leachate collection system. Prefabricated synthetic materials commonly used in the construction of hydraulic barriers include geomembranes and geosynthetic clay liners (GCL). The leachate collection systems can be constructed from geonets with using geotextiles for separation and filtration. Geomembrane and/or GCL materials are the key hydraulic barrier elements within the liner system.

The geomembrane, made from polyethylene polymers, is manufactured through a melting and extrusion process. The finished product can have either smooth surface or textured surface to increase the interface friction properties. Based on the molecular weight of the polymer resin used in the manufacturing process, the geomembranes can be classified as:

1) High density polyethylene (HDPE) membranes with a specific gravity greater than 0.935 and,

2) Very low density polyethylene (VLDPE) membranes with specific gravity between 0.89 and 0.91.

The VLDPE membrane has the advantage of flexibility and will allow excessive differential movements. However, the tensile strength at yield and break is lower than the HDPE membrane. Typical applications for VLDPE membranes are in landfill closure caps where significant differential movements may occur. In practice, HDPE membranes are frequently used for construction of liner systems.

The geocomposite membranes represent the state-of-practice in liner system construction. A geocomposite consists of bentonite clay particles that are attached to HDPE membrane at an application rate of 1 pound per square foot. The GCL with bentonite is installed dry. When the bentonite is wetted it hydrates and swells.

Gundle, the industrial partner for this project, manufactures both HDPE membranes and HDPE/bentonite GCL's. Gundle's trade name for HDPE membranes is HDT© and for GCL's is Gunseal©. Discussion in this report and concept development is based on products manufactured by the Gundle Lining Company.

## 3.2 DELIVERY AND INSTALLATION

The HDPE and geocomposite membranes are delivered to the site in the form of rolls on 6" diameters hollow cores. Each roll is fitted with two slings for ease of handling. Typical dimensions and weight of rolls are listed in Table 3.1 for the HDPE membrane and in Table 3.2 for the GCL's.

In case of the HDPE membrane the strength properties including, tensile strength, tear resistance, and puncture resistance increase as a function of thickness. In the case of the GCL, different HDPE thicknesses can be used as a backing for the bentonite material to increase the strength performance. Presently, a 20 mil HDPE membrane is used. It was indicated by Gundle that manufacturing of GCL's with widths less than that specified in Table 2 and HDPE thicknesses greater than 20 mil is possible, if warranted.

Table 3.1
Prefabricated HDPE Membranes
Roll Dimensions and Weight

| Nominal Thickness mils (mm) | Width (ft) | | Length (ft) | Weight (lb) | |
|---|---|---|---|---|---|
| | | | | 22.5' Length | 34.5' Length |
| 30 (0.75) | 22.5 | 34.5 | 840 | 2800 | 4400 |
| 40 (1.0) | 22.5 | 34.5 | 650 | 2800 | 4400 |
| 50 (1.25) | 22.5 | 34.5 | 500 | 2800 | 4400 |
| 60 (1.5) | 22.5 | 34.5 | 420 | 2800 | 4400 |
| 80 (1.5) | 22.5 | 34.5 | 320 | 2800 | 4400 |
| 100 (1.5) | 22.5 | 34.5 | 250 | 2800 | 4400 |
| 120 (2.0) | 22.5 | NA | 210 | 2800 | NA |
| 140 (2.5) | 22.5 | NA | 180 | 2800 | NA |

Table 3.2
Prefabricated Gundle GCL
Roll Dimensions and Weight

| HDPE Membrane Backing | Coating | Width (ft) | Length (ft) | Weight (lb) |
|---|---|---|---|---|
| 20 mil | Sodium Bentonite<br>1 lb per square foot | 17.5 | 200 | 3950 |

## 3.3 INSTALLATION AND SEAMING

The geomembranes and GCL's are installed in panel form with seaming at the ends of two adjacent panels. Field panels are usually placed one at a time. Installation of the geomembranes and/or GCL's requires a smooth subgrade with no sharp stones or hard protruding objects. In addition, the surface should be free of abrupt breaks in grade or sharp changes in elevations. Care should be taken during unrolling of the panels to avoid scratches or crimps in the membrane material.

Once the membranes are installed, placement of backfill on the membrane should be performed to prevent wrinkling. Placement of backfill should not be performed through lateral spreading or pushing.

### SEAMING OF HDPE MEMBRANES

The installed HDPE field panels should be rigorously seamed to avoid leakage at the joints. Field joints are seamed using two methods discussed below:

1) Hot Wedge Welding: the hot wedge system is the primary seaming system for installation. It is used for seaming the joints between adjacent panels. Sheets are overlapped a minimum of 4 inches and a self-propelled welder is used to draw a hot wedge between the overlapped sheets. The hot wedge lifts the two sheets to be welded and fusion is imposed by compressing the two melted surfaces together at a pressure of approximately 100 psi. Figure 3.1 shows an illustration of typical hot wedge detail. In above-ground applications and under favorable conditions, Gundle's hot wedge welder can seam sheet thicknesses that range from 20 mil to 140 mil with a production rate of 15 feet per minute.

2) Extrusion Welding: this type of seaming is commonly used for detail work such as seaming pipe sleeves and patching repair of defective areas or areas where "coupons" for QA/QC testing are obtained. In this case adjacent sheets are overlapped a minimum of 3 inches, as shown in Figure 3.1. An extrusion welding gun is used to stir molten HDPE material into the seam. The welded membrane is also temporarily bonded using hot air track weld to allow for the cool down of the extrusion weld bead.

Nondestructive testing is commonly used to test the integrity of welds. In addition, destructive testing is usually conducted for hot wedge and extrusion welds according to a specified QA/QC plan. Description of the different types of tests for the seams is as follows:

<u>Nondestructive Testing:</u>

Nondestructive testing is conducted in the field to check the integrity of the finished welds. Based on the weld type the tests can be either:

1) Air pressure testing for hot wedge welds: in this case air pressure is applied into the air channel created by the hot wedge welding process. Air pressure is applied using an air pump with the pressure magnitude varying based on the thickness of the seamed membrane. The pressure is maintained for 5 minutes with the maximum allowable pressure drop being 3 psi for a successful seam.

2) Vacuum Testing for extrusion and hot wedge welds: in this case a soap solution is sprayed on the seams. A vacuum box is place on the top of the test area and 5 psi vacuum pressure is applied. Visual inspection is used to detect areas of defected seams.

<u>Destructive Testing:</u>

Samples, referred to as coupons, are cut from the welded seams and are subjected to shear testing according to the ASTM D638 procedure and to a peel test according to the ASTM D413 procedure. The test results are interpreted in terms of Film Tear Bond (FTB) criterion. The seam passes the test if the upper and lower sheet separate by tearing rather than weld separation.

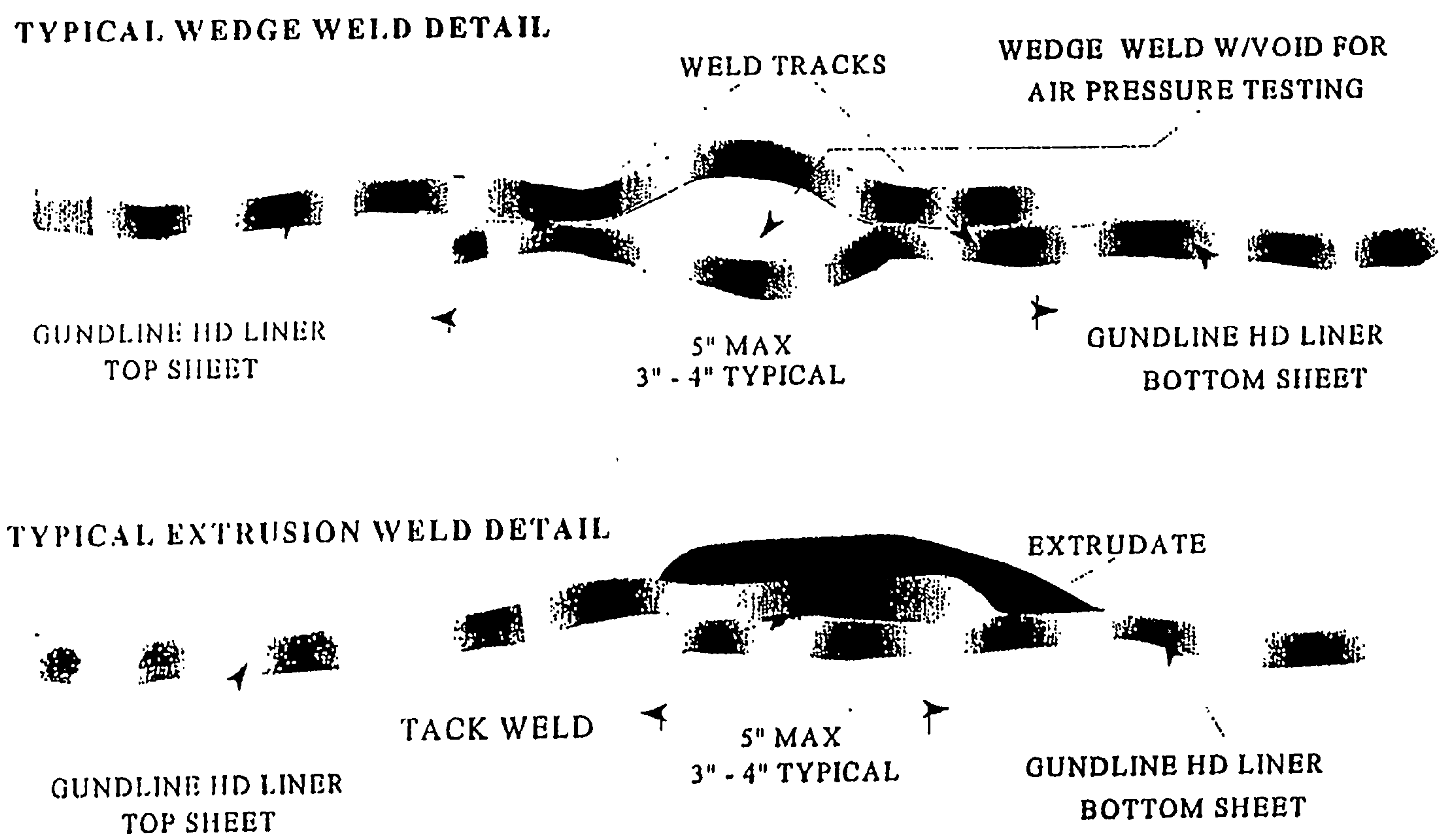



Figure 3.1
Typical Details for Hot Wedge Seam
and Extrusion Seam (After Gundle)

### 3.3.2 SEAMING OF THE GCL (GUNDSEAL)

In this case seaming is accomplished by overlapping the adjacent sheets a distance of 4 to 6 inches. In case of a leak, contact with a polar fluid will cause the bentonite to swell and form a low permeability seam. A study conducted by University of Texas (Estornell & Daniel, 1992) indicated that a four inch overlap of Gundseal is equivalent to approximately 33 feet of $1x10^{-7}$ cm/sec clay layer. Figure 3.2 shows a typical seam configuration using Gundseal.

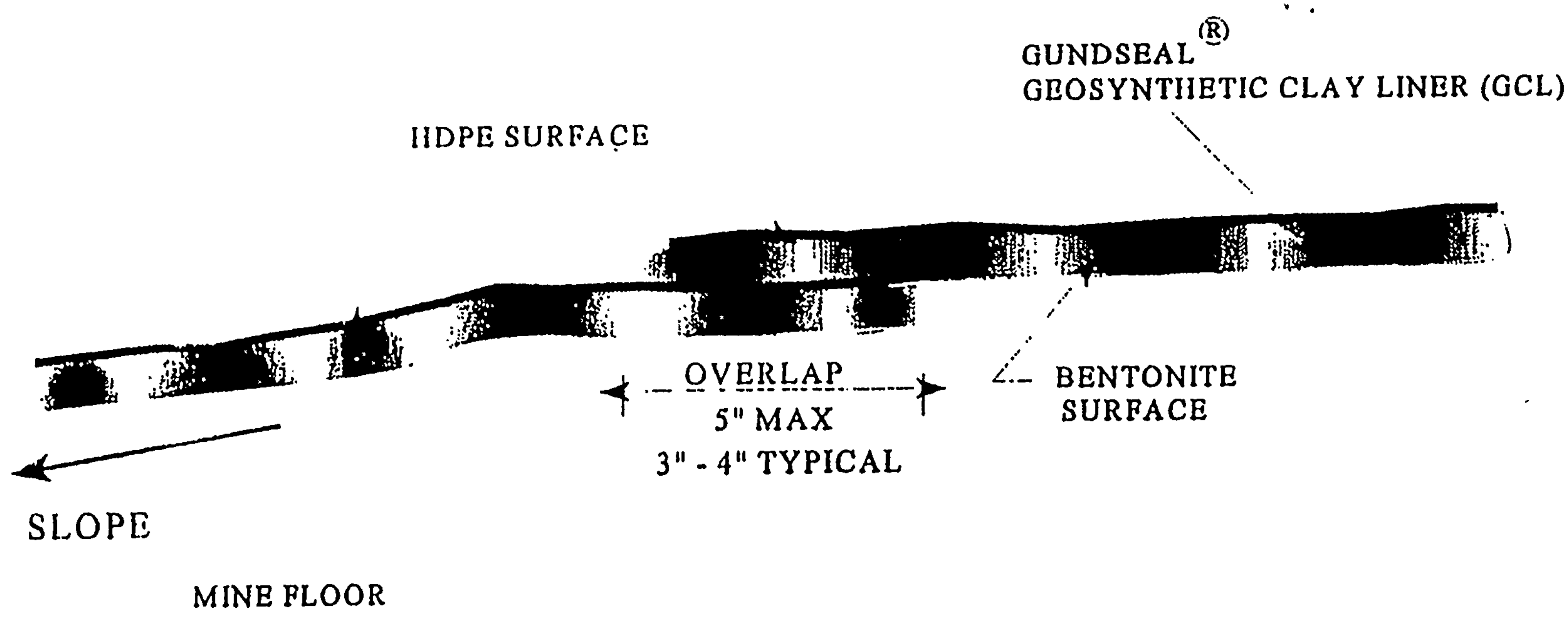



**Figure 3.2**
**Gundseal Overlap Seam**

# 4.0 EVALUATION OF IN SITU FORMED LINERS

Actual formation of a synthetic liner underground in a mine situation has several advantages when compared with installing a synthetic liner which has been manufactured and transported to a site. These include ease of material handling and continuity of the liner when installed. Against these advantages one must weigh several disadvantages including process development and quality control of the installed synthetic liner. The advantages and disadvantages of the in situ-formed liner are given in Table 4.1.

Table 4.1
Considerations for an In situ-Formed Synthetic Liner

| CONSIDERATION | COMMENTS | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| Mat'l Handling | Raw Mat'l Feed Through Tubing to Mine Face | Small Mine Development Shafts, Can Be Feed Through Boreholes to Mfg Process at Mine Face | In situ QA/QC on resign material to be used in liner mixes. |
| Seaming | Mat'l Supply Would be Continuous | No Seams for a Continuous Process | Interrupted Mat'l Supply or Mining Progress Could Result in Cold Seams |
| Mfg Process | Liner forming process to be installed at the mining face. | | No HDPE Technology Can Operate in This Environment Currently |
| Quality Control | Must Determine Index Properties of the Synthetic Liner Underground | | Liner Thickness, Constituent Composition, Strength, Durability and Hydraulic Properties will be Very Difficult to Measure and Control |

After discussions with engineers from Gundle Lining Company, viewing the HDPE manufacturing process and examining information from other manufacturers it can be concluded that the current process is extremely complex and sensitive to minor variations in conditions. The forming environment including ambient temperature, humidity and dust; minor variation in synthetic constituent content; and variation in physical stresses or strains on the material during the process can have severe deleterious effects on the resulting material. These factors are difficult to control in the current manufacturing practice and may possibly be terminal if found within the mining environment.

Given the foregoing discussion, it is anticipated that in situ-formed synthetic liners are not at a stage of development in which they could be readily adapted to the robotic mining process. Major modifications to the manufacturing process would have to be accomplished to accommodate this technique. It is unlikely that such modifications will be made within the next several years in the synthetics industry. As such, in situ-formed synthetics are deemed not to be the target liner process for this project at this time. Engineers at Gundle are preparing additional information with respect to their position on use of in situ-formed liners.

# 5.0 EVALUATION OF NATURAL LINERS

The liner system is composed of several components as shown in Figure 2.1. Principal components include the hydraulic barrier, the leachate collection system and protective layers. In many surface impoundment or landfill applications, these layers are fabricated from natural earth materials. Such materials might include clay for the hydraulic barrier, sand or crushed rock for the leachate collection system and sand or other finely-sized materials to be used as a protective layer above and sometimes below the barrier. For the case of robotically mined and installed in situ liners, it could be beneficial to utilize the mined spoil to construct some or all of the liner components. An advantage of this technique is that there would be a significant reduction in the volume of mine spoil that would be transported to the surface from where it would have to be disposed. Following is a summary of the details, requirements and concerns regarding the use of natural materials for the liner system components.

The performance requirements, production processes and comments regarding individual components of the natural liner system are presented in Table 5.1. The performance requirements apply regardless of the type of spoil material being mined. The processes listed are generic; however, the actual techniques might vary depending on the type of spoil material, e.g., a highly fractured, broken sandstone may require minimal crushing for use in a leachate collection system (LCS) whereas an intact sandstone might require multiple crushing-screening operations before it is suitable for LCS application.

Table 5.1
Requirements and Processes of Components
for a Natural Liners System

| COMPONENT | REQUIREMENTS | PROCESSES | COMMENTS |
|---|---|---|---|
| Hydraulic Barrier | Hydr. Cond. < $10^{-7}$ cm/s, Must Be Compatible With Expected Leachate | Crushing/Screening, Addition of Admixtures and Stabilizers, Mixtures are Typically Compacted Into Place | Handling/Transport, Must obtain Complete Mixing of Admixture, Must provide Compaction Control, |
| Leachate Collection System | Hydr. Cond. > $10^{-2}$ cm/s, Must Be Durable and Not Degrade With Time | Crushing/Screening | Handling, Placement Control will be Difficult |
| Protective Layer | Low Puncture Potential, High Durability, High Strength | Crushing/Screening, Placement | Must Provide Smooth Working Surface |

In the case of in situ containment systems, the material removed during mining or spoil, may range from unconsolidated soil to high strength, intact rock. The different spoil types are more aptly suited toward particular liner components. Hard rock, when crushed can function well in a LCS provided that the fines have been removed and the rock is not weatherable nor reactive with the leachate. Hard rock is not a likely candidate for the barrier or protective layer. Fractured, but stable rock (non-weatherable) when sized at approximately 0.5 to 25 mm can function as the LCS. Unconsolidated clays or pulverized shales can be manufactured into suitable low hydraulic conductivity barriers.

Each type of spoil material and their associated liner component application requires at least some, and in many cases substantial, processing prior to being transported and placed in the particular application. Transporting the materials to the surface for processing and then back into the mine for placement is deemed unmanageable and prohibitively costly. As such, processing facilities would have to be installed underground. Such processing, while occasionally performed for surface applications, has not been attempted underground on such scale as required here.

Placement techniques of processed spoil for the various components is likely to be different. The protective layer and possibly the LCS materials could be placed pneumatically or hydraulically; however, the hydraulic barrier requires low hydraulic conductivity. The value of $1 \times 10^{-7}$ cm/s or less can only be routinely obtained when mixtures containing adequate amounts of clay are compacted to attain high densities. Such compaction and resulting hydraulic conductivities are difficult to attain for surface facilities under optimal conditions and high level quality control. In the underground environment, attaining such control is not likely thereby making it difficult to construct an acceptable hydraulic barrier.

# 6.0 LEACHATE COLLECTION AND REMOVAL SYSTEM

The function of the Leachate Collection and Removal system (LCS) is to eliminate excessive leaks and possible liner damage caused by the build-up of leachate head pressures. The LCS is intended to be placed over the entire liner surface area. Figure 6.1 shows three main components of the LCS system.

The following paragraphs discuss specific aspects of the LCS layer which affect the system's overall performance and long-term efficiency. These aspects should be incorporated into the site specific LCS design.

## 6.1 INSPECTION EFFORTS

Preconstruction: Preconstruction activities include inspection of all material components of the LCS and inspection of the LCS foundation using remote video and inspection equipment.

Material inspection: All components of the LCS should be inspected as they are delivered to the site. Observations should be made to ensure that the components meet the design specifications.

## 6.2 CONSTRUCTION

Foundation preparation: The LCS will be placed directly on top of the primary hydraulic barrier layer(s). The top layer should be free from debris that could affect the construction and subsequent function of the LCS. This would require that the layer(s) underlying the LCS be kept on their specified slopes and free of mined debris.

Bedding layer placement: The LCS will be placed directly on the Flexible Membrane Liner (FML) or optionally on a protective layer of geotextile. Installation must be monitored to ensure that no component of the LCS is damaged and the installation does not damage the underlying containment layers.

Pipe network installation: The LCS collection piping should consist of a single pipe as a minimum, or optimally multiple pipes, to be placed in the sump at the bottom of the mined slope (Figure 3.1). The pipes must be placed as specified to promote the removal of leachate from the sump. Pipes should be inspected to ensure that they are properly connected and aligned in accordance with the system installation procedures. The pipes must be free of any mined debris that would inhibit the flow of leachate from the sump. The pipes must be adequately protected to ensure that they are not damaged during backfilling or roof collapse.

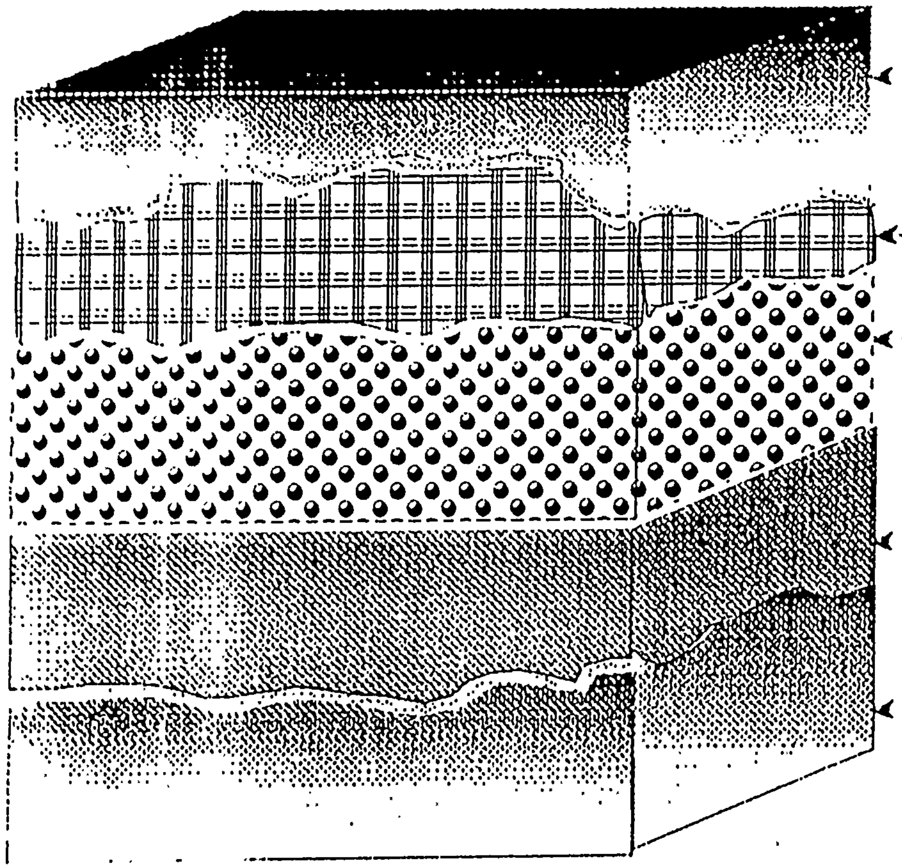



Figure 6.1
Leachate Collection & Removal System
Main Components

## 6.3 DRAINAGE LAYER PLACEMENT

The drainage layer should be constructed of one or a composite of the following materials: granular backfill, processed mine debris, and/or geosynthetic materials. Options for the LCS are shown in Figure 6.2. The specific use of each material is described more fully in the following subsections. All materials should be inspected to ensure conformance with the specified design requirements. The LCS materials must be placed on the proper grades and kept free of fines and organic materials.

Granular Backfill: A granular drainage layer should consist of sand, gravel, or both. The material must be clean, inorganic, non-reactive, and have good drainage properties. It should be tested to ensure that prolonged exposure to leachate will not alter its properties.

Processed mine spoil: One option is to use the mined material as a granular backfill. The material should be tested to ensure that it meets all of the above requirements for granular backfill. In addition, mined material must be processed. This would include crushing the material to a specified size and washing the material to remove excessive fines that could inhibit proper LCS performance. If the mined material is contaminated special precautions must be taken to avoid contaminant migration beyond the site.

Synthetic drainage layers: Geonets, geomats, or geotextile fabrics could serve as drainage layers. They can be used alone or in combination with granular material. The synthetic must be tested to ensure that it will not react with the leachate or be degraded by prolonged exposure to the leachate. Synthetic materials must be inspected to ensure that they are of the proper type and thickness specified. They should be inspected to ensure that they have not been damaged during shipping and must be carefully placed to prevent damage during installation.

| OPTION-1 | OPTION-2 | OPTION-3 |
| --- | --- | --- |
| ***ADVANTAGES***<br>● Geonet properties known<br>● High quality control<br>● Liner seams less critical<br>● Thin layer gives same capacity | ***ADVANTAGES***<br>● Uses mined material<br>● Bulk placement possible<br>● Thick LCS possible<br>● Reduces impact from roof collapse | ***ADVANTAGES***<br>● Bulk placement possible<br>● Thick LCS possible<br>● Reduces impact from roof collapse |
| ***DISADVANTAGES***<br>● More likely to puncture<br>● Geonet may be crushed causing clogging<br>● Multiple layers to place | ***DISADVANTAGES***<br>● Unknown spoil properties<br>● Material must be processed<br>● Contaminated material handling<br>● Damage to liner likely | ***DISADVANTAGES***<br>● Damage to liner likely |

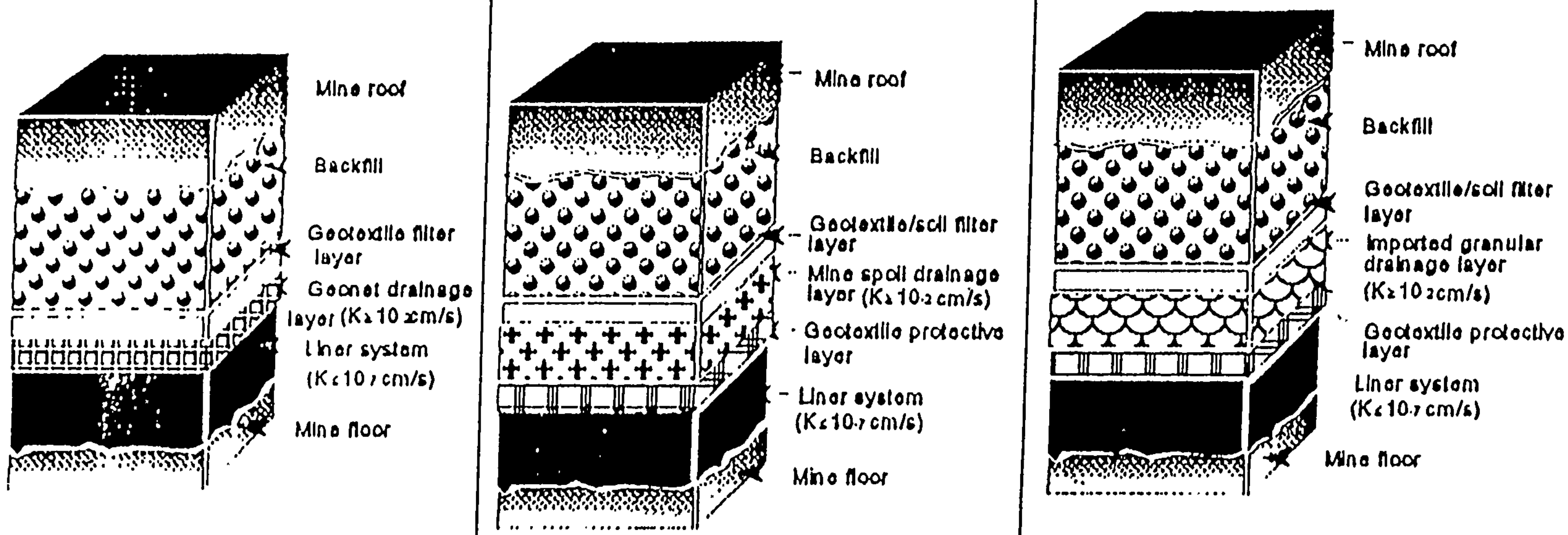



Figure 6.2
Leachate Collection and Removal System Options

## 6.4 FILTER SYSTEMS

A filter layer is required to protect the drainage layer and pipe network from the intrusion and accumulation of fines and organics. Filter layers can be constructed from synthetic material or granular soil.

Soil filter layers: A soil filter that will not permit the intrusion of the filtered material can be used if the drainage layer is constructed using a graded granular material. The filter soil should also be tested to ensure that it is free of fines or organic materials and that prolonged exposure to the leachate will not alter its properties.

Synthetic filter layers: Geotextile filters can be used with either synthetic or granular drainage layers. They should be inspected for damage during shipping and should be placed as specified to prevent damage during installation. They should meet all design criteria including apparent opening size (AOS), tensile strength, and permittivity. They should be inspected to ensure that they will not be degraded by prolonged exposure to leachate.

Any LCS system must be constructed with multiple avenues for leachate access to the LCS. Failure of a single access system could lead to failure of the entire containment system.

## 6.5 SUMPS AND ASSOCIATED STRUCTURE INSTALLATION

The choice of precast structures or cast-in-place structures is site specific. All concrete structures should be tested to ensure that they will not be damaged by leachate. The use of precast HDPE units should be maximized where possible.

Mechanical and electrical equipment installation: One of the final activities in the construction of the LCS is the installation of the pumps, valves, motors, liquid-level monitors, and flowmeters. The equipment must be functioning properly to detect and prevent an excess head above the FML. The maximum head allowed by EPA in a landfill application is 1 foot (30 cm). A similar guideline is applicable to this system.

# 7.0 SELECTION OF LINER TYPES

Selection of the groundwater liner types for underground application are based on the component system requirements discussed in Section 2.0 - Liner System Configuration. Two containment options, Option 1 and Option 2, have been developed from design iterations and installation scenarios. These options are shown in Figures 7.1 and 7.2. The components used in each of these options are discussed in detail in the following report sections.

## 7.1 OPTION METHOD 1

Figure 7.1 shows containment system Option 1. The components of this option are:

1) processed backfill spoil material,
2) geonet HDPE leachate collection system with upper geotextile protective layer,
3) primary HDPE hydraulic barrier, and
4) secondary bentonite clay liner incorporated onto bottom surface of the primary layer.

The associated advantages and disadvantages of this option are listed in Table 7.1.

Table 7.1
Option 1 Comparison

| Advantages | Disadvantages |
|---|---|
| all material is placed from rolls by the robotic miner, | thin liner layers are more susceptible to punctures |
| high construction quality assurance and quality control on materials and placement | leachate system is susceptible to clogging |
| seaming of the geosynthetic clay liner is less critical | |
| utilization of multiple geosynthetic clay liner layers for adaptability to site specific variations | |
| thin containment cross section | |

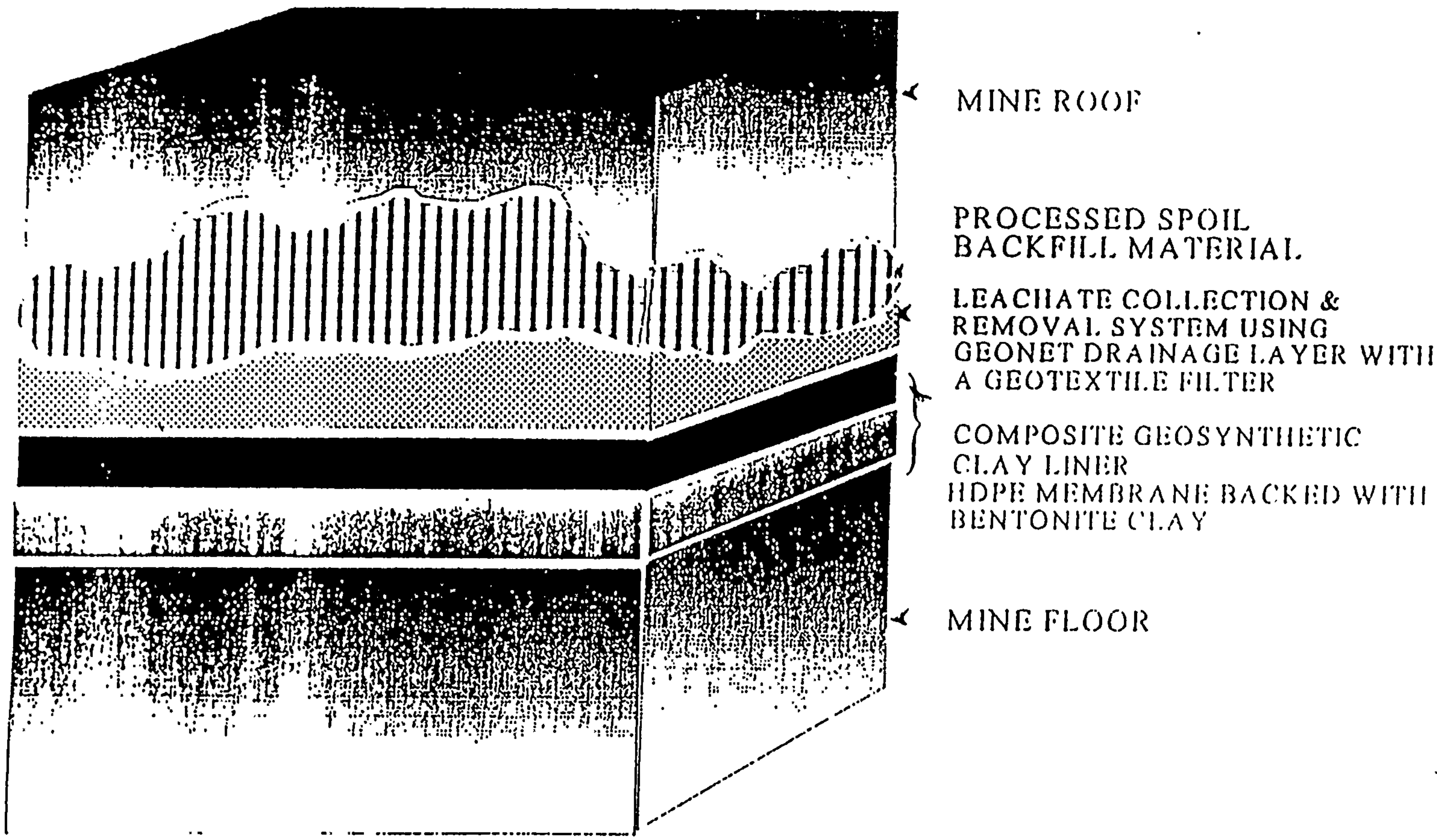



**Figure 7.1**
**Option 1**
**Synthetic Material Containment System**

## 7.2 OPTION METHOD 2

Figure 7.2 shows containment system Option 2. The components of this option are:

1) processed backfill spoil material,

2) high permeability leachate collection system utilizing natural materials, e.g., sand, crushed stone or mine spoil,

3) primary HDPE hydraulic barrier with overlapped seams,

4) secondary liner constructed using well graded processed mine spoil with a bentonite clay admixture.

The associated advantages and disadvantages of this option are listed in Table 7.2.

Table 7.2
Option 2 Comparison

| Advantages | Disadvantages |
|---|---|
| utilizes mine spoil materials | mined spoil materials may not be suitable. e.g., shale degradation would clog leachate collection system |
| bulk material placement possible | spoil processing and placement is a major cost |
| thick leachate collection system and liner system | contaminated mine spoils difficult and expensive to handle |

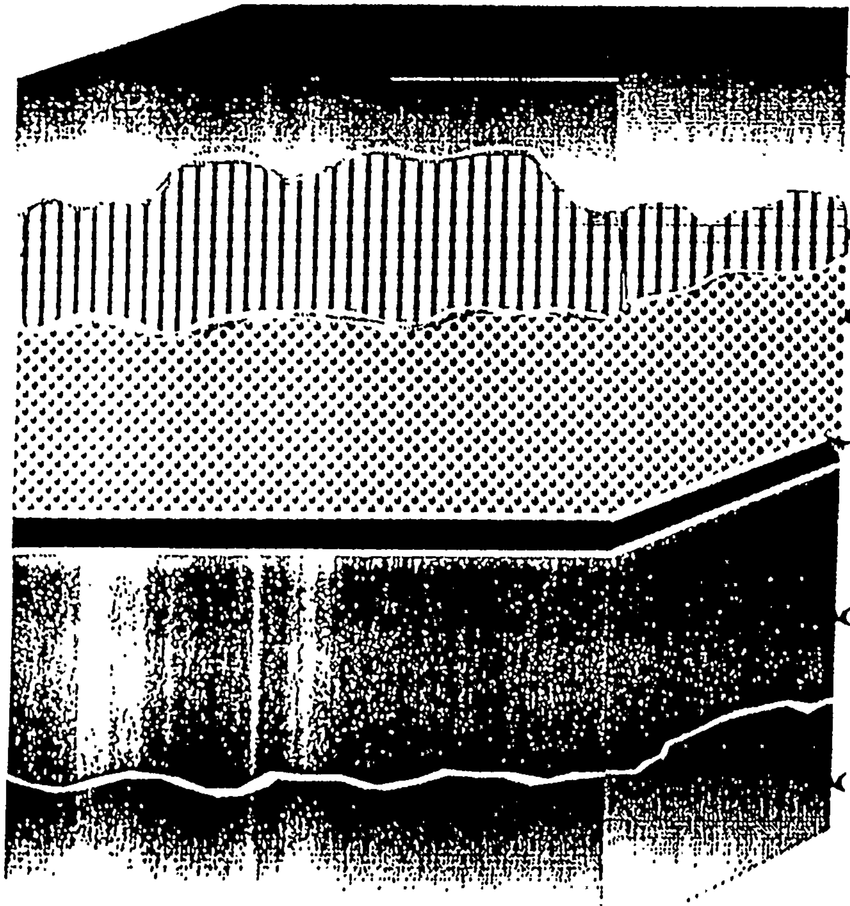



Figure 7.2
Option 2
Natural Material (Spoil) Containment System

# 8.0 PREFERRED LINER TYPE

## 8.1 INTRODUCTION

Numerous options exist for the containment of contaminates at surface facilities; however, in the case of in situ placement of the containment system, the number of feasible options are decreased. In the present case, a containment system must not only be compatible with the contaminants but must also be compatible wit the robotic installation process. This process represents unique and challenging demands on the design of the containment system.

### 8.1.1 CONTAINMENT SYSTEM FUNCTIONS

The primary function of the containment system is to provide an impermeable hydraulic barrier to prevent groundwater contamination from in situ hazardous waste. A secondary function of the containment system is to provide a leachate collection and removal system.

Requirements of the containment system are: (1) that it be remotely installed by a robotic miner, (2) the installed liner must be continuous and hydraulically impervious, and (3) the containment system must permit the waste leachate removal.

### 8.1.2 CONTAINMENT SYSTEM COMPARISON AND EVALUATION

The main components of the liner system are the hydraulic barrier and the leachate collection system. Selection of the liner components focused on evaluating both natural and synthetic liner materials that are currently standards in the waste containment industry. Determination of the materials best suited for the leachate collection system concentrated on using a high density polyethylene synthetic geonet drainage layer and incorporating a geotextile as a filtration and separation media.

The natural materials include using clay for the hydraulic barrier, sand or crushed rock for the leachate collection system and sand or another finely-sized material as a protective layer above and sometimes below the primary hydraulic barrier. The synthetic prefabricated liners are manufactured from high density polyethylene (HDPE) and include geomembranes and geocomposite membranes. A geocomposite consists of bentonite clay particles attached to the HDPE membrane and represents state-of-practice in liner system construction. The bentonite is installed dry then when wetted by the leachate it hydrates and swells closing off the leachate flow paths. An option to using the leachate as the primary source for hydrating the bentonite is to introduce potable water to the bentonite seams during the GCL's placement. This option would be applicable to environments where the leachate showed evidence of high chemical contamination or was non-aqueous.

The drainage of the waste leachate is of primary importance for maintaining the integrity of the containment system. The success of the containment system requires that the leachate collection system function properly. Placement of the leachate collection system and the backfilling of the mined area must be performed in a manner which avoids damage to the hydraulic barrier.

Utilizing a leachate collection system constructed with a geonet drainage layer and a geotextile as a separation and filtration media offers the advantage of a significant reduction in the volume of mine spoil that would be transported to the surface from where it would have to be disposed. A secondary function of this layer is to provide protection for the hydraulic barrier from damage caused by the mining equipment during placement and from damage that may be caused by mine roof collapse.

## 8.2 PREFERRED CONTAINMENT SYSTEM

The preferred containment system developed for this project is shown in Figure 8.1. Descriptions of the components for the containment system are discussed below:

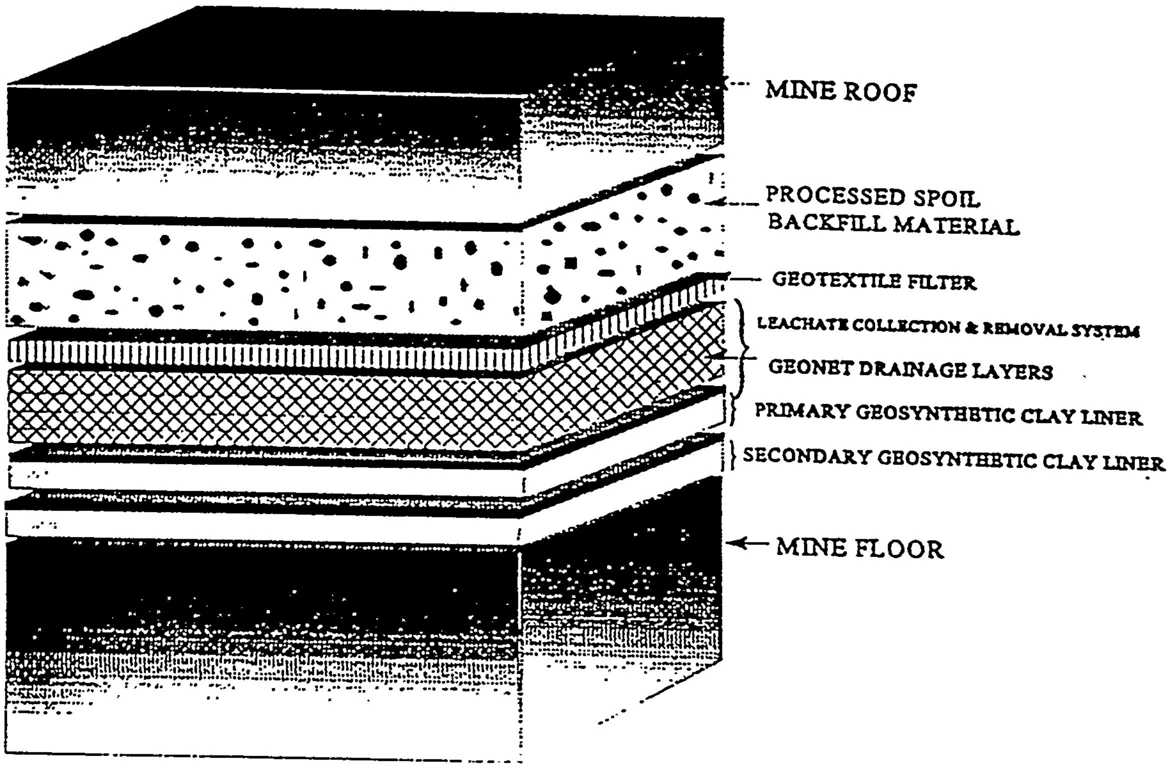
8.2.1 MINE ROOF: The upper surface of the mine must maintain structural stability while the underlying layers are constructed.

8.2.2 PROCESSED SPOIL BACKFILL MATERIAL: The backfill will consist of processed mine spoil. The mined material is transported to the surface, crushed to a specified gradation, washed to remove fine particles, then replaced in the mined strata. The backfill material must be inorganic, non-reactive, free of contaminants, and have good drainage characteristics. The backfill material will provide drainage to the Leachate Collection and Removal System (LCS).

8.2.3 GEONET DRAINAGE LAYER: A geonet drainage layer will be used as the primary LCS. The geonets are overlapping polyethylene strands formed into a net-like material which provides in plane drainage. The geonets have sufficient compressive strength to maintain their hydraulic characteristics under loads greater than 20,000 psf. A filter layer constructed using a non-woven geotextile, with a specified Apparent Opening Size (AOS), will be attached to the upper surface of the geonet. This filter will prevent the intrusion of fine materials from the backfill to prevent clogging of the geonet. The geonets will transmit the leachate to a central trench collection system where the leachate will be pumped to the surface for treatment.

8.2.4 COMPOSITE GCL: The primary and secondary (optional) barriers in the containment system will utilize composite Geosynthetic Clay Liners (GCL). The GCL is a HDPE membrane backed with bentonite clay. The bentonite will hydrate and swell when exposed to leachate, this effect will enable the containment liner to self-seal the overlap seams and any punctures occurring during the liner placement. Installation of the optional secondary GCL layer placed with the HDPE surface on the mine floor, with offset seams, would provide a double layer of bentonite. This arrangement is beneficial because it increases the flow path of any intruding leachate.

8.2.5 MINE FLOOR: The robotic miner shall construct the mine floor subgrade at the specified slope and produce a smooth surface free of obstructions or projections. The strata shall have sufficient bearing strength to provide an adequate foundation for the overlying layers. Deformations in the mine floor may result in damage to the containment system.




SYNTHETIC MATERIAL CONTAINMENT SYSTEM
OPTION - 1

Figure 8.1
Preferred Containment System

## 8.3 QUALIFICATIONS FOR SELECTED CONTAINMENT SYSTEM

Table 8.1 identifies the qualifying items and the advantages associated with the selected containment system.

Table 8.1
Preferred Containment Advantages

| QUALIFYING ITEM | ADVANTAGES |
|---|---|
| Material Properties (GCL and Geonet) | Factory manufacture of geosynthetic materials allows for an effective QA/QC. |
| Thin Material Cross Section | 1) Contributes to minimizing the height of the mined strata.<br>2) Allows for the use of multiple geosynthetic clay liner layers for adaptability to site specific variations. Redundant layers may be installed to increase the factor of safety against groundwater contamination. |
| Seaming | 1) Use of bentonite GCL in overlap construction is a non-mechanical seaming method and does not rely on specific seaming equipment or a controlled environment.<br>2) Cleaning of the HDPE surfaces not as critical with overlap seaming.<br>3) High probability of attaining quality seams and seam overlap requirements will incorporate placement tolerances.<br>4) Quality of seams enhanced with use of bentonite. Seams will self seal when in contact with water.<br>5) QC can be performed visually using remote cameras on the miner. Overlap seams require less inspection efforts than mechanical seaming. |
| Processed Backfill Spoil Material | 1) Backfill will protect underlaying layers of containment system from damage caused by mine roof collapse.<br>2) Processing of backfill will provide a secondary drainage layer to support the primary Geonet leachate collection and removal system.<br>3) Reuse of the mine spoil will minimize mine material disposal and will provide a suitable fill and mine roof bridging material. |

## 8.4 GCL OVERLAP SEAMS

Tests were conducted to determine the performance of a GCL overlap seam. In the experiments, a three inch GCL seam was subjected to a static head of one foot for five months with no measurable leakage. Since no flow was acheived, no calculations would be used to determine the hydraulic conductivity of the seam. Other tests using a flexible wall permeamter indicated a hydraulic conductivity of $1x10^{-9}$ cm/s for the Gundseal/Paraseal (Estornell and Daniel, 1992). A 4 inch overlap seam of $1x10^{-9}$ clay would be equivalent to 33.3 feet of $1x10^{-7}$ cm/s clay. With the use of two GCLs the flow path is increased to 28-32 inches of bentonite. This is equivalent to 233.3 to 266.7 feet of $1x10^{-7}$ cm/s clay.

In the event that subsidence of the mine floor occurs, research has shown that the thin layer of bentonite (approx. 1/8 - 1/4 inch) can withstand tensile strains of up to 29% with no leakage. The overlap was again tested with a static head of 1 foot. The tests were conducted on an overlap of 9 inches. No horizontal displacement of the GCL layers took place (LaGatta, 1992).

## 8.5 ORIENTATION OF A SECOND (optional) GCL LAYER

For the installation of a secondary GCL layer, two orientation alternatives were reviewed. In method #1 both GCLs are laid with bentonite surfaces face down. In method #2 the GCLs are laid with the bentonite surfaces face-to-face. Evaluation of the placement orientations were considered for the following scenerios: puncture in upper membrane, puncture in lower membrane, and flow through the bentonite layer.

PUNCTURE IN THE UPPER MEMBRANE: In this scenerio method #1 would seal more rapidly. Because the thin layer of bentonite would require less leachate to become saturated, it will saturate more rapidly around a punctured area and seal faster than a thick layer. This would reduce the amount of leachate contaminating the bentonite layer.

PUNCTURE IN THE LOWER MEMBRANE: In this scenerio it is assumed that leachate has already migrated into the interior bentonite layer. Leachate flowing through a lower membrane puncture in method #1 would encounter the exterior layer of bentonite. Leachate in method #2 would have previously saturated the interior bentonite and would escape the containment system.

FLOW THROUGH THE BENTONITE LAYER: In this scenerio the volume of leachate flow through the internal bentonite layer will be greater in Method #2. The hydraulic gradient and permeability will be the same for either placement alternative. Thus, the flow velocity will be the same. Since the cross sectional flow area of Method #2 is twice that of method #1, more flow will occur in Method #2.

Based on the above scenerios, the preferred arrangement for the placement of a two GCL system would be Method #1, where both GCLs are placed with bentonite surfaces face down.

# 9.0 PERIMETER CONTAINMENT AND SURFACE CLOSURE

## 9.1 PERIMETER CONTAINMENT

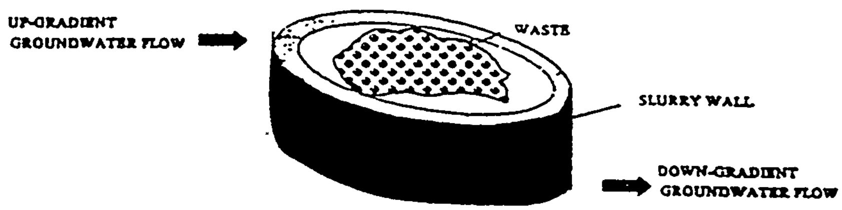
Complete groundwater containment requires construction of vertical and horizontal hydraulic barriers. The Preferred Liner System, shown in Figure 8.1, is designed as the primary vertical groundwater barrier system for installation by the robotic miner. The horizontal or lateral component of the groundwater flow will be controlled using a perimeter containment system. The perimeter containment system functions to prevent lateral groundwater inflow and outflow from the perimeter boundaries of the vertical barrier. Existing technologies will be used for the design and construction of the perimeter groundwater containment system.

## 9.2 EXISTING TECHNOLOGIES

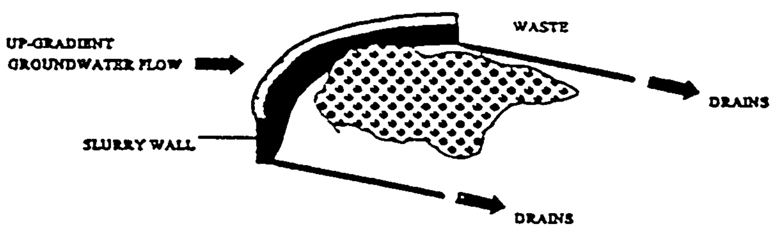
Currently the most common method of controlling lateral groundwater flow is through the use of diaphragm walls, grout pile walls, and injection grouting. A diaphragm, or slurry wall, is a continuous barrier system constructed in a slurry supported trench and backfilled with tremie-placed concrete or composite HDPE panels. Grout pile walls are continuous grout piles staggered and interlocked in alternating offset rows to form a wall. Injection grouting is a process where grout is injected under high pressure into the subsurface soil or rock through drilled grout pipes to develop grout masses which decrease the in situ permeability. (Koerner, 1984)

## 9.3 SLURRY WALLS

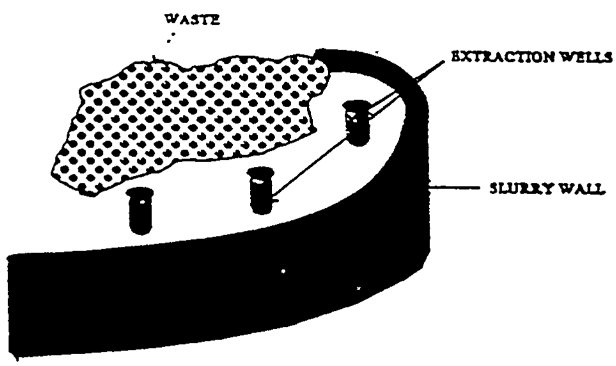
Slurry walls are constructed according to their intended function and requirements for mechanics of containment. Slurry walls are installed in configurations that include circumferential, up-gradient with drains, and down gradient with withdrawal pumping wells as shown in Figure 9.1. Slurry walls are keyed into the underlying impermeable stratum to curtail groundwater flow beneath the wall.




CIRCUMFERENTIAL SLURRY WALL




UP-GRADIENT CONTAINMENT WALL




DOWN-GRADIENT CONTAINMENT WALL

Figure 9.1
Slurry Wall Placement Configuration

Construction Materials:

The slurry wall consists of two components: 1) slurry fluid. and 2) slurry mix. The slurry fluid serves two functions: 1) it provides trench support by hydrostatic fluid pressure, and 2) provides for development of a thin layer of bentonite against the trench walls and bottom.

The main types of slurry material mixes include bentonite-soil, cement-bentonite, cement-gravel-bentonite, structural concrete, and new composite synthetic barriers. The material mixes and their application features are shown in Table 9.1.

Table 9.1
Slurry Material Mix & Applications

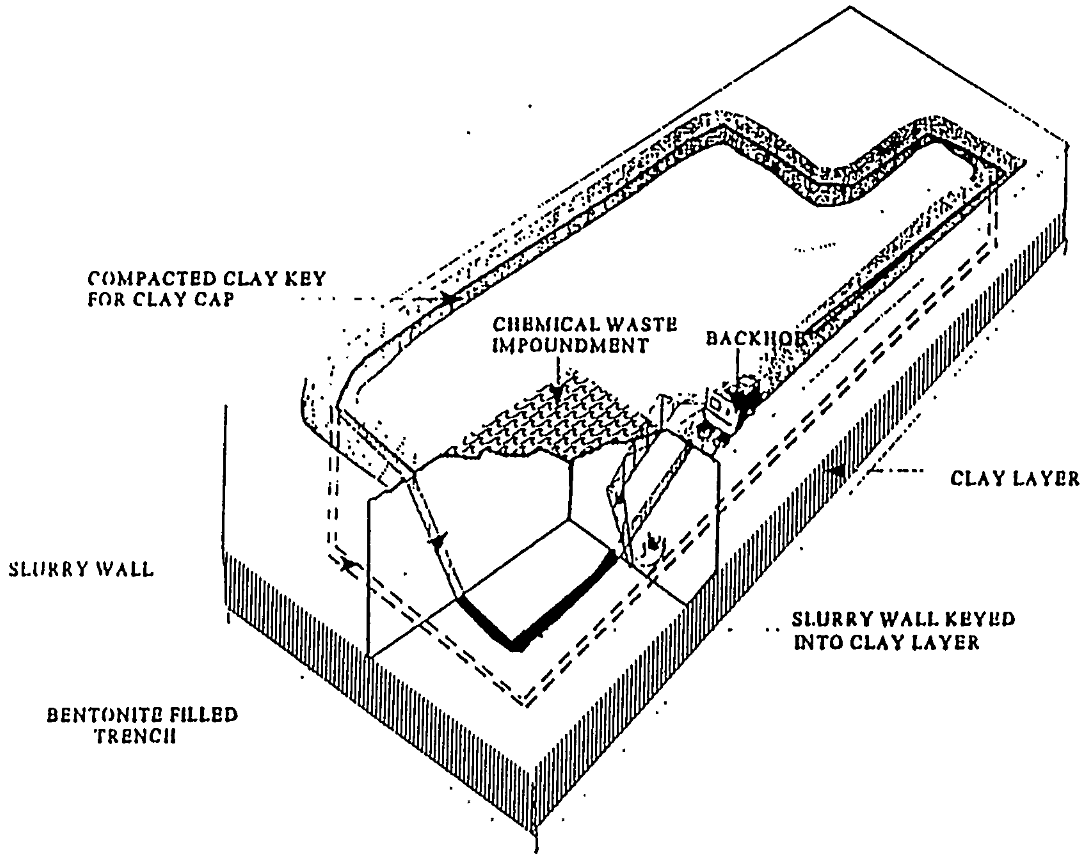
| Material Mix | Application Feature |
|---|---|
| Bentonite - Soil | Used as both slurry fluid & slurry mix |
| Bentonite - Cement | Cement used to fully hydrate bentonite |
| Bentonite - Cement - Gravel | Gravel produces low permeability & adds wall strength |
| Structural Concrete | Used where wall acts as a retaining structure rather than a hydraulic barrier |
| Composite - HDPE (Gundwall) | Incorporates HDPE barrier and Geonet drainage layers. Composite system produces low wall permeabilities and geonet permits leachate collection and removal. Redundancy achieved using multiple layers |

Construction & Placement Configuration:

Slurry wall construction starts with excavation of the slurry trench. Excavation of the in situ soil is accomplished using conventional excavation/backhoe equipment for shallow to moderate depths (0-25 feet), and using a crane equipped cable-hung clamshell bucket for deep excavations (greater than 25 feet). Gundle has reported successful installation of HDPE slurry walls to depths of 100 feet. Excavation operations for a circumferential slurry wall are shown in Figure 9.2.

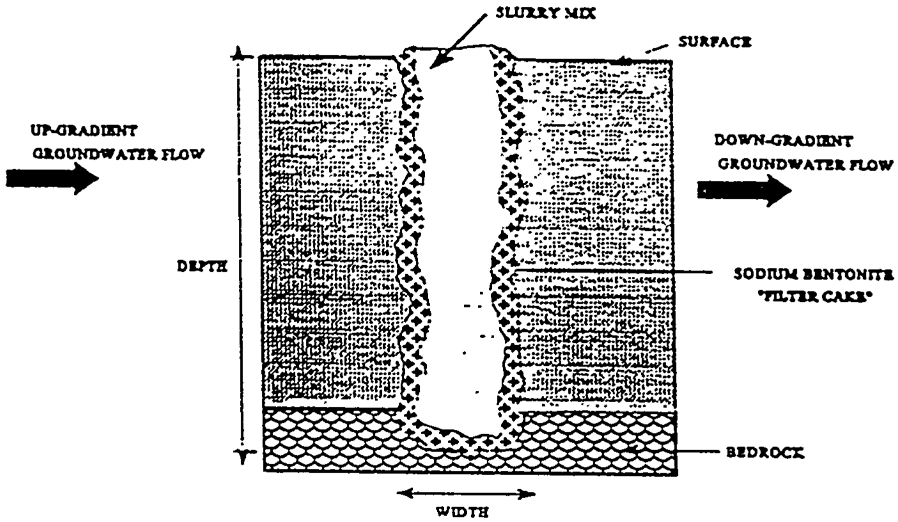
As the trench excavation proceeds, slurry fluid is pumped into the trench with the slurry fluid level being maintained at the top of the trench. The slurry fluid introduces hydrostatic forces against the trench walls and bottom, thereby supporting the excavation against collapse and causing the bentonite mix to form a thin layer against the trench. This layer, commonly referred to as a "filter cake", develops an in-place, low permeability hydraulic barrier. The filter cake will typically exhibit permeabilities on the order of $1x10^{-9}$ cm/s. The slurry fluid is typically made from sodium bentonite and water in a mix ratio of 5% bentonite to 95% water.

After the trench excavation has substantially progressed, the trench is backfilled with the slurry mix (bentonite, cement, gravel). The backfilling is performed using the tremie method. The slurry fluid is pumped out, remixed with bentonite, and recycled. Figure 9.3 shows slurry wall cross sectional details constructed using conventional materials, and using a HDPE composite wall system.

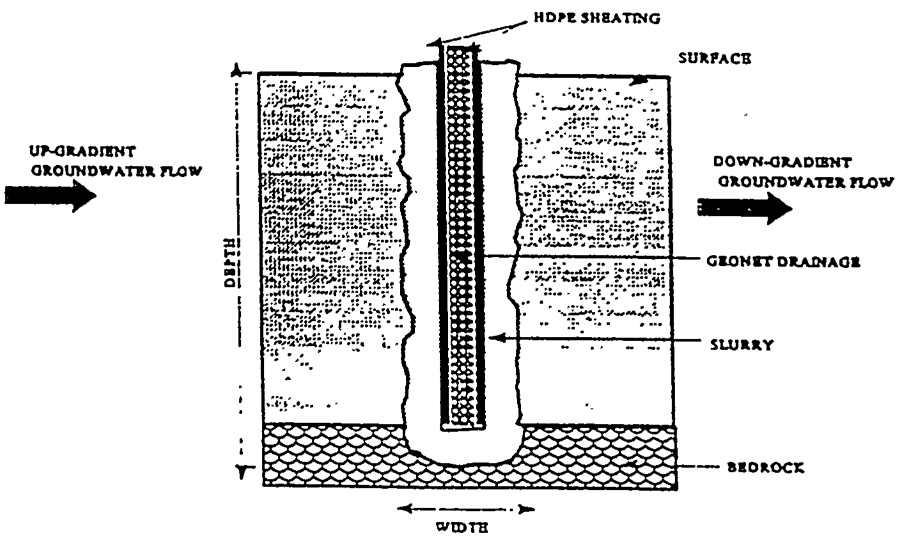



SCHEMATIC SKETCH OF CHEMICAL WASTE CONTAINMENT
USING SLURRY WALL CONSTRUCTION

**Figure 9.2**
**Circumferential Containment Wall Installation**




BENTONITE SLURRY WALL




GUNDWALL

Figure 9.3
Slurry Wall Cross Sectional Details

## 9.4 GROUT PILE WALLS

Grout walls are usually constructed by a continuous-flight hollow-stem auger or with augers excavating within a slurry-supported hole. A grout mixture is injected through the auger or by a tremie pipe beneath the slurry to make a cast-in-place grout pile. Grout pile walls have been installed to depths exceeding 800 ft. (Koerner, 1984).

The grout piles are typically arranged in either tangent or secant configurations. Tangent pile installations place staggered piles along a common wall center line. Intermediate piles are next installed and located as closely as possible to the original piles and are augured to remove a small arc of the adjoining piles. This technique gains an interlocking effect and is shown in Figure 9.4.

Secant piles are arranged in two rows with offset center lines and at a uniformly gaped distance. The gaped distance permits fracturing and compression of the soil/rock material, resulting in densifying the in situ subgrade. This effect is shown in Figure 9.4.

## 9.5 INJECTION GROUTING

Injection grouting is a process used to modify the in situ characteristics of the subsurface soil or rock. The grout is injected under high pressure through grout pipes into the subsurface to accomplish the following: 1) decrease permeability, 2) increase shear strength, and 3) decrease compressibility of the subsurface soil or rock.

The decrease in permeability of the in situ subsurface soil or rock is achieved when the grout flows into the soil or rock voids without causing significant subsurface structure changes. The subsurface shear strength increase is a result of the grout mass exerting pressure on the soil or rock and densifying the weaker in situ material. The decrease in compressibility of the in situ subsurface soil or rock is accomplished using grouting pressures higher than the tensile strength of the soil or rock being grouted. This process permits the grout to rapidly penetrate fractured zones and develop solid grout formations within densified in situ soil or rock.

The two classifications of grout materials currently in use are suspension grouts and solution grouts. Solution grouts can generally permeate finer soils than suspension grouts. Suspension-type grouts consist of soil, cement, lime, and asphalt emulsion. Solution grout types are numerous and include silicate and lignosulfite derivatives. mineral and organic solutions. and bituminous emulsions. (Koerner. 1984)

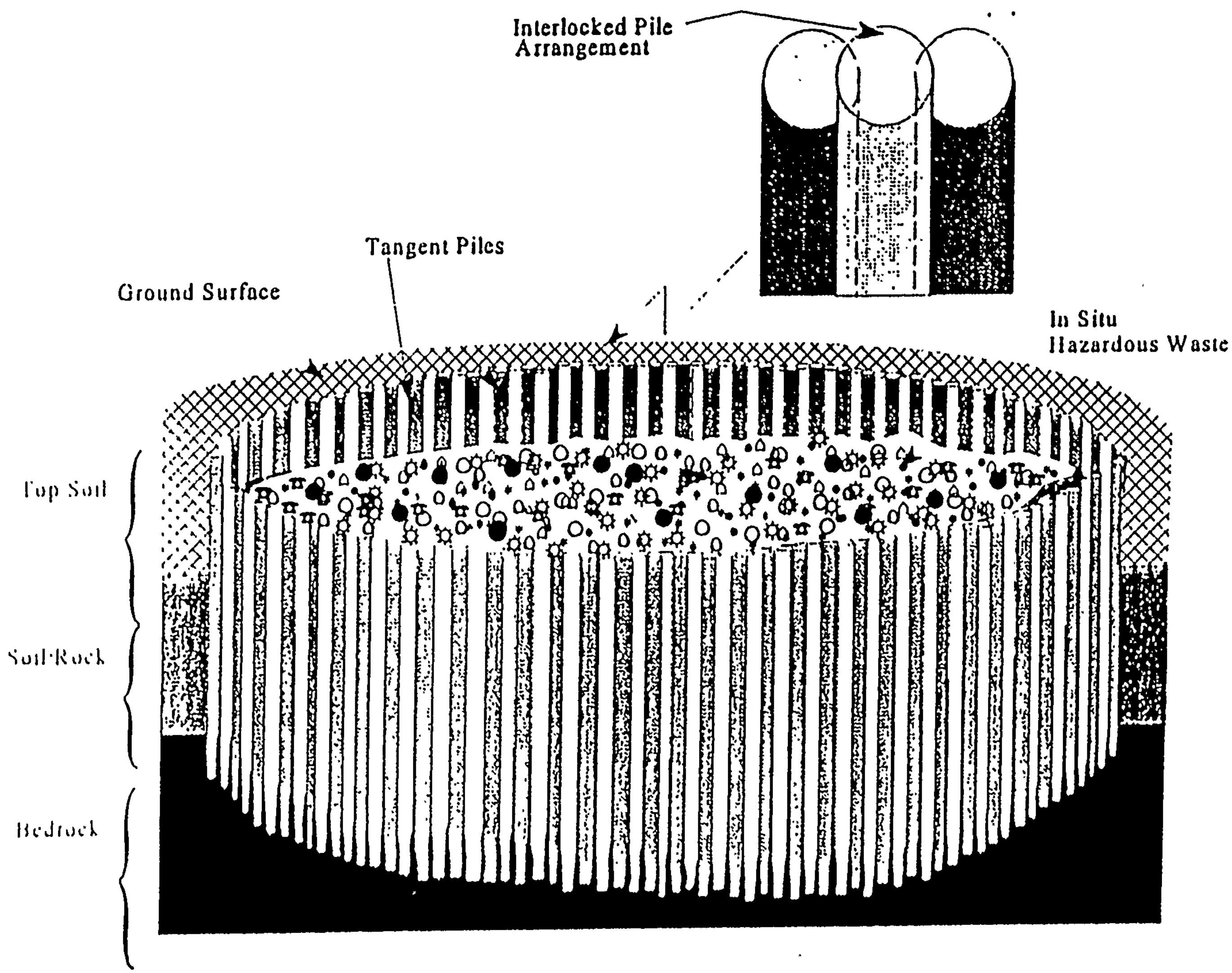



**Figure 9.4**
**Tangent Pile Wall**

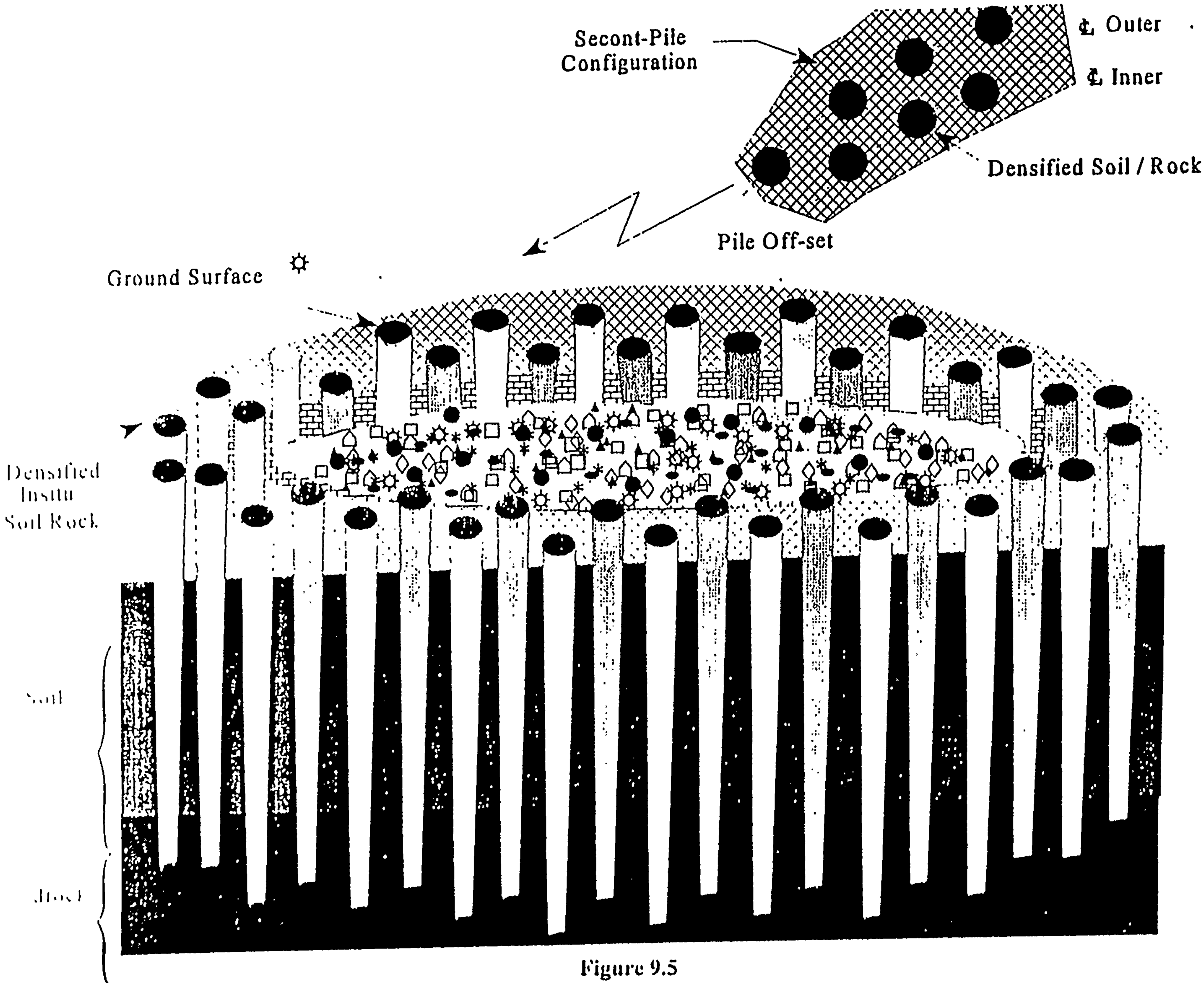



Figure 9.5
Secant Pile Wall

## 9.6 DESIGN PARAMETERS & TECHNICAL ISSUES

Perimeter containment used in combination with a vertical hydraulic barrier is required for developing a complete groundwater containment system. Application of lateral containment technologies to this project present design and installation constraints. Table 9.2 lists the advantages and associated disadvantages of sequencing the slurry wall construction with the remote mining operation for installation of the vertical hydraulic barrier.

Table 9.3 lists the various lateral containment methods with associated advantages and disadvantages of each technology for application to the robotic mining for the in situ waste containment project. Several key design parameters and relevant technical issues for application of slurry wall technology to an in situ groundwater containment system are listed in Table 9.4.

Table 9.2
Perimeter Containment Wall Installation Sequence

| Construction Sequence | Advantages | Disadvantages |
|---|---|---|
| Pre-vertical GCL Barrier placement | May reduce the groundwater flow into the mining environment | Wall damage from settlement and roof collapse.<br>Difficult to develop tie-in connection at bottom of wall to GCL liner. |
| Post--vertical GCL Barrier placement | May extend Gundwall (composite wall) sheeting into the perimeter mine tunnels, then fill tunnels with bentonite slurry. | Horizontal liner damage possible from collapse of mine roof. |

Table 9.3
Lateral Containment Systems Applied to Robotic Mining

| Lateral Containment System | Advantages | Disadvantages |
|---|---|---|
| Bentonite Slurry Wall | Provides low permeabilltiy.<br>Typical installation for shallow depths < 100 ft.<br>Cost effective | Limited depth application < 100 ft.<br>Mining subsidence may damage wall integrity. |
| Composite HDPE Slurry Wall | Provides lowest permeability Allows for drainage of leachate<br>Cost effective<br>Impervious to most waste streams.<br>Mining subsidence may not damage wall integrity. | Limited depth application < 100 ft. |
| Grout Pile Walls | Feasible installation to depths in excess of 500 ft.<br>In situ inspection performed using seismic refraction, electrical resistivity, and ground-probing radar. | High costs. |
| Injection Grouting | Provides dense grout masses.<br>Feasible for deep installation depths.<br>May work concurrently with Pile walls. | May not provide a continuous grout mass.<br>Soil/Rock subsurface may mix with grout forming inclusions that will effect the grouted mass permeablitiy. |

Table 9.4
Slurry Wall Design Parameters & Technical Issues

| Design Parameter | Technical Issue |
|---|---|
| Waste Characterization | Organic compounds induce flocculation of soil-bentonite which results in increasing wall permeability. |
| Subsurface Soil Conditions & Characterization | Compatibility testing for characterization of the site soil's physical and engineering properties to evaluate soil mineralogy for prediction of possible chemical reactions with slurry wall materials. |
| Groundwater Characterization | Groundwater flow should be established to determine the seasonal changes, flow magnitude, and direction.<br>Chemical analysis should determine the levels of dissolved contaminants and the existence of immiscible contaminants. |
| Structural Stability | Characterize the strength and stability of slurry mix.<br>determine consolidation of slurry and associated volume reduction.<br>Evaluate wall thickness, surface cover, slurry mix properties, curing time and conditions, and expected life cycle. |
| Wall Hydraulic Conductivity | Dependent on bentonite mix, permeability values low as 1x10EE-9 cm/s. |
| Depth Limitations | Conventional excavation equipment approximately 25' deep,<br>Crane equipped cable-hung clamshell bucket > 25',<br>New composite HDPE up to 100' deep. |
| Site Disposition | Site soil contamination levels, suitability of excavated soil for disposal, buried objects, and soil disturbance |
| Monitoring & Post Construction Maintenance | Install of up-gradient and down-gradient groundwater wells to monitor wall performance.<br>Post construction activities include visual inspection for desiccation, cracking, and root penetration. |
| Cost | Bentonite and mix materials, excavation difficulty, construction obstructions, source of backfill, maintenance and monitoring. |

## 9.7 SURFACE CLOSURE SYSTEM

After installation of the vertical and lateral containment systems a final surface cover should be constructed. The surface cover is placed over the entire waste site to provide the following:

1) an impermeable hydraulic barrier to prevent surface water from infiltrating into the contained hazardous waste,
2) a surface water runoff and collection,
3) to raise the ground elevation,
4) to restrict landfill/hazardous waste gas migration or enhance gas migration.

The final surface cover is a requirement for satisfying regulatory concerns (40 CFR 264, Subpart G) with respect to closure and post closure efforts. Without a surface cover system, meteorological water would build-up in the contained area resulting in increased waste contamination and potential liner damage.

The surface cover systems discussed in this section are based on proved designs and are in compliance with current regulatory requirements. Two types of closure systems are presented. The first is the conventional hazardous waste scheme and the second is a modification showing additional layers for biotic protection and installations in arid climates.

## 9.8 SURFACE CLOSURE SYSTEM COMPONENTS

The surface closure system applicable for hazardous waste applications is shown in Figure 9.6. Component descriptions for the system are discussed below:

9.8.1 VEGETATIVE COVER LAYER: The vegetative cover layer will consist of a minimum of two feet of top soil with appropriate regional vegetation. Only lite, non-woody vegetation may be used, this includes grass and small bushes or shrubs but no trees or larger bushes. Vegetation with dense shallow root systems should be chosen.

The vegetative layer has the following functions:

1) it provides protection from wind and water erosion,
2) it reduces downward percolation of surface water,
3) it maximizes evaporation and evapotranspiration,
4) it enhances aesthetics, and
5) it provides a self sustaining ecosystem.

Of these functions, the two most important are the reduction in erosion of the protective top soil and increased evaporation of surface water.

9.8.2 GEOTEXTILE FILTER LAYER: A non-woven geotextile will overlay the geonet drainage layer to prevent the intrusion of soil from the vegetative layer from infiltrating into the geonet. This will prevent the clogging of the geonet and insure that it remains in good working order.

9.8.3 GEONET DRAINAGE LAYER: This layer will provide for drainage of infiltrating surface water off the cover. The layer will be constructed of one or more layers of geonet to provide drainage necessary to keep infiltrating water from building up on the covers hydraulic barrier.

9.8.4 COMPOSITE GEOSYNTHETIC CLAY LINER OR FLEXIBLE MEMBRANE LINER: A GCL or FML shall be used as the hydraulic barrier in the cover. This layer will be the primary barrier against the infiltration of surface water into the enclosed waste.

9.8.5 GRADED SITE SURFACE: The site surface shall be graded before the placement of the above mentioned layers for two primary reasons: (1) to provide a slope for drainage purposes and (2) to remove any obstructions or protrusions that would likely puncture the GCL/FML.

The site will be graded to a slope of 2% to 8%, which will provide adequate drainage while limiting runoff speed and corresponding erosion.

## 9.9 OPTIONAL LAYERS

In areas with high populations of burrowing animals (ground-hogs, prairie dogs, mice, moles, etc.) a biotic barrier component, refer to Figure 9.7, is incorporated to prevent damage to the cover system. The biotic barrier component consists of a protective sand or soil layer, a large stone layer, and a small stone layer. The protective sand/soil layer prevents large stones from damaging the lateral drainage layer.

In arid climates, where vegetation is difficult to maintain, the soil layer is overlain by a layer of stone to prevent wind and water erosion. This is shown in Figure 9.7. The stone covering has little effect on the evapotranspiration and thus more infiltration of meteorologic water, when it occurs, should be expected. The drainage layer should be designed for the additional hydraulic load.

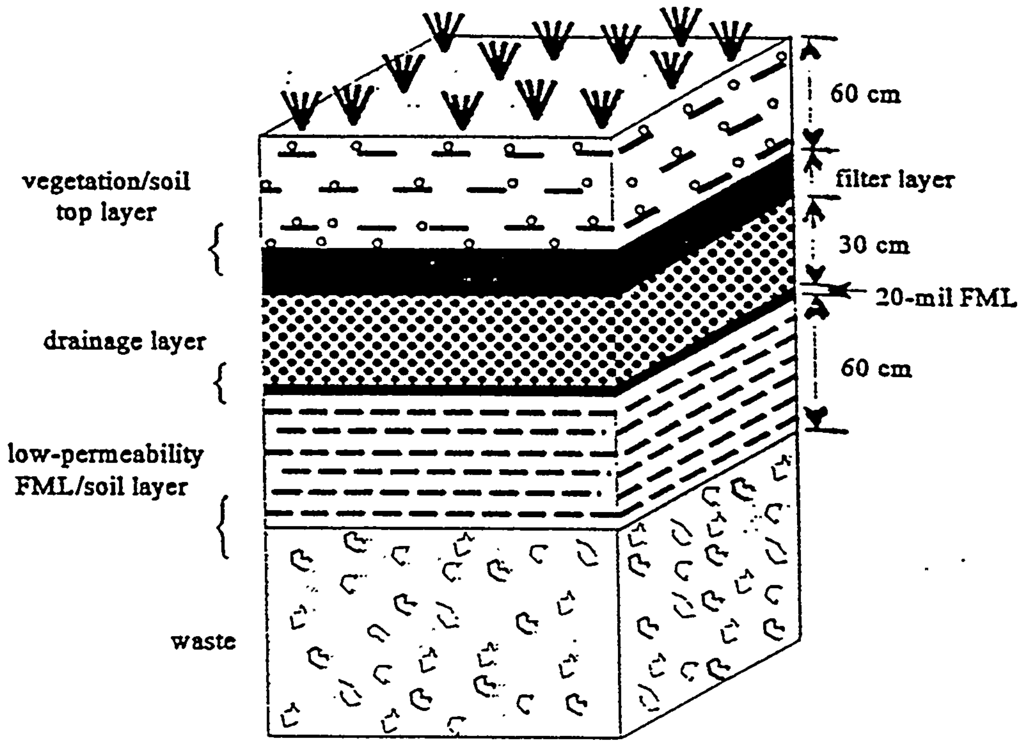



Figure 9.6
Standard Surface Closure System

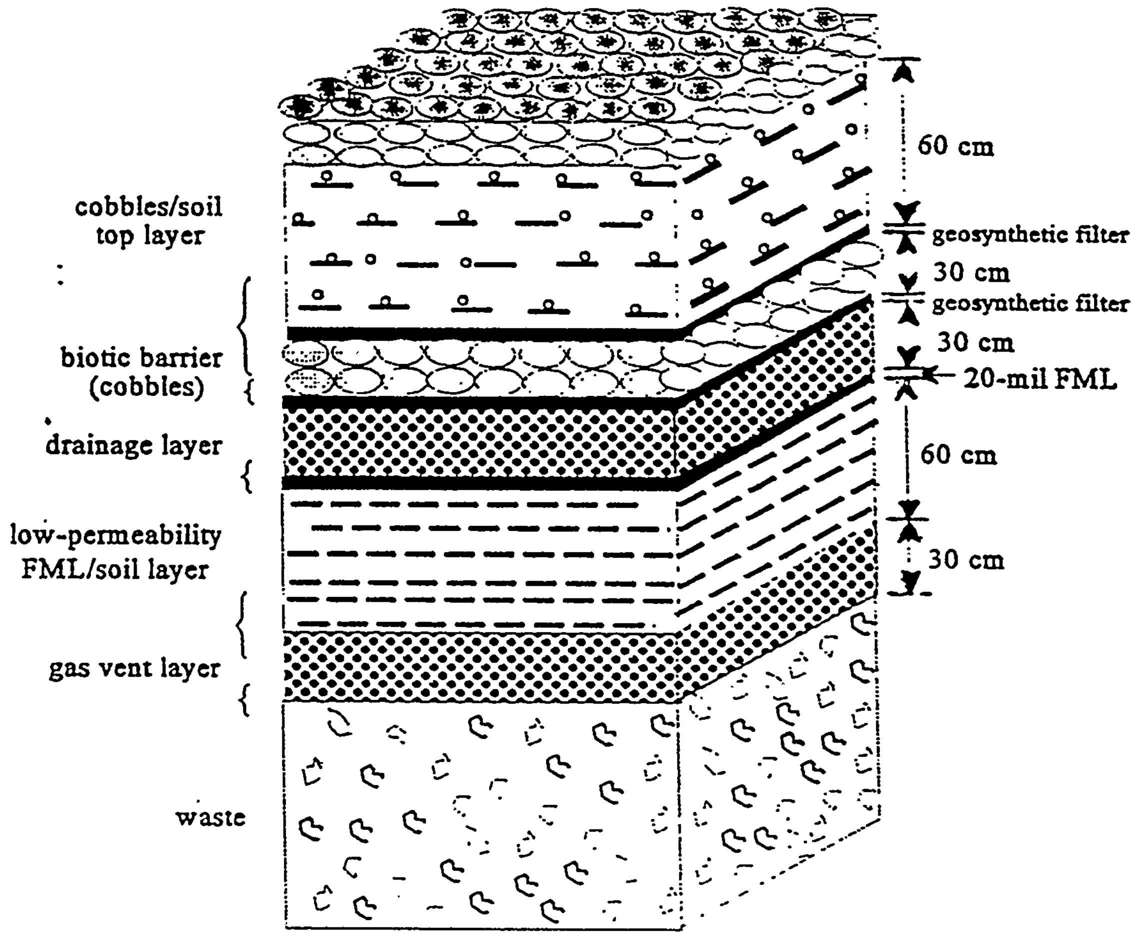



Figure 9.7
Biotic Barrier Surface Closure System Option

## 10.0 PLACEMENT METHOD DEVELOPMENT

The proposed placement of the liner system in a mine situation is in a piecewise fashion. The miner would clear a strip of earth as it travels forward and upward at a given slope. The mining method is shown conceptually in plan view in Figure 10.1. Once the miner has progressed the width of one liner layer, the liner is then installed. The liner is placed with overlapping self-sealing edges which prevent the leachate from penetrating the liner system, refer to Figure 10.2.

After a placement of the liner section, the leachate collection and removal system is then installed followed with the final backfill material. This method of mining minimizes the undercut area and reduces the potential of significant roof collapse.
The up-slope miner progression will eliminate the buildup of groundwater at the mine face where the cutting equipment operates and will significantly reduce equipment complications.

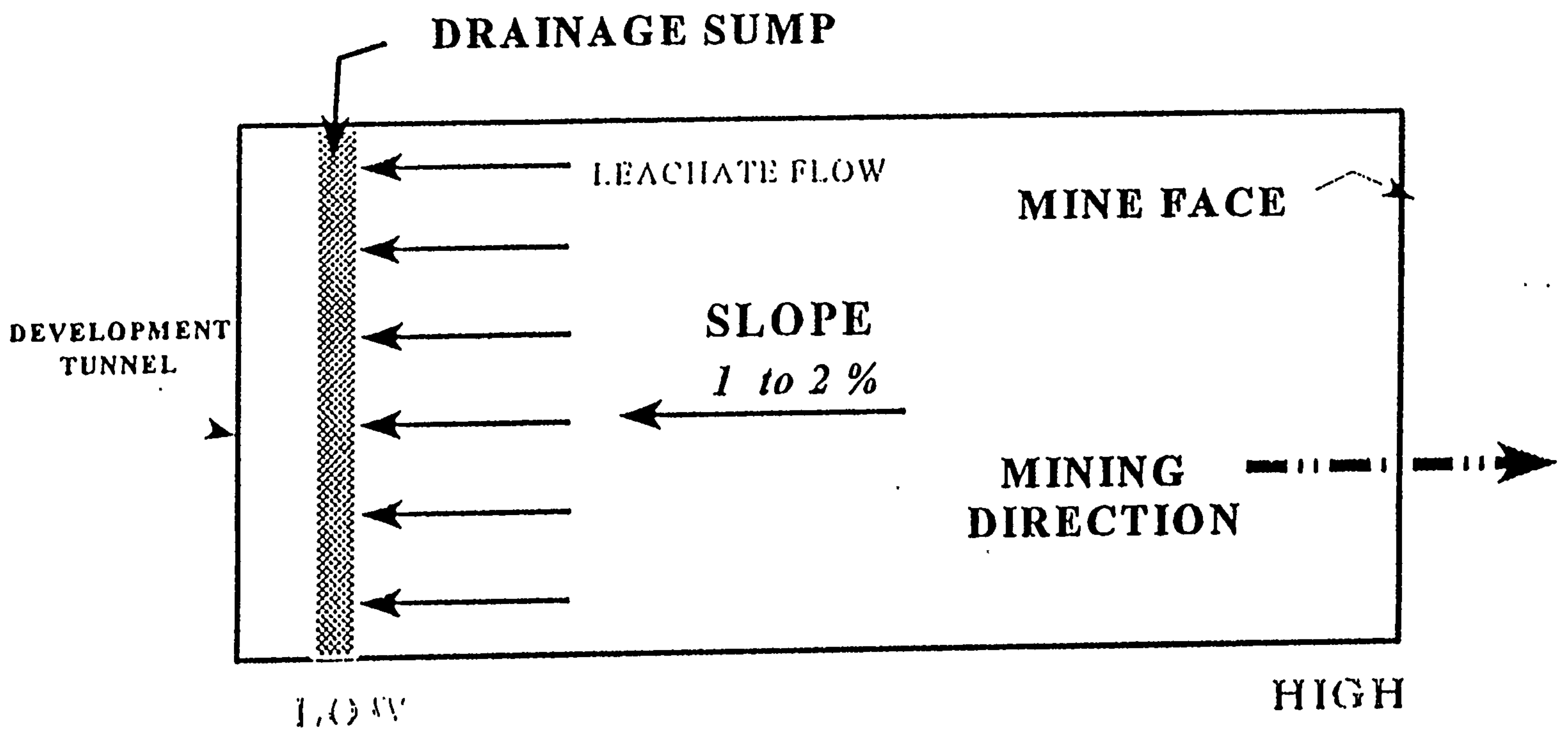



**Figure 10.1**
**Plan View**

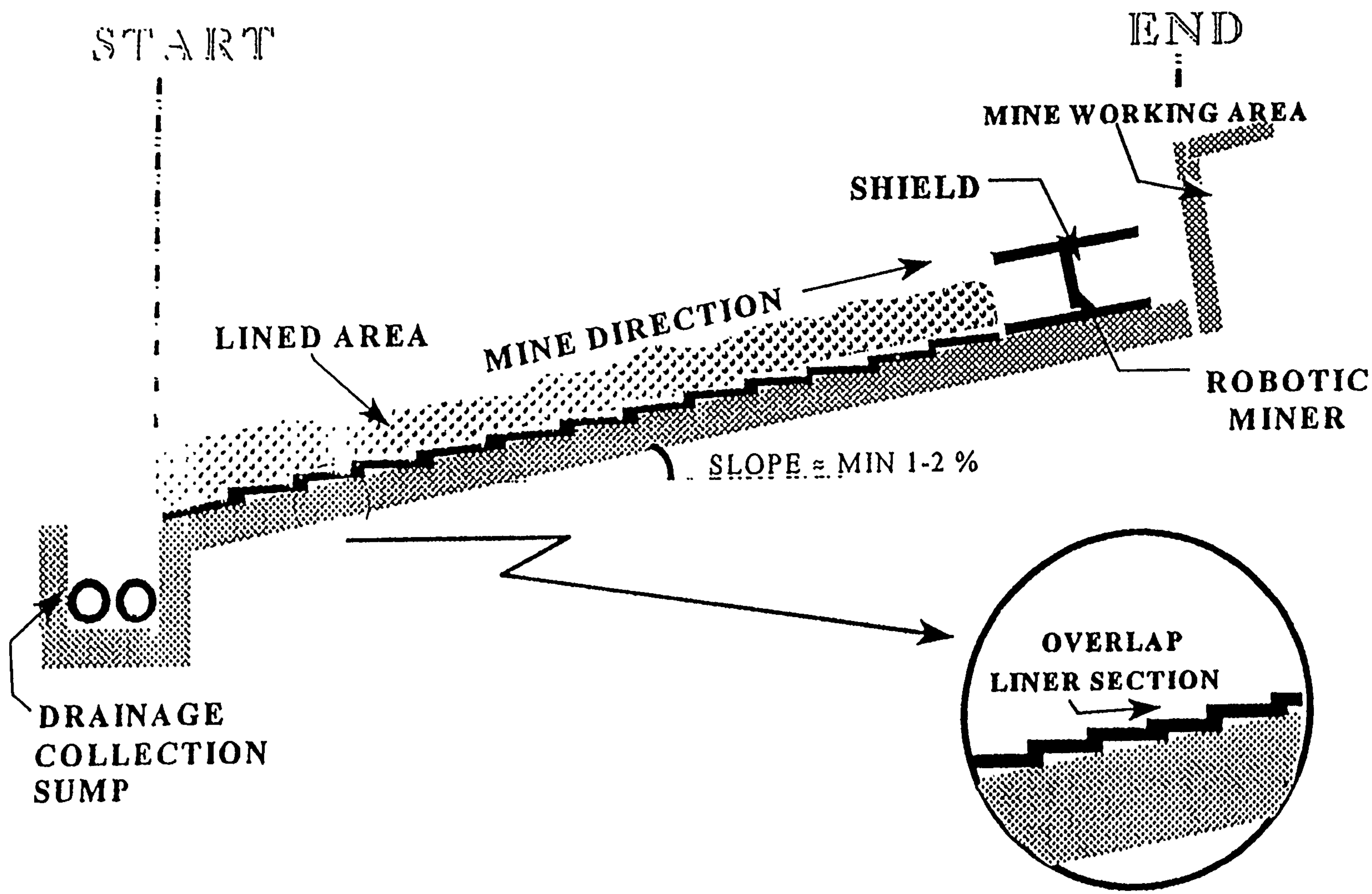



**Figure 10.2**
**Elevation View**

# 11.0 CONTAINMENT SYSTEM PLACEMENT MECHANICS

This section addresses the installation and placement requirements for the preferred containment system shown in figure 8.1. This section is formatted from an activities based approach. It presents information for use by the robotic and mining design teams for the development of prototype liner placement equipment. The placement requirements are formatted in this report as follows:

| Section | Topic |
|---|---|
| 11.1 | Mine Environment and Subgrade Testing |
| 11.2 | Geosynthetic Material Storage and Handling |
| 11.3 | Underground Geosynthetic Installation/Placement |
| 11.4 | Processed Spoil Backfill Material Requirements |
| 11.5 | Leachate Collection & Removal Trench |

## 11.1 MINE ENVIRONMENT AND SUBGRADE TESTING

The requirements for the mine environment are listed in Table 11.1. These requirements insure an environment condition which will not adversely impact liner materials prior to, and during installation. These conditions should be monitored and maintained within limits established through field and laboratory testing.

**Table 11.1**
MINE ENVIRONMENT REQUIREMENTS

| Items of Interest | Poor Project Conditions | Required Project Conditions |
|---|---|---|
| Relative humidity, | High humidity | Low humidity |
| Water content subsurfaces of FML | Groundwater Infiltration | Dry mine environment<br>No Ponded Water |
| Proper preparation of the liner surfaces | Dirty and damp FML surface at overlap interface | Cleanliness of the seam interface and no airborne dust or debris present. |

The subgrade testing requirements are listed in Table 11.2. These requirements insure that the subgrade is of sound quality and suitable as a foundation for the overlying containment system layers.

**Table 11.2**
**SUBGRADE TESTING REQUIREMENTS**

| Analyzed Parameter | Test Methods | Test Frequency | Application to Remote Mining |
|---|---|---|---|
| Soil Type | Visual-manual procedure<br>Particle size analysis<br>Atterberg Limits<br>Soil classification | 1,000 sf<br>50,000 sf<br>50,000 sf<br>50,000 sf | Visual inspection by camera and physical evaluation on recovered specimens. |
| Moisture Content | Oven-dry method<br>Nuclear method | 50,000 sf<br>1,000 sf | Assurance testing on recovered samples. Robotically performed in mine. |
| In-place density | Nuclear method | 1,000 sf | Robotically performed in mine. |
| Strength | Unconfined compressive strength | 10,000 sf | Not required unless mining at steep slopes. |

## 11.2 GEOSYNTHETIC MATERIAL STORAGE & HANDLING

The following are requirements for the storage and handling of geosynthetic materials. GCL, Geonet, and Geotextile roll weights and roll diameters/dimensions are presented in Section 11.5 (Geosynthetic Weights & Measures).

- material handling equipment operating at the surface and underground should be adequate and not pose risk of damage to any geosynthetic materials.

- All geosynthetic material rolls should be visually inspected for exterior damage. They should not be unrolled, unless damages are found or suspected.

• All geosynthetic material shall be shipped and stored in a manner that protects the material from water, dirt, or mechanical damage.

• GCLs, in particular, should be stored in a dry environment, covered, and elevated so moisture does not contact the bentonite backing and cause swelling prior to installation.

• Geotextile rolls shall be shipped and stored in opaque wrappings for protection from ultraviolet light exposure.

## 11.3 UNDERGROUND GEOSYNTHETIC INSTALLATION/REQUIREMENTS

The following requirements apply to the geosynthetic and leachate collection system materials placed underground.

• The GCL shall be installed such that no tears or punctures result from contact with the mine floor or by malfunctioning placement/mining equipment.

• Buckling and twisting of the materials shall be monitored to minimize strains and damage to the bentonite backing and to prevent membrane tears/punctures.

• Loss of the bentonite backing due to abrasion on the mine floor shall not be permitted. Visual inspection of the GCL placement using remote video equipment shall be performed to monitor the placement and to check the completeness of the factory bentonite adhesion/application.

• All GCL edges shall be overlapped 6 inches minimum.

• Additional layers shall be placed with edges offset to previous layers as shown in figures 11.3 & 11.4. The advantages to this arrangement are: 1) A decrease in thickness at the overlapped seams and 2) An increased flow path length which will impede leachate permeation and increase the factor of safety against leakage.

• All geosynthetic components shall be placed evenly with good contact between adjacent layers at the overlapped seams.

• The membrane surface at the seams shall be kept free of dirt. excess moisture. or material which would prevent a good seal/contact surface.

• The FML surface of the upper GCL shall be kept free of mine debris that would obstruct geonet placement and subsequently restrict leachate flow through the geonet drainage layer.

• The geonets and geotextiles shall be installed with successive sections placed end to end. no overlap shall be made. Refer to figures 11.1 & 11.2 for placement arrangements.

• The geonet shall be placed evenly and shall be kept free of foreign material which would reduce the hydraulic characteristics or degrade the geosynthetics.

• The geonet drainage layers and geotextile layers shall be installed in a manner that does not damage the underlying layers of the containment system.

• The geotextile shall be placed with no twisting, buckling, and wrinkling.

## 11.4 GEOSYNTHETIC COMPONENT PLACEMENT SEQUENCE

Figures 11.1 and 11.2 show the sequence of placement for the GCL liner and geonet drainage components in a double GCL containment system arrangement. All QA/QC and mechanics of placement requirements involving the cleanliness and character of the components and the mine environment shall be monitored and maintained throughout the placement processes.

Step 1. (Previously Completed Section)

- A completed pass with all components in place.

Step 2. (Placement of First GCL Layer)

- The first GCL layer is positioned with the typical 6 inch overlap onto the previous GCL liner.

- The GCL liners are placed with the FML surface up and the Bentonite surface against the subgrade.

Step 3. (Placement of Second GCL Layer)

- The second layer of GCL is installed with a 2' offset from the first GCL layer.

- The second GCL layer is offset 2 feet on the first GCL layer.

•Step 4. (Placement of First Geonet Layer)

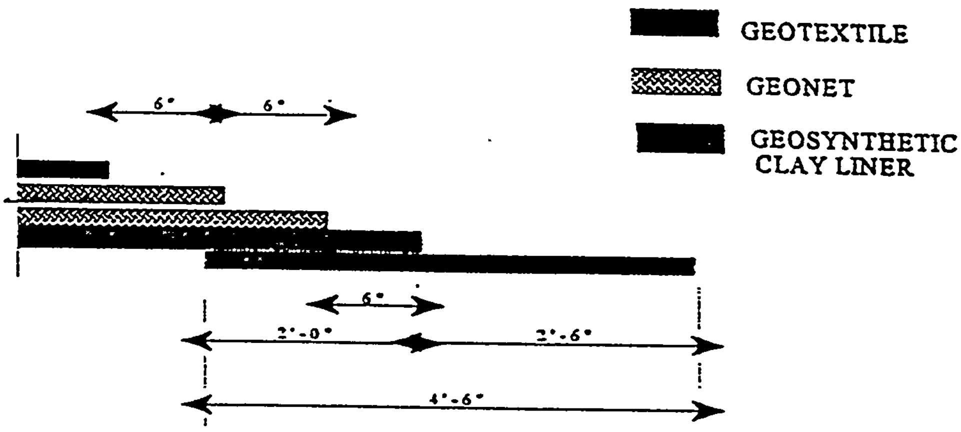
- The first of two geonet layers is placed on top of the second GCL layer.
- Geonet is placed evenly with no overlaps.

Step 5. (Placement of Second Geonet Layer)

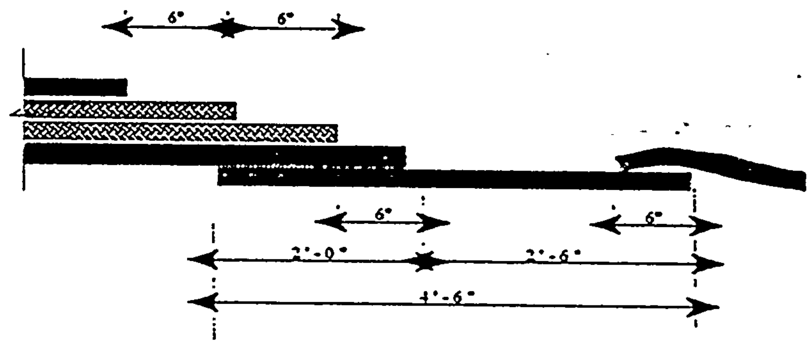
- The second geonet is offset to the first by 6 inches.
- The second geonet is placed with no overlaps.

Step 6. (Placement of Geotextile)

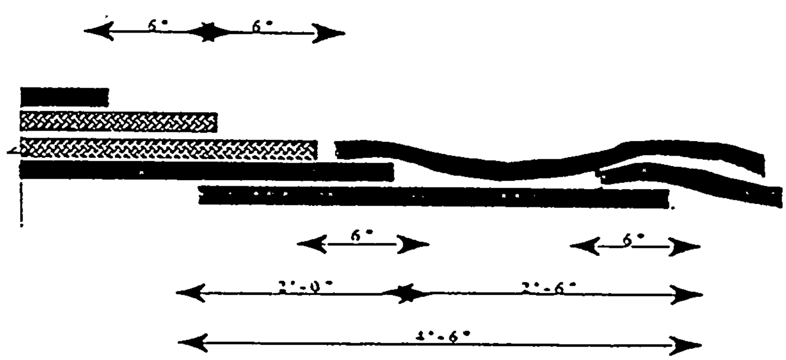
- Textile is offset 6 inches from the seams of the second geonet layer.
- Textile is also placed evenly with no overlaps.




**STEP 1:** Previously completed section and preparation of mine floor for next section.

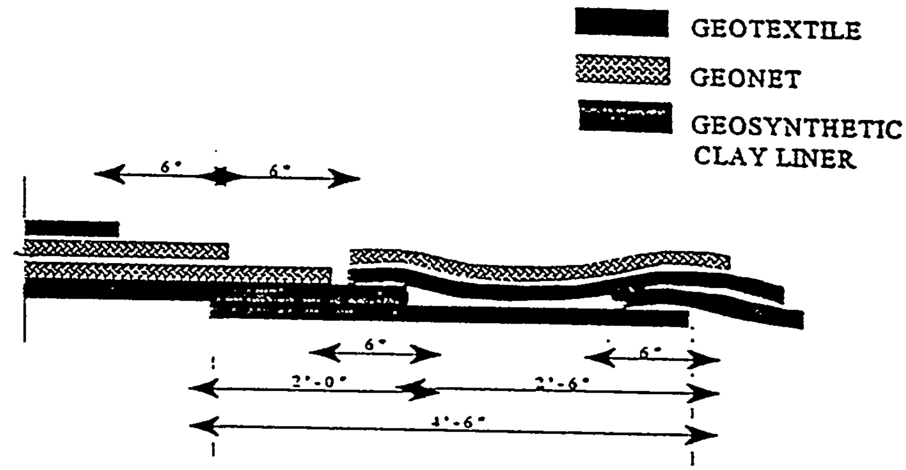



**STEP 2:** Placement of first GCL layer with 6 inch overlap.

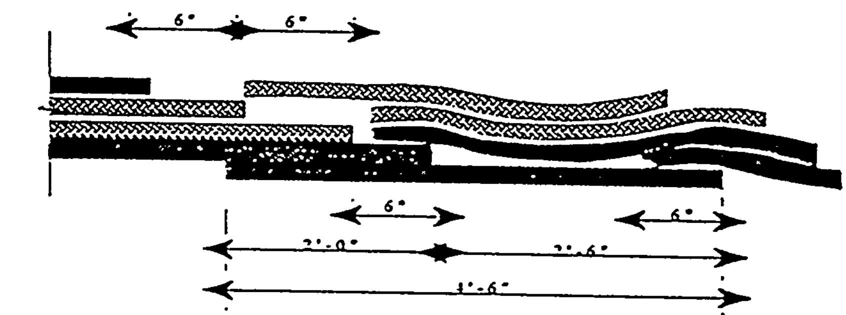



**STEP 3:** Placement of second GCL layer with 6 inch overlap. Seams are offset.

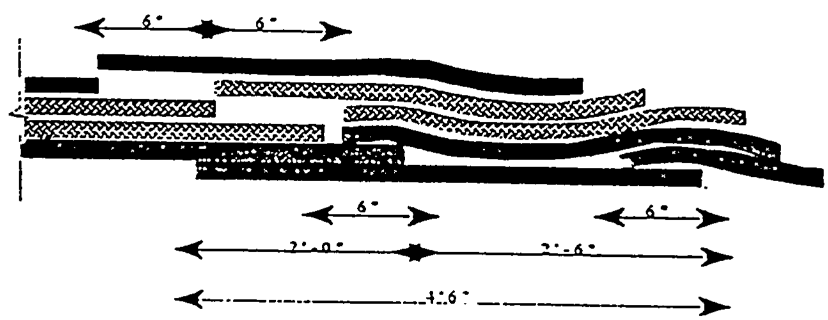
**Figure 11.1**
**Liner Placement**




**STEP 4:** Placement of first geonet with no overlap.



**STEP 5:** Placement of second geonet with no overlap. Joints are offset.



**STEP 6:** Placement of geotextile with no overlap.

Figure 11.2
Liner Placement

## 11.5 PROCESSED SPOIL BACKFILL MATERIAL REQUIREMENTS

Processed Spoil Gradation Requirements: The processed gradation shall be designed to provide adequate drainage and protection to the underlying leachate collection system. The material shall consist of clean, washed, non-angular material conforming to the gradation ranges listed in TABLE 11.3.

**Table 11.3**
**PROCESSED SPOIL GRADATION**

| Standard Sieve | % Passing |
|---|---|
| 1" | 100 % |
| 1/2" | 60 to 90 % |
| No. 4 | 30 to 70 % |
| No. 10 | 15 to 50 % |
| No. 40 | 0 to 12 % |
| No. 100 | 0 to 8 % |
| No. 200 | 0 to 4 % |

Chemical Compatibility

- The processed spoil shall be laboratory tested to insure that its properties will not change after exposure to the leachate.

- The mined material shall be tested for contamination and, as required, shall be replaced by suitable non-contaminated material. The backfill material will be tested on a site specific basis.

- Stone types that are susceptible to cementing shall be replaced by inert materials.

- No chemicals shall be added to the spoil for stabilization purposes or which will break down the soil structure and/or cause a cementing reaction. This effect would adversely affect the desired high hydraulic flow characteristics of the leachate collection system.

Mechanical Compatibility (Abrasion)

• The mined material shall be tested to insure that it will not change gradation during backfilling operations in the mine or cause a cementing reaction. The gradation ranges listed in Table 11.3 are for final placement values. End point sampling of the backfill should be performed to assure placement gradation is within the specified limits of Table 11.3.

Storage/Handling

• The processed spoil shall be handled such that its gradation is not altered by abrasion, vibration, separation, or settling at any time.

• If stored above ground it should be kept dry and free of debris that would alter its properties or gradation.

Installation

• The backfill shall be placed in a way as not to damage the underlying layers of the containment system.

## 11.6 LEACHATE COLLECTION & REMOVAL TRENCH

The leachate collection & removal trench will be constructed as the lowest point in the containment section. The trench is the central collection point for the leachate captured within the LCS & backfill system and is shown in Figure 11.3. The trench shall be lined using two (2) GCL layers with a gravel bedding material. The collection piping is shown wrapped in geotextile and placed in the trench at a designed slope and is covered with processed backfill drainage material. The geonet drainage layer is continued into the trench to assure complete leachate drainage. A geotextile filter layer is placed over the trench to minimize fine particle intrusion.

The installation requirements for the drainage piping are listed below:

• All drainage piping and fittings shall be HDPE.

• HDPE pipes should be inspected to ensure proper connection and alignment in accordance with the system installation procedures and design.

• The pipes must be maintained to be free of all debris that would impair leachate flow and removal.

• The pipes must be adequately covered to ensure their integrity during backfilling or subsequent roof collapse.

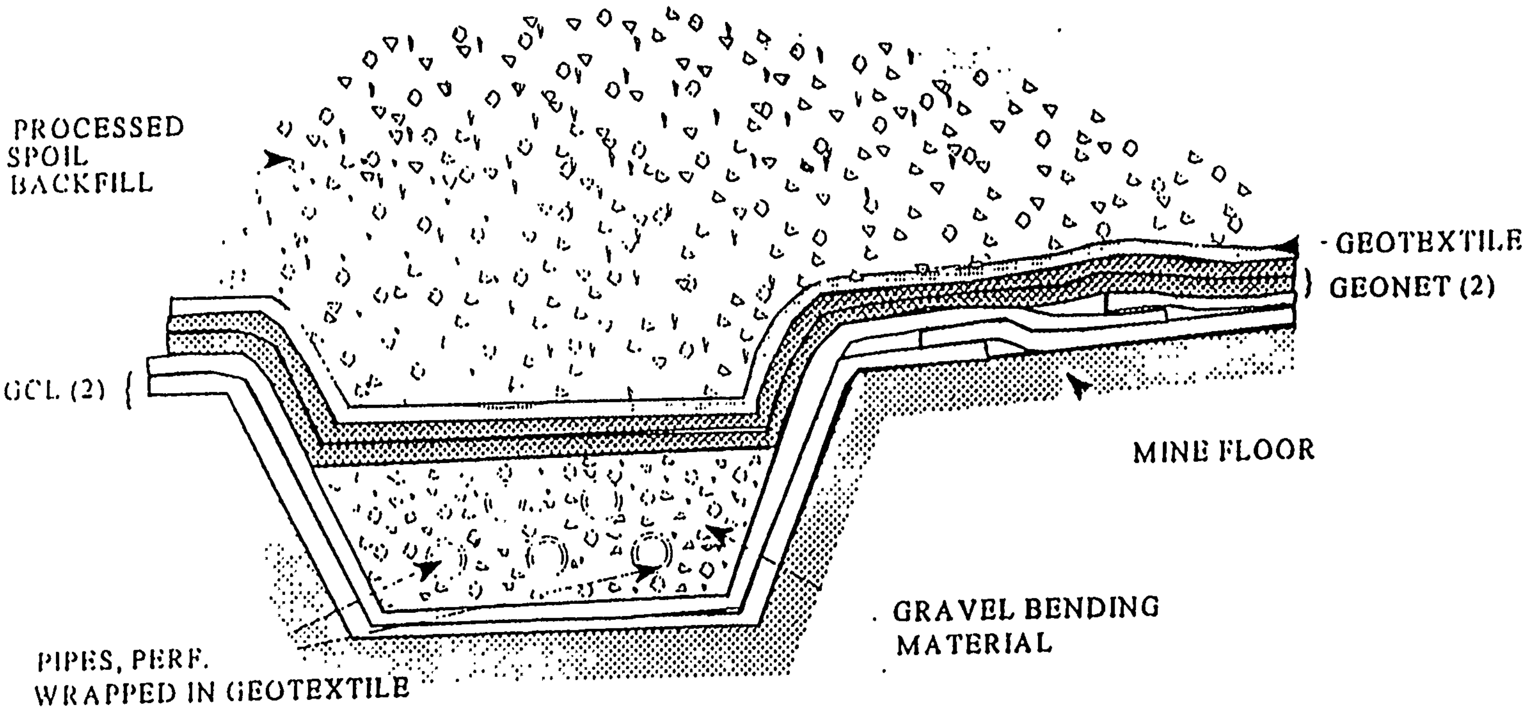



**Figure 11.3**
**Leachate Collection & Removal Trench**

## 11.7 GEOSYNTHETIC WEIGHTS & MEASURES

Table 11.4 lists the weights and measures of the geosynthetic materials as referred to in figures 11.1 & 11.2. Diameters (inches) and weights (pounds) for various lengths of geosynthetic products are given. These values are estimates and are not referenced from product literature.

**Table 11.4**
**GEOSYNTHETIC WEIGHTS & MEASURES**

| Roll Length - | 200 ft | 300 ft | 400 ft | 500 ft |
|---|---|---|---|---|
| Geosynthetic Material | roll diam/ roll wt. (in/lb) | roll diam/ roll wt. (in/lb) | roll diam/ roll wt. (in/lb) | roll diam/ roll wt. (in/lb) |
| GCL - 60 mil[1] 4' - 4" wide | 32 / 1123 | 39 / 1686 | 45 / 2247 | 50 / 2809 |
| GCL - 80 mil[1] 4' - 4" wide | 33 / 1204 | 40 / 1806 | 46 / 2407 | 51 / 3010 |
| GCL - 60 mil[1] 4' - 6" wide | 32 / 1167 | 39 / 1751 | 45 / 2333 | 50 / 2917 |
| GCL - 80 mil[1] 4' - 6" wide | 33 / 1250 | 40 / 1875 | 46 / 2500 | 51 / 3125 |
| Geonet - 250 mil 4' - 0" wide | 29 / 217 | 35 / 325 | 40 / 433 | 45 / 542 |
| Geotextile 155 mil 4' - 0" wide | 23 / 78 | 28 / 117 | 32 / 156 | 35 / 195 |

1) Application of bentonite at 1 lb/ft$^2$.

The thicknesses of the geosynthetic components are listed in tables 11.5 & 11.6. See Figures 11.4 and 11.5 for the cross sectional reference locations. These values were determined for single layer and double layer GCL systems. The values are based on a maximum Bentonite thickness of .25 inches (1.0 lb /SF application) applied to a HDPE FML backing of 60 and 80 mils.

**Table 11.5**
**LINER THICKNESSES FOR SINGLE GCL LAYER SYSTEM**

| Geosynthetic Component | Section A-A 60 mil | Section B-B 60 mil | Section A-A 80 mil | Section B-B 80 mil |
|---|---|---|---|---|
| Geotextile | 0.155 in. | 0.155 in. | 0.155 in. | 0.155 in. |
| Geonet | 0.250 in. | 0.250 in. | 0.250 in. | 0.250 in. |
| Geonet | 0.250 in. | 0.250 in. | 0.250 in. | 0.250 in. |
| GCL | 0.31 in. | 0.31 in. | 0.33 in. | 0.33 in. |
| GCL | N\A | 0.31 in. | N\A | 0.33 in. |
| GCL | N\A | N\A | N\A | N\A |
| TOTAL THICKNESS | .965 in. | 1.275 in. | .985 in. | 1.315 in. |

**Table 11.6**
**LINER THICKNESSES FOR DOUBLE GCL LAYER SYSTEM**

| Geosynthetic Component | Section C-C 60 mil | Section D-D 60 mil | Section C-C 80 mil | Section D-D 80 mil |
|---|---|---|---|---|
| Geotextile | 0.155 in. | 0.155 in. | 0.155 in. | 0.155 in. |
| Geonet | 0.250 in. | 0.250 in. | 0.250 in. | 0.250 in. |
| Geonet | 0.250 in. | 0.250 in. | 0.250 in. | 0.250 in. |
| GCL | 0.31 in. | 0.31 in. | 0.33 in. | 0.33 in. |
| GCL | 0.31 in. | 0.31 in. | 0.33 in. | 0.33 in. |
| GCL | N\A | 0.31 in. | N\A | 0.33 in. |
| TOTAL THICKNESS | 1.275 in. | 1.585 in. | 1.315 in. | 1.645 in. |

SINGLE GCL SYSTEM

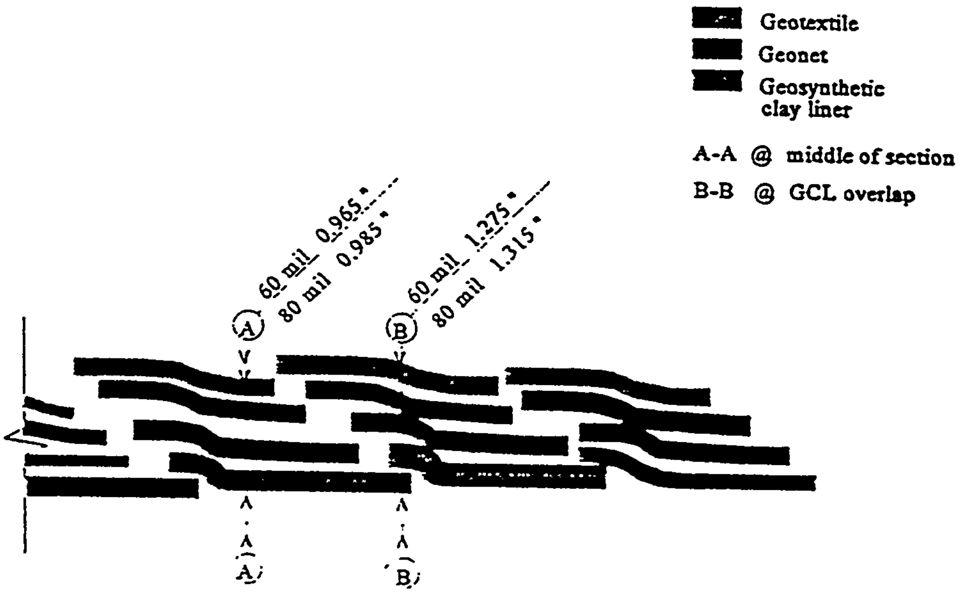



Figure 11.4
Single GCL Layer System

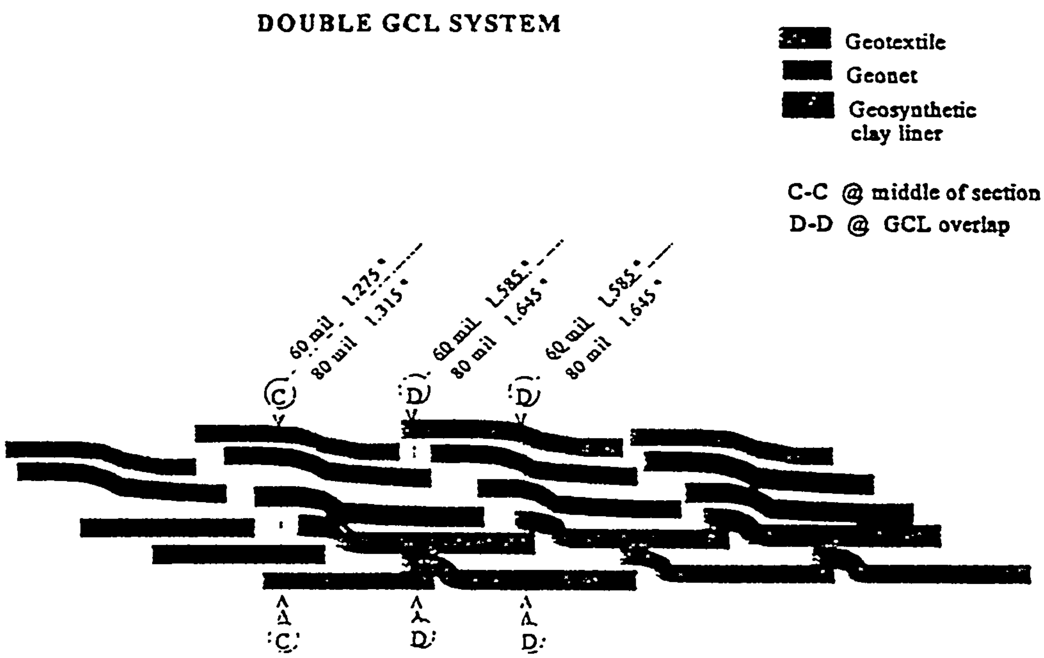



Figure 11.5
Double GCL Layer System

# 12.0 QUALITY ASSURANCE OF LINERS

The content of this Construction Quality Assurance/Quality Control (QA/QC) guidance document is for the waste containment liner system. The document is written from an overview perspective to provide performance guidelines for development of a site-specific QA/QC plan, (hence referred to as the plan). The content of this overview plan incorporates several minimum key elements which should be included in a site-specific plan developed for the hazardous waste containment at a robotically mined waste site. These key elements are summarized below and are described in greater detail in the following subsections of this document.

## 12.1 ORGANIZATIONAL OVERVIEW, RESPONSIBILITY AND AUTHORITY

The responsibility and authority of organizations and key personnel involved in designing, permitting, constructing, and oversight of the project should be clearly described in the QA/QC plan. This will help establish the necessary lines of communication that will facilitate an effective decision making process during implementation of the containment system. It is essential that the organization performing the QA/QC operate independent and are not responsible to the organizations involved in performing the mining and containment system installation efforts.

QA/QC Personnel Qualifications: The qualifications of the QA/QC personnel should be presented in the plan in terms of the training and experience necessary to fulfill their identified responsibilities.

Inspection Activities: The observations and tests that will be used to ensure that the construction or installation meets or exceeds all design criteria, plans, and specifications for each component of the liner system should be thoroughly described in the plan.

Sampling Strategies: The plan should stipulate the sampling activities, sample size, methods for determining sample locations, frequency of sampling, acceptance and rejection criteria, and methods for ensuring the corrective measures are implemented as stipulated in the engineering design criteria, plans, and specifications.

Documentation: The reporting requirements for the QA/QC plan should be described in full detail within the plan. This should include such items as daily summary reports, inspection data sheets, problem identification and corrective measures reports, block evaluation reports, acceptance reports, final documentation, and final storage of all records should be addressed by the plan.

The QA/QC plan shall require each participating organization to develop procedures during the preconstruction, construction, and post-construction processes. These procedures should describe detailed work activities to support the QA/QC program mission.

This guidance document includes minimum key elements for the QA/QC for clay and geosynthetic liners. The elements of the site-specific QA/QC plan should include procedures developed to address the elements discussed in the following subsections.

## 12.2 QUALITY ASSURANCE/QUALITY CONTROL FOR CLAY LINERS

Key factors to be considered for development of the QA/QC plan for installation of a clay liner as the primary or secondary waste containment system are listed below.

Subgrade Requirements:

Soil and rock comprising the floor of the underlying mined strata must exhibit adequate strength and hydraulic conductivity characteristics to assure the soundness of the groundwater containment system. Laboratory and on-site bearing capacity tests which may be performed on the mined floor during the mining operation should be performed. Applicable technologies for testing include surface impact penetrometers which would monitor probe penetrations along the length of the mine face as the miner progresses. The engineering site design and construction plans should include specifications to provide for preparation of adequate foundation if the mined base is not suitable.

Clay Liner Materials:

Application of the in situ mined material for use as a primary liner material or for application within a secondary composite liner system (bentonite /cement admixture), laboratory and on-site tests of the material should be performed. Table 12.1 and Table 12.2 lists conventional soil material tests currently used for surface landfill construction and their applicability for use underground. These tests should include visual observations to ascertain the soundness and homogeneity of the material prior to its use underground. Screening of the materials for compatibility testing should be conducted to verify the compatibility of the liner and contaminant waste stream to deter adverse physio-chemical reactions with the containment system. This screening should be integrated with the Construction Quality Control tests.

Appropriate samples of materials from potential borrow areas should be laboratory tested and verified with on-site conformance testing if the materials are used to construct the clay liner. If clay admixtures are used for a composite liner system, laboratory tests should be performed to determine the amount of admix needed to meet the engineering requirements. On-site tests should be performed to verify the completeness of the clay additive's mix efficiency and conformance with the required hydraulic conductivity.

## 12.3 CONSTRUCTION OF THE CLAY/COMPOSITE LINER

The QA/QC plan should include testing of the intended liner material's water content, type of compaction, compactive effort, size of clay clods, and the bonding between the liner lifts. Table 12.1 and Table 12.2 lists conventional soil material tests currently used for surface landfill construction and lists their applicability for use underground. Visual inspection efforts should be focused on verifying the effectiveness of the compaction efforts, mixing of the clay admix, and that on-site variances within the mined area do not change the physical or chemical characteristics of the liner. Such variances would include the presence of contaminated or uncontaminated groundwater, and damage to the liner caused by collapse of the mined roof.

Based on the compaction requirements, compaction specifications should be developed to indicate the minimum percent of maximum density and the water content relative to the optimum water content at which the soil should be compacted within the mined envelope.

Construction Quality Control Tests: Recommended laboratory and on-site tests are listed below. Details of the testing program should include a random sampling pattern.

Table 12.1
Conventional Surface Soil Material Tests
for Surface Landfill Construction and
Underground Application

| Conventional Surface Testing & Frequency | Robotic Waste Containment Application & Testing Frequency |
|---|---|
| 1. Clay/admixture borrow source testing: | |
| Grain size<br>1,000 cy | Standard above ground testing methods applicable,<br>1,000 cy. |
| Moisture Content<br>1,000 cy | Standard above ground testing methods applicable.<br>1,000 cy. |
| Atterberg Limits<br>5,000 cy | Standard above ground testing methods applicable,<br>5,000 cy. |
| Moisture-density curve<br>5,000 cy & material changes | Standard above ground testing methods applicable,<br>5,000 cy. |
| Lab permeability<br>10,000 cy(remolded samples) | Standard above ground testing methods applicable,<br>10,000 cy. |
| 2. Construction testing: | |
| Density (nuclear)<br>5 tests / 10,000 sf | Robotically tested underground |
| Moisture content<br>5 tests / 10,000 sf | Robotically tested underground |
| Undisturbed permeability<br>1 test / 10,000 sf | Not feasible due to underground conditions and mine environment. |
| Dry density<br>1 test / 10,000 sf | Not feasible due to underground conditions and mine environment. |
| Atterberg Limits<br>1 test / 10,000 sf | Lab testing on recovered specimens.<br>1 test / 10,000 sf. |
| Grain size<br>1 test / 10,000 sf | Lab testing on recovered specimens<br>1 test / 10,000 sf. |
| Moisture-density curve<br>5,000 cy | Lab testing on recovered specimens.<br>5,000 cy |

Table 12.2
Soil Material Test
Methods and Standards for Underground Application

| Analyzed Parameter | Methods | ASTM Test Method | Comments: Robotic Application |
|---|---|---|---|
| Soil Type | Visual-manual procedure<br>Particle size analysis Atterberg Limits Soil classification | ASTM D2488<br>ASTM D422<br>ASTM D4318<br>ASTM D2487 | Visual inspection by camera and physical evaluation on recovered specimens. |
| Moisture Content | Oven-dry method<br>Nuclear method | ASTM D2216<br>ASTM D3017 | Assurance testing on recovered samples.<br>Robotically performed in mine. |
| In-place density | Nuclear method<br>Sand cone | ASTM D2922<br>ASTM D1556 | Robotically performed in mine.<br>Not feasible to perform underground. |
| Moisture-density | Standard effort | ASTM D698 | Assurance testing on recovered samples. |
| Strength | Unconfined compressive strength | ASTM D2166 | Not required unless mining conditions require steep slope. |
| Hydraulic Conductivity (laboratory) | Fixed-wall double ring permeameter | EPA, 1983 SW-870<br>Anderson et. al., 1984 | Required for compatibility testing with site leachate. |
| Flexiwall Hydraulic Conductivity | | ASTM 5084 | Assurance testing on recovered samples. |

## 12.4 QUALITY ASSURANCE/QUALITY CONTROL FOR FLEXIBLE MEMBRANE LINERS

Preconstruction quality control activities for flexible membrane liners (FMLs) should include inspection of the raw materials, manufacturing operations, fabrication operations, and final product quality; observations related to transportation, handling, and storage of the membrane; inspection of the foundation preparation; and evaluation of the personnel and equipment to be used to install the FML. Construction activities include inspection of FML placement, seaming of the FML, installation of anchors and seals, and placement of an upper and lower protective layer. Post construction activity includes surface quality control efforts to maintain the integrity of the FML during material handling operations in the mine.

The quality of the FML liner, seams, and seaming process must be estimated from the results of inspecting representative samples of the containment system installed underground. The quality of all materials is assessed under a 100 percent inspection program coordinated using the robotic mining technology. The site specific QA/QC plan should address the following performance items.

The foundation of the mine floor provides support for the liner system, leachate collection and removal systems. A comprehensive QA/QC effort should be established to ensure that the foundation is structurally stable for its intended design function. If the foundation is not structurally stable, the liner system may deform, thus restricting or preventing its proper performance. Severe deformations of the liner system may result in failure to any of its components.

Subgrade Requirements:

Soil and rock comprising the floor of the underlying mined strata must exhibit stable bearing capacity satisfying the engineering requirements and hydraulic conductivity characteristics to assure the soundness of the groundwater containment system. Laboratory and on-site bearing capacity tests on the mined floor should be performed if the engineering design requires shallow mining depths. The site design and construction plans should include specifications that provide for preparation of an adequate foundation if the mined base is not suitable.

FML Performance Requirements:

The QA/QC plan should address the performance requirements listed in Table 12.3. These requirements include low permeability, chemical compatibility, mechanical compatibility, and durability. The engineering design performed for the site-specific containment system should incorporate requirements to ensure the system's soundness in accordance with proved performance standards. The QA/QC plan should correlate the FML's field construction with the specifications intended in the engineering design.

The QA/QC plan should require the laboratory and field testing of the following liner components.

Seam Testing: Non-destructive seam testing should be performed within the mining envelope on the field installed FML. Non-destructive seam tests which should be performed are listed in Table 12.4. Destructive tests on seams fabricated by the robotic mining equipment should be performed in both the laboratory and underground. The intent of this testing is to evaluate and determine the strength characteristics of the seam sample by stressing the bond until either the seam or the FML sheeting fails. Destructive testing of factory and field seam samples involves determining seam strength in both shear and peel modes, which is performed on a tensile testing machine.

If the test results for a seam sample do dot pass the QA/QC requirements criteria, then samples must be cut from the same field seam on both sides of the rejected sample location or a secondary patch seam should be installed over the failed area to ensure the FMLs integrity. The secondary patch seam should be applied until the primary seam test samples pass the testing requirements and the areal limits of the low quality seam(s) is defined.

Seaming Control: Seam control includes postponement of seaming until conditions within the mine envelope can accommodate the seaming process. Table 12.5 lists conditions within the mine envelope which should be continuously monitored during the FML installation and lists additional items to monitor during sheet seaming/patching operations.

Table 12.3

FML Performance Requirements

| Information | Standard Practices | Comments: Robotic Waste Application |
|---|---|---|
| Description of Flexible Membrane Liner (FML) | Descriptions of:<br>FML Type<br>Construction Materials<br>Thickness, Brand Name, Manufacturer<br>Detailed Material specifications | Standard procedures currently in use for surface applications. |
| Liner Compatibility | Results of Liner/waste compatibility.<br>Data testing demonstrating strength and performance adequate after exposure to representative waste and to primary and secondary leachates. | Standard procedures currently in use for surface applications. |
| Liner Strength | Demonstration that liner and seams will have sufficient strength to support expected load/stresses after exposure to waste and leachates. | Ability to withstand installation stresses underground. |
| Adequacy of Liner | Demonstration that sufficient bedding will be provided above and below FMLs to prevent rupture during installation. | Possible damage caused by robotic miner and mine roof collapse during installation and operation. |
| Construction Specifications | Procedures for placement of FMLs.<br>Procedures for protection of liner before and during placement and covering with the leachate collection system. | - Inspection of the liner bedding layer and mine floor for protrusions, unevenness, or ponded water which would adversely effect seaming.<br>- Placement procedures for operation of the robotic miner.<br>- Liner seam bonding techniques. |

Table 12.4
FML Seam Tests and Objectives

| Test Method | Detection Objectives | Application to Robotic Testing |
|---|---|---|
| Probe test & Air lance | Leak paths and unbonded edges of seams. | Not feasible for underground application. |
| Vacuum box | Leak paths in seams or pinholes in sheets. | Not feasible for underground application. |
| Ultrasonic pulse echo | Major voids or effective areas in the seam. | Performable by robotic miner. |
| Ultrasonic Impedance plane | Leak paths and unbonded factory field seams. | Performable by robotic miner. |
| Electrical spark test | Voids, pinholes, or unbonded areas in HDPE welds and solvent bonds. | Not feasible for underground application. |
| Pressurized dual seam | leak paths and unbonded edges of double-seam wedge, thermally welded seams where an air chamber exists between the parallel bonds of the dual seam. | Not feasible for underground application. |
| Electrical resistivity | Holes, seam unbonds, and improper penetration seals in FML installation. | Performable by robotic miner. |
| Hydrostatic test | Any leaks in the FML including pinholes, tears, seam unbonds and faulty attachments to penetrations. | Not feasible for underground application. |

Table 12.5
Seaming Control / Environment Requirements

| Items of Interest | Poor Project Conditions | Required Project Conditions |
|---|---|---|
| Ambient temperature at which the seams are made | Low temperatures | Consistent moderate temperature. |
| Relative humidity, | High humidity | Low humidity |
| Water content subsurfaces of FML. | Groundwater Infiltration | Dry mine environment |
| Supporting surfaces on which the seams are bonded, | Uneven seaming surfaces or yielding mine floor | Rigid and even seaming surfaces. |
| Precision of the seaming equipment and completeness of seams. | Incomplete FML sheet overlap.<br>Improper sheet alignment. | Complete FML sheet overlap and alignment.<br>The requirements of the adhesive systems are the same as the seaming systems except that the adhesive takes the place of the heat. |
| Quality and consistency of the adhesive or welding material and equipment, | Incomplete QA/QC criteria. | Comprehensive QA/QC plan and inspection criteria.<br>Appurtenances must be mechanically and chemically compatible for use in mine environment<br>Sealing the FML to appurtenances and penetrating structures should be preformed in accordance with detailed drawings included in the engineering design plan and specifications. |
| Proper preparation of the liner surfaces to be joined | Dirty and damp FML surface at seam interface and high amount of airborne dust and debris | Cleanliness of the seam interface and no airborne dust or debris present.<br>Thermal methods of seaming require cleanliness of the FML bonding surfaces, and the seam equipment's heat, pressure, and dwell time to produce high-quality seams. |

## 12.5 QUALITY ASSURANCE/QUALITY CONTROL FOR GEOSYNTHETIC CLAY LINERS

Geosynthetic Clay Liners (GCLs) are FMLs with a backing of bentonite clay. Preconstruction quality control activities for GCLs should include efforts given for FMLs. Construction activities specific to GCLs include: 1) inspection of GCL placement with careful attention to alignment of the sections; 2) proper overlapping of the sections; 3) installation of anchors and seals; and 4) measures to prevent moisture from contacting the bentonite backing of the GCL prior to final placement.

Subgrade Requirements:

The subgrade requirements for the GCL include those for FMLs with the following additions: 1) The mine floor must be kept as dry as possible to prevent the premature hydration of the bentonite, and 2) the mine floor should be maintained at the designed slope to prevent gaping of the GCL.

Placement/Sealing Control:

The sealing of the GCL will be performed by overlapping one section of the GCL a specified amount on the previously placed section. The overlayed sections of the GCL must be properly aligned and the upper membrane surface must be clean. Contact between the membrane surface of one section and the bentonite backing of the next section must be maintained to assure sufficient sealing of the membranes.

In the field, the overlap seal will be inspected visually or mechanically as the GCL sections are layed. Lab efforts will concentrate on determining if the seal will leak under various conditions. Technical specifications should stipulate appropriate corrective actions in the event of a seal failure. Required patching of the GCL would be performed in the same manner as for an FML.

The QA/QC plan should include provisions to insure that the mine environment is adequate for the sealing process. The conditions that should be monitored in the mine during GCL placement are the same as those listed in Table 12.5 regarding FMLs.

GCL Performance Requirements:

In addition to the requirements listed in Table 12.3 regarding FMLs. the QA/QC plan should include the requirements listed in Table 12.6. These additional requirements include specifications regarding the bentonite's structure. hydration. permeability, chemical resistance. mechanical compatibility, and durability.

Table 12.6
GCL Performance Requirements

| Information | Standard Practices | Comments: Robotic Waste Application |
|---|---|---|
| Description of Geosynthetic Clay Liner (GCL) | Descriptions of:<br>GCL Type<br>Construction Materials<br>Thickness, Brand Name, Manufacturer<br>Detailed Material specifications | Standard procedures currently in use for surface applications. |
| Bentonite Specifications | Description of:<br>Bentonite application rate,<br>Chemical/material Structure,<br>Adhesion Consistency | Standard procedures currently in use for surface applications. |
| Liner Compatibility | Results of Liner/waste compatibility. | Standard procedures currently in use for surface applications.<br>No degradation of bentonite when exposed to leachate. |
| Liner Strength | Demonstration that liner will have sufficient strength to support expected load/stresses after exposure to waste and leachates. | Ability to withstand installation stresses underground. No deformation to bentonite layer or uplifting of overlap seals. Also, strained liner will not drop bentonite. |
| Adequacy of Liner | Demonstration that sufficient bedding will be provided above and below GCLs to prevent liner and seam rupture/displacement during installation. | Possible damage caused by: 1) robotic miner, 2) mine roof collapse during installation and operation, and 3) by groundwater causing premature hydration of the bentonite. |
| Construction Specifications | Procedures for placement of GCLs & Procedures for protection of liner before and during placement and covering with the leachate collection system and backfill. | Inspection of the liner bedding layer and mine floor for protrusions, unevenness, or ponded water which would adversely effect sealing and proper alignment.<br>Placement procedures for operation of the robotic miner. |

Seal Testing:

Table 12.7 lists seal testing methods that are applicable to the GCL overlap seal type. Non-destructive testing will be performed within the mine environment. The intent of this testing is to insure constant contact between the membrane and bentonite surfaces of adjoining sections along the entire length and width of the seal.

Table 12.7
GCL Seal Tests and Objectives

| Test Method | Detection Objectives | Application to Robotic Testing |
|---|---|---|
| Vacuum box | Leak paths in overlap seals or pinholes in FML sheets. | Not feasible for underground application. |
| Ultrasonic pulse echo | Major voids or defective areas in the seam and with bentonite application. | Performable by robotic miner, and visually. |
| Visual Inspection | Visual Verification of Seam Overlapping and Alignment | Performable by remote video. |
| Mechanical Measuring System | Set Alignment and Overlap with Placement Equipment | Performable by robotic miner. |
| Hydrostatic test | Leaks in the GCL consist of: pinholes, tears, and faulty attachments to penetrations. | Lab tests used to determine seam capacity. |

# 13.0 CONTAINMENT SYSTEM TECHNICAL GUIDANCE SPECIFICATIONS

## 13.1 INTRODUCTION

This section addresses the technical engineering design and installation specifications for the preferred liner system shown in Figure 8.1. The specifications are presented from a performance perspective, providing guidelines and requirements for the development of engineering design specifications. The design specifications for this section are modeled from existing EPA guidance documents for surface waste impoundments.

These specifications are divided into four sections. Section 13.1 is the introduction. Section 13.2 lists the components of the containment system covered by these specifications. Section 13.3 lists the Codes and Standards referenced by these specifications. Section 13.4 details specifications for various fabrication and construction activities. This section covers the aspects listed in the format below:

- 13.4.1 Material Specifications
  - 13.4.1.1 Processed Spoil Backfill
  - 13.4.1.2 Geotextile Filter Layer
  - 13.4.1.3 Geonet Drainage Layer
  - 13.4.1.4 Composite Geosynthetic Clay Liner (GCL)
- 13.4.2 Transportation/Handling & Storage (Above and Below Ground)
  - 13.4.2.1 Processed Spoil Backfill
  - 13.4.2.2 Geotextile Filter Layer
  - 13.4.2.3 Geonet Drainage Layer
  - 13.4.2.4 Composite Geosynthetic Clay Liner (GCL)
- 13.4.3 Underground Installation
  - 13.4.3.1 Processed Spoil Backfill
  - 13.4.3.2 Geotextile Filter Layer
  - 13.4.3.3 Geonet Drainage Layer
  - 13.4.3.4 Leachate Collection System Piping and Pumps
  - 13.4.3.5 Composite Geosynthetic Clay Liner (GCL)
  - 13.4.3.6 Mine Floor (Subgrade)

## 13.2 COMPONENTS OF THE CONTAINMENT SYSTEM

The components of the containment system covered by these specifications are described below. The components include the processed spoil backfill layer, geotextile filter layer(s), geonet drainage layer(s), geocomposite clay liner layer(s), optional flexible membrane liner and/or geotextile protective layer(s), and the mine floor or subgrade.

Processed Spoil Backfill: The processed spoil backfill is mined material that has been transported to the surface, processed, and then replaced in the mine.

Geotextile Filter Layer: The geotextile filter will consist of a non-woven geotextile with a specified apparent opening size (AOS). This filter will overlay the geonet drainage layer and prevent fine particles from entering and clogging the leachate collection system (LCS).

Geonet Drainage Layer: The geonet drainage layer is the primary LCS. The geonets are strands of polyethylene overlapped to form a semi-rigid net-like material that provides in plane drainage.

Composite Geosynthetic Clay Liner (GCL): The composite GCL is a high density polyethylene (HDPE) membrane backed with bentonite clay. The GCL is the primary hydraulic barrier.

Mine Floor: The mine floor is the subgrade for the described groundwater containment components.

## 13.3 CODES AND STANDARDS

ASTM; American Standards for Testing and Materials.

GRI - GM; Geosynthetics Research Institute.

EPA; Environmental Protection Agency
CERI-88-33 Seminars-Requirements for Hazardous Waste Landfill Design, Construction and Closure

## 13.4 TECHNICAL SPECIFICATIONS

13.4.1 Material Specifications: The following technical specifications detail the fabrication and material properties for the containment system components.

### 13.4.1.1 PROCESSED SPOIL BACKFILL:

Processed Spoil Gradation Requirements: The processed gradation shall be designed to provide adequate drainage and protection to the underlying leachate collection system. The material shall consist of clean, washed, non-angular material conforming to the gradation ranges in TABLE 13.1:

TABLE 13.1PROCESSED SPOIL GRADATION

| Standard Sieve | Passing |
|---|---|
| 1" | 100 % |
| 1/2" | 60 to 90 % |
| No. 4 | 30 to 70 % |
| No. 10 | 15 to 50 % |
| No. 40 | 0 to 12 % |
| No. 100 | 0 to 8% |
| No. 200 | 0 to 4 % |

Chemical Compatability: The processed spoil should be laboratory tested to insure that its properties will not change after exposure to the leachate.

Mechanical Compatibility (Abrasion): The mined material shall be tested to insure that it will not change gradation during backfilling operations in the mine.

Stone Type: Stone types that are susceptible to cementing shall be replaced by inert materials.

Contaminated material: The mined material shall be tested for contamination and as required, shall be replaced by suitable non-contaminated material. The backfill material will be tested on a site specific basis.

13.4.1.2 GEOTEXTILE FILTER LAYER:

13.4.1.2.1 The geotextile supplier shall provide a list of guaranteed minimum average roll values for the specified geotextile to be installed.

13.4.1.2.2 Geotextile rolls shall be tested according to the requirements listed in TABLE 13.2:

TABLE 13.2
GEOTEXTILE TESTING METHODS

| TEST | METHOD | FREQUENCY |
|---|---|---|
| Thickness | ASTM D1777-84 | Design Dependant |
| Mass per Unit Area | ASTM D3776-84 | Design Dependant |
| Apparent Opening Size | ASTM D4751-87 | Design Dependant |
| Permittivity | ASTM D4491-85 | Design Dependant |
| Flow Rate | ASTM D4491-85 | Design Dependant |
| Puncture | ASTM D4833 | Design Dependant |
| Mullen Burst | ASTM D3786 | Design Dependant |
| Trapezoidal Tear Strength | ASTM D4533-85 | Design Dependant |
| Grab Tensile/ Elongation | ASTM D4632-86 | Design Dependant |
| Wide Width Strength/Elong | ASTM D4595-86 | Design Dependant |
| UV Resistance | ASTM D4355-84 | Design Dependant |

13.4.1.2.3 Each roll of geotextile material shall bear a label which identifies the following:

Manufacturer
Product identification
Unique roll or lot number
Roll dimensions

13.4.1.3 GEONET DRAINAGE LAYER:

13.4.1.3.1 Resin materials shall be tested according the specifications listed in TABLE 13.3:

TABLE 13.3
RESIN TESTING METHODS

| TEST | METHOD | REQUIRED VALUE | FREQUENCY |
|---|---|---|---|
| Density (min) | ASTM D1505 Condition A | 0.935 g/cm³ | Eight times per Batch |
| Melt Index (max) | ASTM D1238 Condition E | 0.3 g/10 minutes | Eight times per Batch |
| Carbon Black Content | ASTM D1603 | 2.0% - 3.0% | Twice per Day |

(Gundle, Feb. 1993)

13.4.1.3.2 The geonet supplier shall provide a list of guaranteed minimum physical properties for the specified geonet to be installed.

13.4.1.3.3 Each roll of geonet shall bear a label which identifies the following:

Manufacturer
Product identification
Unique roll or lot number
Roll dimensions

13.4.1.3.4 Finished Rolls shall conform to the specifications listed in TABLE 13.4:

TABLE 13.4
GEONET TESTING METHODS

| TEST | METHOD | REQUIRED VALUE | FREQUENCY |
|---|---|---|---|
| Mass per Unit Area | ASTM D3776 | 0.16 lb/ft$^2$ | Once per 5 Rolls |
| Thickness | ASTM D1777 | 0.200"-0.265" | Once per 5 Rolls |
| Density | ASTM D1505 Condition A | 0.940 g/cm$^3$ | Every 10,000 square feet |
| Melt Flow Index | ASTM D1238 Condition E | 0.3 g/10minute maximum | Every 10,000 square feet |
| Carbon Black Content | ASTM D1603 | 2.0% - 3.0% | Every 5,000 square feet |
| Crush Strength | ASTM D1621 | Design Dependant | Every Roll |
| Tensile Strength at Break (min) | ASTM D751 2"X5" Specimen Pulled apart at 2 in/min | 25 lb min in mach. dir. 15 lb min in X-mach. dir. | Once per 5 Rolls |
| Transmissivity | ASTM D4716-87 | 10 gal/min/ft or $2 \times 10^{-3}$ m$^2$/sec | Reference only or upon Request |

(Gundle. Feb. 1993)

13.4.1.4 COMPOSITE GEOSYNTHETIC CLAY LINER (GCL):

13.4.1.4.1 Composite Properties:

The GCl shall conform to the specifications in TABLE 13.5:

TABLE 13.5
COMPOSITE PROPERTIES

| TYPICAL PROPERTY | VALUE |
|---|---|
| Bentonite Loading | 1 lb/ft$^2$ or Specified Amount for special applications |
| Effective Hydraulic Conductivity (Gundseal) | No Measurable Leakage |
| Coefficient of Permeability (Membrane), ASTM E96 | 2.7 X $10^{-13}$ cm/sec |
| Hydraulic Conductivity (Bentonite) | 1 X $10^{-9}$ cm/sec |
| Resistance to Hydrostatic Head (ft of water), ASTM D751 | Tested to 150 ft Head<br>No Failure |
| Resistance to Water Migration Through Overlap | No Measurable Leakage |
| Resistance to Water Migration Under Membranes | Tested to 150 ft Head<br>No Measurable Leakage |
| Wet/Dry Cycles. ASTM D559 | No Effect |
| Freeze/Thaw Cycles. ASTM D559 | No Effect |
| Pliability: 180° bend over 1" mandrel @ -25° F. ASTM D146 | 10.000 cycles<br>No Failure |

(Gundle. Feb. 1993)

13.4.1.4.2 Membrane Properties:

Geomembrane Raw Material: The raw material shall be first quality polyethylene resin containing no more than 2% clean recycled polymer by weight, and meeting the specifications listed in TABLE 13.6:

TABLE 13.6 RESIN TESTING METHODS

| TEST | METHOD | REQUIRED VALUE | FREQUENCY |
| --- | --- | --- | --- |
| Spécific Gravity | ASTM D792 Method A or ASTM D1505 | 0.935 g/cm$^3$ | Eight times per Batch |
| Melt Index | ASTM D1238 Condition E | 0.05 - 0.3 g/10 minutes | Eight times per Batch |

(Gundle, Feb. 1993)

Prior to liner installation, Manufacturer shall provide the Project Manager with the following information:

The origin (resin supplier's name, resin production plant), identification (brand name, number), and production date of the resin;

Reports on tests conducted by Manufacturer to verify the quality of the resin used to manufacture the geomembrane rolls assigned to the considered facility [these tests should include the tests listed in TABLE 13.6];

Reports on the tests conducted by Manufacturer to verify the quality of the sheet.

The Owner or Owner's Representative will verify that: The property values certified by the Geomembrane Manufacturer meet all the specifications and the measurements of properties are properly documented. and that the specified test methods were used.

Membrane Testing Methods: The membrane shall be tested in accordance with testing methods listed in TABLE 13.7:

TABLE 13.7
MEMBRANE TESTING METHODS

| TEST | METHOD | REQUIRED VALUE | FREQUENCY |
|---|---|---|---|
| Thickness | ASTM D1593 | Varies | Every Roll |
| Density | ASTM D1505 | 0.94 (min) | Every 10,000sf |
| Melt Flow Index | ASTM D1238 Condition E | 0.3g/10 min. (max.) | Every 10,000sf |
| Carbon Black % | ASTM D1603 | 2.0 - 3.0 % | Every 5,000sf |
| Carbon Black Dispersion | ASTM D3015 | A-1, A-2, B-1 | Every 10,000sf |
| Tensile Properties<br>Strength at Yield<br>Strength at Break<br>Elong. at Yield<br>Elong. at Break | ASTM D638 Modified Type IV Dumb-bell @ 2"/minute | <br>Varies<br>Varies<br>13 %<br>700 % | Every other Roll |
| Tear Resistance | ASTM D1004, C | Varies | Every other Roll |
| Puncture Resistance | FTMS 2065, 101B | Varies | Every other Roll |
| Environmental Stress Crack | ASTM D1693 Condition B | 1500 hours (min.) | Once per Resin Batch |
| Dimensional Stability | ASTM D1204 | +/- 2.0 % | Every 50,000 square feet |
| Resistance to Soil Burial | ASTM D3083 With ASTM D638 | +/- 10 % | Every Roll |
| Thermal Stability OIT - Oxidative Induction Time | ASTM D3895 | 2000 minutes (min.) | Once per Resin Batch |

TABLE 13.7
MEMBRANE TESTING METHODS (cont.)

| TEST | METHOD | REQUIRED VALUE | FREQUENCY |
|---|---|---|---|
| Low Temp. Brittleness | ASTM D746 Procedure B | -112°F | Every 50,000 square feet |
| Coefficient of Linear Thermal Expansion | ASTM D696 | $2.0 \times 10^{-4}$ cm/cm°C | Every 50,000 square feet |
| Tensile Impact | ASTM D1822 | Varies | Every 5,000 square feet |
| Hardness Type D | ASTM D2240 | 50 | Every 5,000 square feet |
| Volatile Loss | ASTM D1203 | 0.3 % (max.) | Every 50,000 square feet |
| Water Abs. | ASTM D570 | 0.1 % (max.) | Every 5,000 square feet |
| Hydrostatic Resistance | ASTM D571 | Varies | Every 5,000 square feet |
| Water Vapor Transmission | ASTM E96 | 0.1 g/m²/day (max.) | Every 5,000 square feet |
| Modulus of Elasticity | ASTM D638 Modified | Design Dependant | Every 10,000 square feet |
| Differential Scanning Calorimeter - DSC | ASTM D3417 | Design Dependant | Once per Resin Batch |
| Thermogravi-metric Analyzer - TGA | | Design Dependant | Once Per Resin Batch |
| Multi-Axial | GRI - GM 4 | Design Dependant | Every 10,000 square feet |

13.4.1.4.3 Bentonite Properties:

The bentonite used to back the GCL shall conform to the properties listed in TABLE 13.8:

TABLE 13.8
BENTONITE PROPERTIES

| PROPERTY | TYPICAL VALUE |
|---|---|
| Percent Montmorillonite | 80 - 90 % |
| Silicon Dioxide ($SiO_2$) | 55 - 64 % |
| Aluminum Oxide ($Al_2O_3$) | 16 - 22 % |
| Ferric Oxide ($Fe_2O_3$) | 3 - 6 % |
| Sodium Oxide ($Na_2O$) | 1 - 3 % |
| Magnesia (MgO) | 2 - 4 % |
| Lime (CaO) | 1 - 3 % |
| Miscellaneous | 1 - 5 % |
| Water Content | 5 - 10 % |
| Bulk Density | 77 $lb/ft^3$ |
| Dry Particle Size | 20 - 50 mesh |
| Free Swell | 22 - 28 ml/2 gm |

13.4.2 Transportation/Handling & Storage (Above and Below Ground)

13.4.2.1 PROCESSED SPOIL BACKFILL

The processed spoil shall be handled such that its gradation is not altered by abrasion, vibration, seperation, or settling.

If stored above ground it should be kept dry and free of debris that would alter its properties or gradation.

13.4.2.2 GEOTEXTILE FILTER LAYER

During shipment and storage, the geotextile shall be protected from ultraviolet light exposure, precipitation or other inundation, mud, dirt, dust, puncture, cutting or any other damaging or deleterious conditions. Geotextile rolls shall be shipped and stored in opaque and watertight wrappings.

13.4.2.3 GEONET DRAINAGE LAYER

Geonets shall be shipped and stored in a manner that protects the material from mud, dirt, and damage, or any other deleterious conditions.

13.4.2.4 COMPOSITE GEOSYNTHETIC CLAY LINER (GCL)

GCLs, when off-loaded, should be placed on a smooth raised surface free of rocks or any other protrusions which might damage the material and covered so that moisture can not come in contact with the bentonite backing.

Prior to off-loading the GCL it should be verified that handling equipment used on the site is adequate and does not pose any risk of damage to either the geomembrane or bentonite backing.

Upon arrival at the site, surface observation of all rolls for defects and damage shall be conducted. This inspection shall be conducted without unrolling rolls unless defects or damages are found or suspected.

Storage space should be protected from theft, vandalism, passage of vehicles, and be adjacent to the area to be lined. Geosynthetic clay liner storage should be elevated and dry.

13.4.3 Underground Installation

13.4.3.1 PROCESSED SPOIL BACKFILL

The backfill shall be placed in a way as not to damage the underlying layers of the containment system. The backfill shall have a large slope angle and low moisture content.

13.4.3.2 GEOTEXTILE FILTER LAYER

The geotextile shall be installed in a manner that does not damage any underlying layer or is itself damaged.

The geotextile shall have no overlap.

The geotextile shall be laid smoothly. Slight tension shall be maintained during placement to prevent twisting, buckling, and wrinkling of the geotextile.

13.4.3.3 GEONET DRAINAGE LAYER

The geonet drainage layer shall be installed in a manner that does not damage the underlying layers of the containment system.

The geonet shall be placed evenly and the surface shall be kept free of dirt or grease which would inhibit the geonet's performance after installation.

13.4.3.4 LEACHATE COLLECTION SYSTEM PIPING AND PUMPS

The leachate collection system shall be constructed in accordance with the site specific design plans. The leachate removal system pipe shall conform to the material specifications provided by the site design specifications.

Riser pipes and attachments shall conform to the site design plans and the design specifications.

The submersible pump shall be designed to handle the expected leachate removal requirements. The pump shall be constructed of material proven to be compatible with the chemical composition of the leachate.

### 13.4.3.5 COMPOSITE GEOSYNTHETIC CLAY LINER (GCL)

The GCL shall be installed in a manner that it is not damaged by the mine floor or installation equipment. This includes damage to both the bentonite backing and membrane.

The GCL shall be kept as dry as possible during the installation. Protective measures shall be taken to prevent loss of the bentonite backing due to abrasion on the mine floor.

The GCL shall be overlapped at all edges 6 inches with a ±1 inch tolerance. Additional layers shall be placed with edges offset to previous layers. The GCL shall be placed evenly and steps shall be taken to insure good contact between layers. The membrane surface shall be kept free of dirt, grease, or excess moisture that could prevent a good seal.

Installation shall be done in a way that no excess strains are placed on the liner. Tension required to prevent buckling and twisting shall be carefully monitored to insure no damage is done to the bentonite backing and to prevent tears or punctures in the membrane.

### 13.4.3.6 MINE FLOOR (SUBGRADE)

The mining shall progress at a rate that will leave the mine floor as smooth as possible. Debris shall be removed before placement of overlying layers.

The mine floor shall be checked for voids and protrusions and to insure that it is smooth and has adequate bearing strength to support the overlying layers.

The mine floor shall be tested according to TABLE 13.9:

TABLE 13.9
SUBGRADE TESTING

| TEST | METHOD | FREQUENCY |
| --- | --- | --- |
| Nuclear Density | Robotically Tested | Every 1,000 sf |
| Moisture Content | Robotically Tested | Every 1,000 sf |
| Atterberg Limits | Lab Tested | Every 10,000 sf |
| Grain Size Dist. | Lab Tested | Every 10,000 sf |
| Moisture-density Curve | Lab Tested | Every 5,000 sf |

# APPENDIX A

# APPENDIX A

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