- Rills or deposition beyond berm crests
- Recently patched or reshaped sections of berms
- Subsurface flow escape from ditches and berms
- Mass slope failure or hummocky terrain and seepage downslope from berms or on the outer slopes of road fills
- Unexplained local patterns in vegetation
- Lack of vegetation
- Patterned deposition of dispersed soils below berms, at culvert outlets, or on road fill slopes
- Outflow around rather than through culverts.

Control of Water and Water Quality

Effects of Surface Mining

Water Flow

Whether water runs off or infiltrates during a rainstorm depends on slope, vegetative cover, soil conditions, and soil compaction. Infiltration will be increased by mining activities that produce cast spoil that is full of voids. This may also result in greater permeability and significant increases in water-holding capacity. But overburden moved by either scraper or truck will tend to be compacted and will likely have more runoff than the undisturbed site.

Surface mining may increase groundwater storage capacity. Any increase in capacity will depend on both the method of spoil placement and the character of the spoil itself. It is possible that "recharge zones" may be created by selecting those portions of the spoil that have the best infiltration characteristics and placing them where surface water can be diverted into them.

Increased infiltration usually means higher and longer baseflow of streams when the water eventually reappears in springs or seeps. Increased streamflow during dry weather and prolonged flow in streams that normally flow only intermittently are generally considered desirable. Studies have shown an increase in dry weather streamflow following surface mining. Other studies have shown that storm peak flows may be several times higher from mined watersheds than from unmined areas during and immediately after mining, but that after reclamation is complete, peak flows in mined areas can be significantly lower. The amount and velocity of runoff during storms will be a major factor in the amount of erosion and hence the amount of sedimentation.

Water Quality

Acid mine drainage (AMD), the detachment and transport of solid particles by flowing water, and the subsequent settling of those particles (sedimentation) are the major water quality problems caused by surface mining.

Sediment. Many experiments have quantified the sediment resulting from erosion on both active and abandoned surface mines. Current technology for control of erosion and sediment has evolved from experimental data as well as from field trials of a variety of sediment control features.

Preventing erosion and subsequent sedimentation is important to prevent:

- Sediment deposition in stream channels
- Continual exposure of toxic- or acid-forming spoil by erosion of unstable slopes
- Loss of soil needed to support a vigorous vegetative cover.

Acid Mine Drainage. When coal is mined, previously protected strata are exposed to oxygen, and in the case of surface mines, to direct weathering as well. When water and oxygen come into contact with iron disulfides (pyrite and marcasite), these minerals will oxidize and release sulfuric acid and ferrous sulfate. These oxidation products, together with an assortment of trace elements soluble in acid, are commonly called acid mine drainage (AMD). In most cases AMD will eventually find its way into streams and groundwater. The ferrous sulfate can oxidize further to produce an insoluble precipitate of ferric hydroxide and additional sulfuric acid. Iron disulfide that is under water or buried in impermeable materials will be effectively protected from oxygen, so no significant oxidation will take place. The only pyritic material in natural systems that can be oxidized at an environmentally significant rate is that which is exposed to atmospheric oxygen. The amount and rate of acid formation and the quality of water discharged are functions of the amount and type of pyrite in the overburden and coal, the duration of exposure to oxygen, the characteristics of the overburden, and the amount of water available.

If the overburden also contains alkaline material such as limestone, acid may be partially or entirely neutralized before it is discharged. However, discharges may be high in sulfate.

The pattern of acid discharge tends to be erratic. Streams may be damaged by continuous acid discharges that occur when streamflows are at low and moderate levels. However, the extremely high discharges when mines are dewatered can also be damaging. Likewise, "flushouts" of acids by the first storm following a drought can be devastating.

Acid Prevention. All techniques for preventing acid formation are based on the control of oxygen. There are two mechanisms by which oxygen can be transported to pyrite: convective transport and molecular diffusion.

The major energy source for convection transport is likely to be the heat generated by the oxidizing pyrite. As hot gases surrounding the pyrite rise, they are replaced by cool air containing oxygen. Changes in atmospheric pressure also induce exchanges between spoil gases and the atmosphere. Wind currents against steep slopes can drive oxygen deeper into the spoil mass. As pyrite is oxidized, oxygen is removed from the spoil atmosphere, thus creating a partial vacuum and drawing in still more outside air.

Molecular diffusion occurs whenever there is a gradient of oxygen concentration between two points, in this case, the spoil surface and some point within the spoil. Molecular diffusion is applicable to any fluid system, either gaseous or liquid. Oxygen will move from the air near the surface of the spoil, where the concentration is higher, into the gases or liquid-filled pores within the spoil, where the

concentration is lower. The rate of oxygen transfer is much higher in gases than in liquids. For example, the diffusion of oxygen through air is approximately 10,000 times as fast as in water. Therefore, even a thin layer of water (several millimeters) serves as a good oxygen barrier.

Artificial barriers such as plastic or bituminous films or concrete would probably be effective, but they have high original and maintenance costs and could be justified only in special situations.

Surface sealants such as lime, gypsum, sodium silicate, and latex have been tried, but they too are costly, require repeated application, and are only marginally effective. The two most effective barrier materials are soil, including nonacid spoil, and water. The thickness of soil or nonacid spoil required as a barrier is a function of the soil's physical characteristics, compaction, moisture content, and vegetative cover. Deeper layers of a sandy, porous material would be required than of a tightly packed clay that is essentially impermeable. Soil thickness should be designed for the worst situation—when the soil is dry and oxygen can move more readily through cracks and pore spaces. When water instead of gas occupies the pores it blocks the flow of oxygen. A "safety factor" should be included to account for soil losses by erosion. Vegetation serves as a barrier against wind. As the vegetation dies, it becomes an oxygen user during the decomposing process and increases the effectiveness of the barrier; and the organic matter that is formed increases the moisture-holding capacity of the soil. If organic matter is buried with pyrite and immersed in water, reducing conditions should prevail under which sulfate may be reduced back to iron sulfide and eventually to pyrite or marcasite. Water is an extremely effective oxygen barrier when the pyritic material is permanently covered. However, controversy continues as to whether less AMD would be produced if pyrite were kept above the water table or if it were allowed to alternate between flooded and nonflooded cycles.

Acid Control. Additional measures to control AMD are water control and in-place neutralization. Water not only serves as the transport medium that carries the acid pollutants from the pyrite reaction sites and mine, but it also erodes soil and nonacid spoils to expose additional pyrite to oxidation. Facilities such as diversion ditches that prevent water from entering the mining area or carry it quickly through the area can significantly reduce the amount of water available to transport the acid products. These facilities, which are discussed under "Control of Water and Water Quality", are needed both during and after mining. Terraces, mulches, vegetation, etc. used to reduce the erosive forces of water are effective in preventing further exposure of pyrite.

Alkaline overburden material and agricultural limestone can be blended with acidic material to neutralize the acid in place and assist in establishing vegetation. In some cases, alkaline overburden can be graded so that acid seeps drain through it, neutralizing the acid.

Even neutral or slightly acid soils, spoils, and aquifer materials have considerable potential for removing the acid and trace element components of AMD through ion exchange processes, wherein the acids and dissolved metals from the water are exchanged with the exchangeable bases (calcium, magnesium, sodium, and potassium) from the soils, spoils, and aquifers.

Treatment of Acid Mine Drainage. A number of methods can be used to treat AMD. Where the formation of AMD cannot be prevented, treatment is necessary before the water can be discharged from the permit area. One method of treating AMD is neutralization, which provides the following benefits:

- Neutralization removes the acidity by adding alkalinity.
- It increases pH to somewhere near a neutral level.
- It removes most heavy metals by causing them to precipitate out of solution. The solubility of heavy metals is dependent on pH up to a point: usually the higher the pH, the lower the solubility.
- Soluble ferrous iron, often associated with AMD, oxidizes to ferric iron faster at higher pH values, then quickly precipitates from solution.
- Sulfate can be removed if sufficient calcium ion is added to cause the solubility product constant of calcium sulfate to be exceeded.

Some shortcomings of the neutralization process are:

- Hardness may be increased
- Sulfate may exceed 2,000 milligrams per liter
- The iron concentration usually is not reduced below 3 to 7 milligrams per liter
- A waste sludge is produced that must be disposed of
- Total concentration of dissolved solids is increased.

A typical neutralization system would include adding an alkaline reagent, mixing, aerating, and removing the precipitate. Alkaline reagents that may be used are lime, limestone, anhydrous ammonia, soda ash, and sodium hydroxide (Fig. 1).

Hydrated or slaked lime is the most commonly used treatment. Hydrated lime reacts with AMD as follows:

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 + 2\,H_2O \rightarrow CaSO_4 \bullet 2H_2O \quad (1)$$

(Hydrated Lime) + (Sulfuric Acid) → (Calcium Sulfate) + (Water) → (Gypsum)

$$Ca(OH)_2 + FeSO_4 \rightarrow Fe(OH)_2 + CaSO_4 \quad (2)$$

(Hydrated Lime) + (Ferrous Sulfate) → (Ferrous Hydroxide) + (Calcium Sulfate)

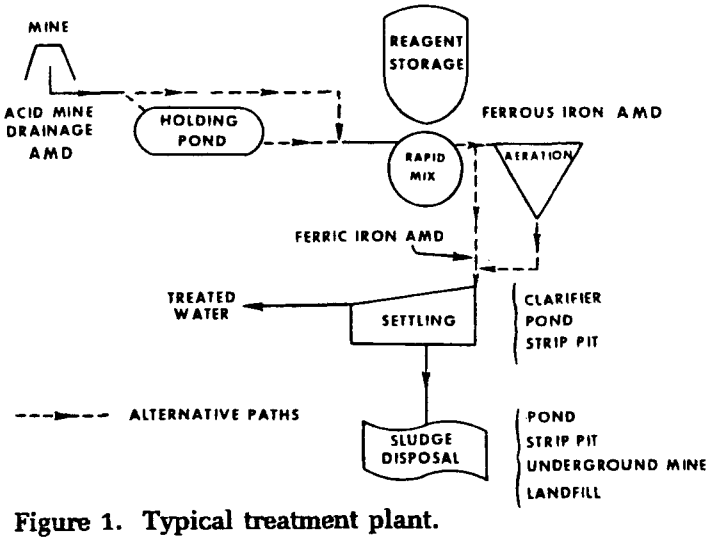

Figure 1. Typical treatment plant.

$$3Ca(OH)_2 + Fe_2(SO_4)_3 \rightarrow 2\ Fe(OH)_3 + 3\ CaSO_4 \quad (3)$$

(Hydrated Lime) + (Ferric Sulfate) → (Ferric Hydroxide) + (Calcium Sulfate)

If the concentration of calcium sulfate exceeds about 4,000 mg/l then the excess is likely to precipitate as gypsum ($CaSO_4 \bullet 2H_2O$). In a typical treatment facility, AMD is discharged directly to a rapid-mix chamber or to a holding/flow-equalizing pond where it flows to the rapid-mix chamber. Hydrated lime is fed either as a slurry or dry to the rapid-mix chamber. If the ferrous iron concentration is low (less than 50 mg/l), the water is treated to a pH of 6.5 to 8 and flows directly to a settling chamber. If ferrous iron is high, the water is usually treated to raise the pH to 8 to 10, and then passed to an aeration tank where the ferrous hydroxide precipitate is converted to ferric hydroxide. Then the water flows to a settling chamber. The settling chamber may be a clarifier or pond. Here the iron, aluminum, calcium sulfate, and other heavy metals precipitate. The supernatant is the treated water. The precipitate or sludge is removed from the settling chamber and disposed of in a second pond, mine pit, underground mine, or landfill. In some cases, the pond serves as a settling chamber and permanent storage place for the sludge.

Except for large surface mines, lime systems are usually much less sophisticated than the one described above. They may be as simple as catching all the AMD in a small pond, then hand broadcasting lime on the surface of the pond. This is effective only when the pond is less than 1,000 square meters (0.25 acres). Excess lime is required in this system because mixing of the lime and acid water is poor. After the water is treated, it is pumped from the pond.

Acid water can be treated as it is pumped from the pit by connecting a lime slurry tank to the suction end of the pump. As water is pumped, the lime slurry is drawn into the AMD by the suction of the pump; the pump also serves to mix the lime and acid water. Discharge from the pump should pass through a settling pond to remove any precipitates.

Limestone reacts with AMD as follows:

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2 \quad (4)$$

(Limestone) + (Sulfuric Acid) → (Calcium Sulfate) + (Water) + (Carbon Dioxide)

$$3CaCO_3 + Fe_2(SO_4)_3 + 3\ H_2O \rightarrow 3\ CaSO_4 + 2\ Fe(OH)_3 + 3\ CO_2 \quad (5)$$

(Limestone) + (Ferric Sulfate) + (Water) → (Calcium Sulfate) + (Ferric Hydroxide) + (Carbon Dioxide)

Although limestone is a cheaper reagent than lime and produces less and denser sludge, it has not received wide acceptance for several reasons: (1) the carbon dioxide produced buffers the reaction, and it is difficult to raise the pH above 6 without using excessive material; (2) limestone is ineffective with water high in ferrous iron; (3) the size, characteristics, and method of application of the limestone are critical; and (4) the system is usually more complex than a hydrated lime system.

Several different treatment schemes have utilized limestone. Those most applicable to surface mine situations are streambed and ground limestone techniques. The simplest method is the placement of limestone in a streambed. The acid water is treated as it flows through the bed. However, this method has proven ineffective in most cases because the limestone quickly becomes coated with various iron precipitates, calcium sulfate, sediment, and biological growths that prevent acid water from reacting with the limestone. The method may have application for short-term situations not exceeding a month. In such an installation, a trench leading from the surface mine should be dug and filled with crushed limestone (2.5 centimeters or 1-inch size). Basins should be used to settle out silt before it reaches the trench and to settle out the precipitate beyond the trench. Surface water should be diverted away from the trench to prevent the limestone from being washed out during storms. If the limestone bed loses its effectiveness, the stone should be replaced or a new trench dug.

Pulverized limestone can be used like lime. The following factors should be considered in the selection of a limestone: (1) high calcium carbonate content, (2) low magnesium content, (3) low amount of impurities, and (4) large surface area, i.e., smallest particle size within economic bounds (200 mesh or smaller is preferable). Pulverized limestone can be fed as a slurry or dry. Two to three times the stochiometric amount of limestone will probably be required, and even then pH will only reach 6 to 6.5. The reaction of pulverized limestone is much slower than that of hydrated lime, and up to 30 minutes of mixing should be provided.

The split treatment of AMD with limestone and hydrated lime may offer some advantages in cost and improved sludge characteristics. It might also be used on ferrous-iron AMD. A two-step process is required. First, the AMD is treated with limestone to a pH of 4.0 to 4.5 to take advantage of the pH range where limestone is most effective. The water then passes to a second reactor where hydrated lime is applied to raise the pH to the desired level. This process may have a cost advantage over hydrated lime alone.

Anhydrous ammonia will neutralize acid as shown in equation 6 and has been utilized for the neutralization of AMD.

$$NH_3 + H^+ \rightarrow NH_4^+ \quad (6)$$

(Gaseous Ammonia) + (Acid) → (Ammonium)

Such a system is easy to operate and maintain. Usually, the only equipment used is a tank of anhydrous ammonia, a length of hose to discharge the material into the AMD, and a valve to control the flow of gas. Anhydrous ammonia is usually supplied by the dealer in pressurized tanks mounted on wheels. The tanks are easily moved from site to site and can be set up in a matter of minutes.

The disadvantages of anhydrous ammonia are: (1) ammonia is lost to the atmosphere by diffusion or by air-stripping where aeration is practiced; (2) more sludge may be produced; (3) the reagent costs more than hydrated lime or limestone; (4) ammonia-neutralized AMD may have a detrimental effect on a receiving stream because of the toxicity of ammonia to fish and aquatic life, the depression of dissolved oxygen levels as a result of nitrification, and nitrate enrichment, which may lead to accelerated eutrophication; and (5) ammonia may oxidize in the streams to nitrate and

acid, thus eventually reacidifying the stream in accordance with the reaction:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \quad (7)$$

(Ammonium) + (Oxygen) → (Nitrate) + (Water) + (Acid)

It is clear from equations 6 and 7 that ammonia has the potential for eventually generating twice as much acid as it initially neutralized.

The detrimental effect on receiving streams is significant enough to warrant the recommendation that anhydrous ammonia not be used to treat AMD except under special conditions. Levels of ammonia nitrogen and nitrate nitrogen far beyond the acceptable limits for streams have been found in AMD treated with anhydrous ammonia. The only situation where anhydrous ammonia may be acceptable is where small volumes of AMD are to be treated, and the treated water is applied to spoil banks as irrigation water so no runoff occurs.

Sodium carbonate neutralizes acid, as shown in equation 8, and has been utilized for the treatment of AMD because simple feeders have been developed.

$$Na_2CO_3 + 2H^+ \rightarrow 2\ Na^+ + H_2O + CO_2 \quad (8)$$

(Sodium Carbonate) + (Acid) → (Sodium) + (Water) + (Carbon Dioxide)

In most cases, soda ash briquettes have been used. A portion or all of the AMD is passed through a container holding the briquettes. The briquettes dissolve, neutralizing the water. These systems, which are usually used on small flows, are temporary and are easily moved. Their disadvantages are that good control of pH cannot be maintained, and very high flows cannot be adequately treated. Also, the higher cost of soda ash militates against its use.

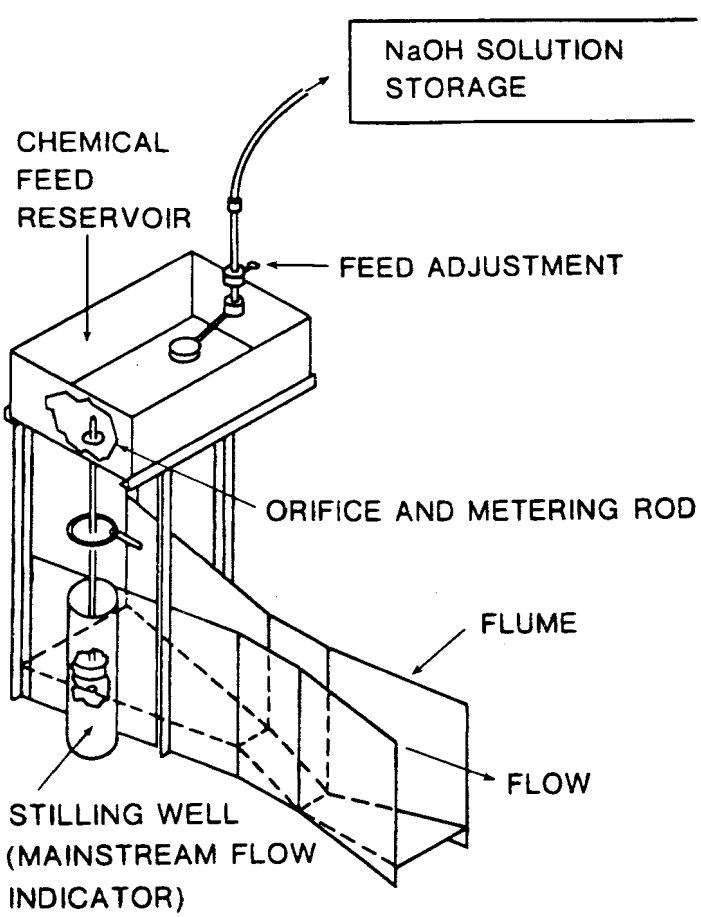

Figure 2. Chemical feeder for treating AMD.

One neutralizing system uses sodium hydroxide to neutralize acid as shown in equation 9.

$$NaOH + H^+ \rightarrow Na^+ + H_2O \quad (9)$$

(Sodium Hydroxide) + (Acid) → (Sodium) + (Water)

The addition of sodium hydroxide is controlled by the water level in a small flume (Fig. 2). The device may be suitable for remote locations because it is easily moved, requires no electricity or power, and is simple to operate. The device is best suited to small flows. A baffle to ensure good mixing is desirable for best operation. Sodium hydroxide costs more than hydrated lime or limestone.

Stream Diversions

Stream diversions are important in the control of water and sediment in many areas. Diversions are often used to intercept clean runoff and streamflow and convey it around the working area. Diverting overland flow before it enters the mine area also helps to keep the working areas dry. Where overburden contains acid-forming materials, diversion of water around the workings will reduce the formation of AMD. Often the diverted flow can be routed to the receiving water course below sediment control structures. In such cases, diversions reduce the amount of flow that must be passed through sedimentation ponds, allowing smaller sedimentation structures to be used.

Sedimentation Ponds

If runoff water is impounded along the way, some of the suspended solids will settle out. The amount of material that will settle depends upon the detention time, the size of the suspended particles, and the amount and valence of electrolytes dissolved in the water. Large heavy particles settle rapidly but small particles may take days to settle (Fig. 3). In some cases settlement can be speeded by adding flocculants to the water. Location, design, construction, and maintenance of sediment ponds are critical to their performance.

Handling Pit Water

Water that accumulates in the mine pit is likely to be polluted with suspended particles or dissolved salts or both. Pit water is exposed to rock dust, coal dust, and associated pyritic materials. Oxidation of pyrite produces acid; dust becomes suspended in the water. Therefore, pit dewatering is likely to result in pollution of receiving waters. If the coal lies below the groundwater table, pumping to keep the pit dry may lower the water table and reduce the yield of nearby wells, springs, and seeps. In most instances, it is economically advantageous to the operator to minimize the volumes of pit water.

Haul Roads

Significant amounts of land affected by surface mining are devoted to access and coal haul roads. The quality of a road depends largely on its drainage facilities. Improper design, construction, and maintenance of haul roads and faulty attempts to bed down the roads after mining operations are completed can lead to erosion and sedimentation. These problems can be minimized by proper construction, proper routine maintenance of haul road surfaces and drainage structures, and control of road gradients during design and field location. Steep gradients tend to increase erosion and may require more maintenance.

Terraces

A terrace is a bench with a reverse grade that intercepts runoff. There are two distinct types of terraces: the level terrace, as implied, is level and simply intercepts and impounds runoff. A gradient terrace is graded to direct water along its length to an outfall on stable ground. The gradient terrace is the most common.

Terraces reduce erosion by intercepting runoff on long slopes and conveying it at nonerosive velocities to a drain or disposal area. Length of slope is an important factor affecting the amount of erosion. Generally, the longer the slope, the greater will be the runoff for a given precipitation event. Erosive capacity, and consequently the formation of rills and gullies, increases with flow volume and velocity. Terracing controls runoff and significantly reduces erosion. Terracing on gently sloping spoils can cut storm peak runoff rates and sediment yields by as much as 50 percent.

By slowing runoff, terraces will also cause more water to infiltrate the regraded spoil. This has two important implications:

- Infiltration into the spoil mass may reduce its shear strength and result in instability and slumping of the mass. Great care should be taken to ensure that runoff does not pond on the terraces where mass instability may become a problem, but flows steadily at a uniform gradient to stable ground.
- Increased infiltration will tend to increase the availability of water for plants, resulting in improved survival and growth of vegetation.

Terraces are commonly used on excess spoil disposal sites, such as head-of-hollow fills, valley fills, and steep outslopes. In such circumstances, a terrace may increase mass stability as well as intercept runoff.

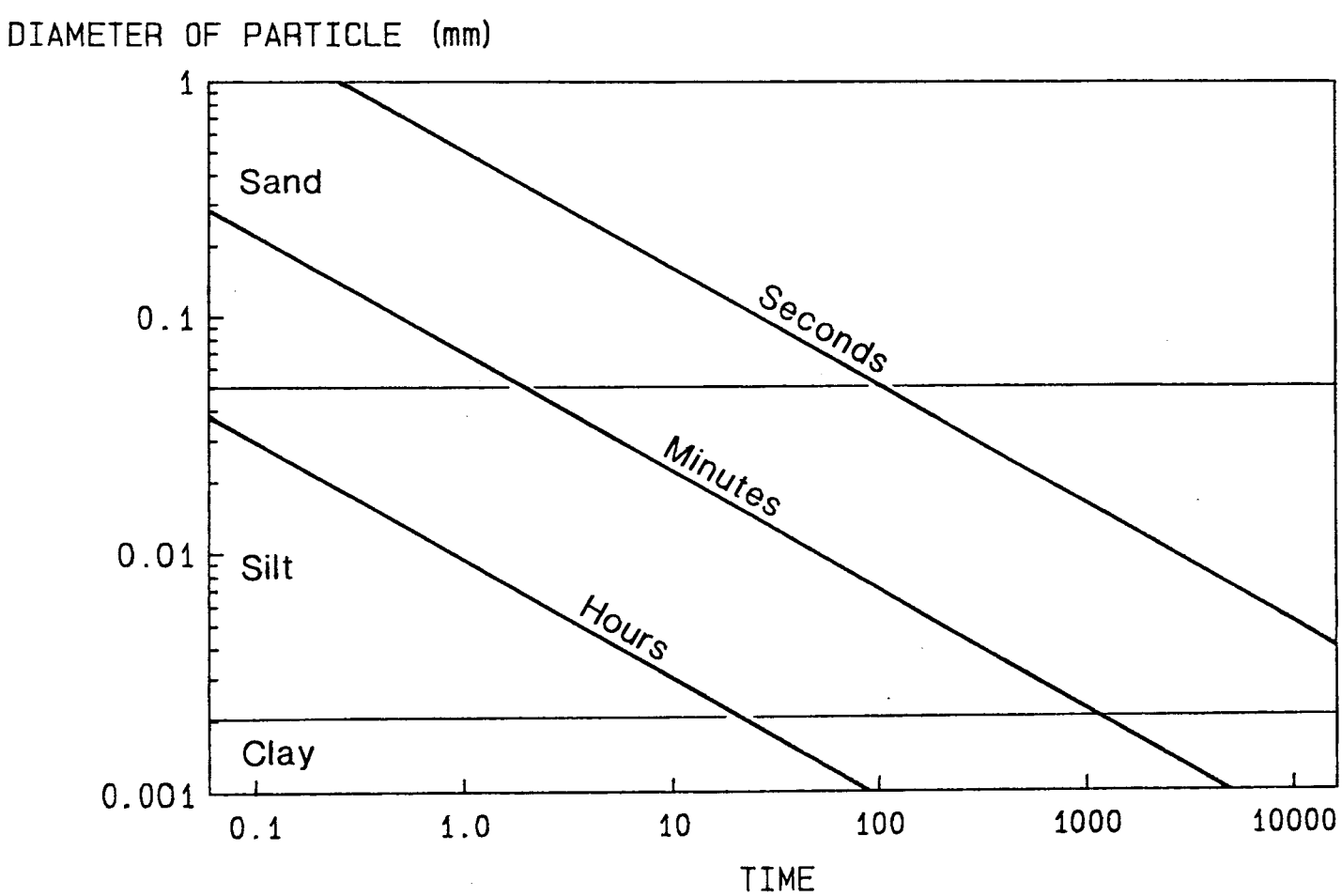

Figure 3. Time required for particles of various sizes to fall 1 foot based on Stoke's law assuming 25 °C and specific gravity of 2.65.

Grass Waterways

Grass waterways are used to convey water at nonerosive velocities to a safe disposal point. Grass waterways may be either temporary or permanent. They carry runoff during heavy rainfall but are otherwise dry. When possible, they should be constructed in natural drainage swales.

Underdrains

Underdrains may be necessary in special cases, such as where the proposed post-mining use is cropland or where overly wet conditions may cause erosion problems in grass waterways. Underdrains are a significant feature of fill construction where they serve to prevent saturation of the fill mass and the formation of a slip-surface between the fill materials and the original ground surface.

Mulches

Where soil surfaces are highly susceptible to erosion, as on steep or long slopes, mulches can provide protection against erosion. Mulches reduce evaporation and increase the availability of soil moisture to young plants. When they decompose most organic mulches provide a small amount of plant nutrients. Mulch will protect soil from the impact of rain and reduce formation of a soil crust. Mulches intercept and disperse much of the radiant energy of sunshine and the kinetic energy of rainfall. Mulches reduce the velocity of runoff, and hence its erosive capacity. Mulches may be mechanically applied to the soil surface or they may be "home grown" in the form of cover crops or plant litter.

Vegetation

A good permanent vegetative cover can be highly effective in controlling runoff, erosion, and sedimentation. The choice of species to be seeded or planted depends upon short-term and long-term needs and the post-mining land use. Choices may include temporary cover crops, permanent herbaceous species, permanent trees and shrubs, or any combination thereof. Each class of vegetation has its place in reclamation programs. Diversity of species is usually desirable to encourage soil stabilization at various depths and to perform functions such as nitrogen fixation.

Cover Crops

Many farm crops make good temporary cover and local agricultural practices and expertise can be used. Extended use of farm crops will normally require that certain criteria for harvest and yield be met.

The use of cover crops for temporary protection on erosion-prone areas is important in the following situations:

- Where both topsoil storage piles and temporary spoil heaps must be protected.
- Where the mining operation results in large quantities of spoil being stored temporarily outside the pit.
- On steep or highly erodible sites where it is feared that the speed of growth of the permanent crop may not give the necessary immediate erosion protection. In these cases the annual cover may be underplanted with the permanent seed mix.
- On sites where topsoil substitutes are being used, a two-step reclamation may give more reliable results. A cover crop is seeded onto the regraded area after the topsoil substitute and necessary amendments have been applied. In late summer the cover crop may be disked into the ground and the permanent vegetation seeded immediately. In lieu of disking, the cover crop may be killed with an herbicide and the permanent vegetation seeded directly. The dead crop then acts as a mulch. These techniques increase the organic matter in the soil and may also make it easier to identify trouble spots.
- On sites with highly variable physical conditions where little or no topsoil is available, cover crops are extremely useful as indicator crops. They can indicate areas where soil conditions are not favorable for plant growth, allowing remedial measures to be taken.
- In some cases, where a site has been regraded but topsoil cannot be redistributed immediately, it may be desirable to seed a temporary cover crop onto the regraded spoil to preserve the spoil texture and resist erosion.
- Cover crops on storage piles of topsoil may help prevent nutrients from being leached out of the soil during the storage period, by transpiring water that would otherwise percolate through the storage pile, and by utilizing and thus stabilizing those nutrients in the surface layers of the pile.

Generally, quick-growing annual grasses or cereals are used for cover crops. Often they are used as an in situ mulch. These include rye, wheat, Japanese millet, and foxtail millet. When these species are seeded in combination with perennial species, care should be taken to insure that the cover crop's vigor or shade does not seriously inhibit the perennial species. Rye has been found to be tolerant to the high levels of aluminum and manganese, which are common in surface-mine spoils.

Herbaceous Species

Herbaceous species may be subdivided into four groups: grasses, herbs, sedges, and rushes. Early establishment of an herbaceous cover is usually an effective erosion control measure. Early establishment is especially important on sites and materials that are highly susceptible to erosion.

Trees and Shrubs

Trees and shrubs are not as effective as herbaceous cover in the initial control of erosion on fresh spoils. Consequently, herbaceous cover is almost always seeded first, even though the approved post-mining land use may call for trees and/or shrubs.

Trees are not an effective erosion control in the early stages of growth, but as crown closure and litter formation occur they can provide long-term or permanent cover and site protection.