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GROUTING TO CORRECT COAL MINE POLLUTION AND SUBSIDENCE PROBLEMS

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ABSTRACT

Grouting techniques have been used for many years to solve various aspects of coal mine pollution and subsidence problems. The principal applications are in preventing roof collapse with subsequent subsidence over old mines, abating acid mine drainage from deep mines, and extinguishing underground fires burning in abandoned mines and coal refuse piles. In general, the equipment and techniques are less sophisticated and capable of higher output at lower cost than, for example, those that apply to dam foundation grouting or tunnel support. Grout materials in coal mine applications are primarily flyash and cement. As with any grouting project, contract specifications must allow the flexibility to deal with underground conditions, especially increases or decreases in the grout quantities, that might not be anticipated even with an adequate pre-design exploration program.

This paper represents primarily a description of the grouting techniques that apply to the above-listed coal mine-related problems, along with guidance for the designer on significant aspects of design and engineering properties.

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INTRODUCTION

The activities of the coal mining industry have resulted in different types of structural and environmental damage to the land. Deep coal mines collapse over a period of time and, under the right conditions, the collapse progressively works its way to the bedrock surface, and overburden soil falls or washes in with consequent subsidence and damage to structures founded at the surface. Water running through abandoned hillside mines becomes acid and eventually seeps out through old portals and rock fissures. The resultant acid mine drainage heavy in iron oxide turns stream beds an unsightly red and kills vegetation and wildlife in its path. Another type of problem has developed at the locations of coal refuse piles. Rock that has been cleaned of coal is heaped up in huge "bony piles"; enough coal remains to cause spontaneous combustion deep within the piles. The resultant refuse pile fires cast a pall of noxious smokey haze over many mining areas and can, under certain conditions, cause forest fires and even violent explosions. In general the problems cited are inherent in older and, in particular, abandoned mining operations. Frequently, the symptoms show up on the land of a neighbor who had nothing to do with the mining operation, or a new owner who, through ignorance, acquires a difficult problem. Due to increasing public awareness and better technology and stricter enforcement of mining laws, newer mining operations tend not to result in so many problems.

The States of Pennsylvania and West Virginia, with heavy concentrations of mining industry have, with aid from several Federal agencies, taken a leading role in solving the subsidence and pollution problems of coal mines. There has been extensive research on technique and there are various methods to combat each of the above-mentioned problems. This paper concentrates on solutions by grouting.

Grouting is the injection of a fluidized suspension of colloidal particles into the underground soil and rock profile. Grout holes are drilled to the desired point of treatment and grouts are pumped down grout pipes into the treatment zone. Grout mixes can vary in consistency and strength and may be altered in the field to suit the conditions encountered. Since mine-related problems require a blanket solution on the basis of data gathered at scattered points, it is precisely the flexibility of grouting that makes it so valuable as a solution. Contracts are normally written on a unit-price basis and bids compared on quantities derived from an engineer's estimate. Actual quantities installed may vary significantly as the grouting program is altered to suit conditions actually encountered.

The types of grouting discussed in this paper usually involve much greater quantities of materials than other more sophisticated types of grouting e.g., dam foundation grouting and grouted structural underpinning. A typical job may involve thousands of tons of dry materials injected. The type of equipment used is suitable for high volume materials handling. Frequently, great economies can be achieved by relaxing some procedural and material specifications from "normal" grouting practice.

For example, in most of the areas of Western Pennsylvania, large diameter air-rotary drill rigs can drill grout holes at a fraction of the cost of water-flush drill holes. Some sacrifice may be made in the cleanliness of fissures in the sides of the drill hole but, in cases where large cracks and voids are the major concern, there is little technical disadvantage. On many projects, flyash is used as a bulk filler. Flyash with most consistent quality is normally delivered dry in bags or pneumatic trucks. It is difficult to handle in the dry state because of dusting problems. It is usually much cheaper to use "wet" ash that has sufficient moisture to hold together in a pile dumped on the ground; this can be handled with any type of conventional trucks and equipment. Wet ash is excavated from flyash holding ponds and may contain rock and bottom ash lumps. This loss of uniformity has virtually no import when grouting all but the smallest fissures.

In the following sections, grouting solutions to coal mine pollution and subsidence are presented. The applicable types of procedures and equipment are discussed as well as the design and construction problems typically encountered.

SUBSIDENCE

The causes and effects of subsidence over mined-out areas have been discussed in numerous publications, a few of which are included in the attached reference list. The type of mining with which this paper is concerned is that where "rooms" and tunnels are cut into the coal seam, leaving coal in place as pillars and the "walls" of the rooms for support. The amount of coal left in place is usually enough to sustain the total weight of rock and soil overhead without crushing. However, the span of mine roof between pillars may be quite large and may with time begin to spall off. If the pillars are far enough apart and the surface is close enough so that arching does not control the progressive spalling and collapse of the mine roof, it will eventually work its way to the bedrock surface. Overburden may then wash into the mine, causing sink holes and damage to surface structures. In the bulk of the Western Pennsylvania areas where subsidence has caused damage, the mines are only 100 feet deep and in may cases, much less.

Grouting has been used in cases where subsidence has already begun to cause surface damage and in cases where sites are treated in advance of construction to counteract potential subsidence. Designing a solution to mine subsidence problems is usually complicated by the fact that the mine voids are usually not empty. Very often the roof may be partially collapsed. There may be water standing or flowing on the mine floor. The mine may be completely flooded. Frequently, mine voids are partially backfilled with "gob" which may be rock fragments placed there as a result of later mining operations or sedimented there by the action of water. The gob may be very soft but stiff enough that it cannot be easily displaced. The actual state of any mine may be complicated by any of the above problems, the extent of which may be difficult to determine through the use of exploratory borings.

The types of treatment basically fall into two general methods: flushing and grout columns. With the flushing method, the entire mine under the area to be protected is filled. Grout columns are used to shorten the free span of mine roof to the point where arching will prevent any spalling from progressing to the ground surface. Details of the two methods and their relative technical and economic advantages are presented in the paragraphs below. In both cases, the zone of treatment is usually taken as the area projected downwards at a fifteen-degree angle of influence outside the structure.

Flushing consists of backfilling the entire mine void in the treatment zone with a weak grout. Holes are drilled around the perimeter, usually on fifteen to twenty-five foot centers. The perimeter is grouted first to contain the grout that will be subsequently pumped into the central area. A thicker grout or crushed stone may be used on the perimeter to help prevent too much grout from flowing out of the treatment zone. Once the perimeter barrier has been established, central holes are drilled, usually on twenty to twenty-five foot centers and a weak grout "flushed" (pumped at a fast rate) into the mine until refusal (Figure 1). Usually grout is allowed to come to the surface so as to fill voids in the rock that may be present due to the early stage of roof collapse. The grout that is used for this application should be designed to withstand crushing by the weight of overburden. Typically, flyash-cement grouts with dry weight ratios in the range of 10:1 are used. In many less critical applications, flyash-water grouts without cement have been used. The flushing technique provides the following technical and economic advantages:

- Lowest cost per unit volume of materials due to maximum use of cheap fillers such as flyash.

- Absolute lowest requirements for quality control of materials. If the grout mix can be pumped, it is probably suitable.

- Lowest reliance on the strength of any gob present, since the overburden pressure is distributed over the widest area possible.

- Essentially full roof contact; does not rely on arching to prevent progressive collapse.

The flush-grouting technique has disadvantages where the perimeter of the area is difficult to seal or where the height of the void means that the volume of material becomes prohibitive. In general, this method is best applied in situations where the mine void is low or where it is mostly backfilled with gob. It is also useful in cases where the void is so close to the surface that point support methods (like grout-columns) cannot rely on arching to develop between supported points.

Once the void height increases beyond a few feet, it is usually more economical to consider grout columns (also called gravel or stone columns). With this technique, holes are drilled on grid spacings narrow enough so that the mine roof will support itself by arching between columns.

Some holes on the grid will encounter solid coal pillars; these are backfilled with grout. The balance of the holes are first filled with a gravel cone -- gravel (3/4-inch crushed stone) is poured down the holes and spread by a jet of compressed air at the bottom. The compressed air maximizes the roof contact. Once this is done, a grout pipe is driven through the gravel and down into any gob below. Grout is injected into the gob and gravel in measured amounts at one-foot intervals with the objective of making a grouted cylinder of sufficient diameter to support the mine roof (Fig. 2). The gravel may tend to slump during the grouting and additional gravel may have to be added.

This process is more expensive on a unit-volume basis than flush-grouting because there is a considerable amount of work needed to be done "down-the-hole," i.e., the grout is injected through grout pipes and measurements of the top of the stone are needed frequently. Also the grout is typically a more expensive 3:1 or 5:1 flyash-cement grout. Good control of material quality is needed since small lumps can plug the grout pipes or prevent the stone column from being properly grouted. Grout columns do present the following advantages, however:

- Lower cost in some cases because only a small percentage of the mine void is actually treated.
- No reliance on creating barriers to seal off the treatment zone.
- Flexibility in spacing to suit load factors and differing degrees of risk.

A major drawback of the technique has always been that there is no way to reliably check the roof contact area on completion. Experience on experimental columns where borehole photography has been used has shown that good technique does result in good contact. Of course, as the void height increases, the volume of the stone columns themselves increases dramatically to the point of sometimes being uneconomical compared to other systems (caissons, etc.) For this technique, as with flush grouting, a good exploration program to lay out the work as well as on-going engineering control during the grouting program is necessary to ensure a good end-product.

The equipment used for both techniques is similar. Large air-rotary rigs drilling a 6-inch diameter hole (Fig. 3) usually provide the cheapest drill-hole. In cases where surface access is obstructed, smaller air-tracks or skid rigs may be used. Grout may be delivered in ready-mix trucks and held in an agitation tank (Fig. 4) or grout materials delivered and mixed on site (Fig.5). Grout pumps are usually of the positive displacement type, either piston pumps or progressing-cavity type (Fig. 6). In cases where gravel is to be injected, it is placed in a hopper and blown down the hole with compressed air.

ACID MINE DRAINAGE

Many of the streams and rivers of the coal regions are polluted by acid mine drainage. Red-bottomed streams and rusty colored slimy swamps with dead vegetation all around are fairly common sights in the coal regions.

Water running along the floors of old mines turns acid and eventually finds its way out through old portals or fissures in the rock. If all exits can be sealed off, the water level will rise in the mine; as long as it is above the mine roof, acid formation is greatly curtailed. The problem of finding all drainage paths is not easy, since they may be covered by subsequent strip mining operations or simply collapsed over time. Using surface indications of drainage in combination with mine maps, a grouting program can often be designed to abate the drainage.

The advantage of grouting is that holes are drilled on centers close enough to discover all old portals on a line far enough back into the slope to increase the chance of finding them still open. In places where no portal is found, a conventional grout curtain if formed using cement or flyash-cement grouts. Zones where large grout takes are experienced may be drilled on a split-spacing and regrouted, utilizing grouting's flexibility to suit encountered conditions. Where portals are found, additional holes are drilled across the portal to define its width as well as possible. Additional holes are then drilled twenty to forty feet upstream and downstream of the primary grout line. Into these secondary lines of holes is dumped crushed stone to form temporary bulkheads. Immediately thereafter, concrete is tremied down the primary grout line holes in an attempt to plug the portal (Fig. 7). Often this will not be totally effective since there is usually gob on the floor of the portal and there may be water flowing along the floor which will wash out the bottom of the concrete plug before it sets. So a third set of holes is then drilled through the plug and pressure grouting is carried out above, below, and on both sides of the plug. Finally, many engineers will check the plug by drilling a core boring through it and pressure testing with water at five-foot increments.

The equipment used for acid mine-drainage abatement is essentially the same as that discussed in the previous section. The principal problems are associated with gaining access to and transporting grout along grout lines which may extend for miles. Occasionally, completely mobile grout mixing and pumping stations are utilized.

REFUSE PILE FIRES

Burning spoil piles are a common problem in coal mining regions. In a survey taken in 1964, almost five hundred such fires were listed in an area covering fifteen states. The piles are the waste product of deep coal mining operations; coal is separated from rock fragments and the rock is stockpiled in large "gob piles." Since the separation process is not completely efficient, significant quantities of combustible material are included in the spoil. The average percentage of coal may be as high as 30 to 60 percent. The method of dumping frequently causes segregation and pockets of material within the pile with even higher percentages of coal. These pockets can ignite through spontaneous combustion and smolder for years, progressing through the piles at a very slow pace (Fig. 8).

The burning piles are a problem from two standpoints: pollution and safety. The noxious smell of hydrogen sulfide gas and the foggy smoke emanating from these fires are familiar to most residents of the coal regions. As to safety, the primary problem occurs in cases where subsequent operations entail cutting into the piles with earth-moving equipment. Not only are the gases dangerous to workers, but coal dust in the air may ignite as hot spots are exposed. A recent incident killed two men and blackened a valley near Logan, West Virginia.

The first step towards extinguishing underground burning is to accurately locate the extent of burning. Surface indications such as cracks emitting smoke, sulphurous deposits, and open flames are not always good indicators of the location of burning. The best method involves interpreting surface indications to determine probable burning areas and then following up with in situ temperature measurements. Pipes are driven into and through suspect areas. A thermal probe is lowered into the pipes and sufficient measurements are taken to determine the extent and depth of burning areas. Combustion temperatures are typically in the range of 600-900°F and may go as high as 2000°F. On projects where further accuracy is required or where a thermal survey is desired before mobilizing construction equipment, aerial thermal imagery may be used to locate burning areas (Fig. 9). The light areas in the thermal image correspond to areas of high heat.

Once the hot zones have been defined, a flyash slurry is pumped into the voids and crevices to extinguish the fire. Flyash is dumped into high volume mixers with about 100-200 gallons of water per ton of ash. The resultant slurry is pumped from the batch plant (Fig. 10), through a high pressure hose and down the grout pipes driven into the ground. The pumping of the grout causes large quantities of steam to be emitted and usually the hot gases forced to the surface will ignite, creating a spectacular display (Fig. 11).

The slurry serves two essential purposes: the fire is "snuffed" due to the blocking and filling of annular spaces and crevices with the flyash which remains in place after the water evaporates; and the burning zone is cooled due to the evaporation of water in the slurry and the heat capacity of the flyash itself. The failures of "covering" operations which are used for underground fire control are frequently caused because the burning zone is not cooled; as soon as oxygen finds new access, the burning resumes, even after a period of years.

When burning is spread over isolated areas, grouting becomes economical because it is well suited to spot treatment. Covering or excavating localized hot zones can be more expensive because of the large areas or volumes required to be treated to extinguish relatively small burning zones. Covering steep slopes to extinguish burning is not practical because the covering material slides away. Excavating out pockets on steep piles may also be impractical because of the danger of earth slides and access problems.

A principal advantage of the slurry injection process is that access for heavy equipment to burning areas is not required. The only equipment located at the burning area is pipe and a hand operated jack hammer. In some cases, grout pipes have been installed on slopes steep enough to require life lines. The mixing plant and pumps can be located wherever convenient, as much as several hundred feet away.

CONCLUSION

In this paper some of the basic applications of grouting to coal mine related pollution and subsidence problems have been presented. There is a considerable amount of literature in this subject; a partial reference list is attached. Many variations of the basic techniques have already been tried and new ones are possible. Complex new grouts that set quickly and expand to fill voids underground are only one example. The basic advantages of grouting, that apply in all the cited problems, are:

- Minimum disturbance - The problems are treated remotely without major excavations; in cases where structures exist on the surface, angle holes can be drilled.

- Flexibility of technical solution - A relatively large number of holes provide information to the engineer on subsurface conditions. Mix ratios, pumping rates and pressures can all be varied to produce desired effects.

- Economical results - The cruder types of grouting that have been discussed in this paper enable large volumes of material to be placed at low cost.

A secondary benefit is the rather neat environmental solution that sees the waste product of burning coal, flyash, returned to the mines from where it came to reduce other coal mine related environmental damage. It is certain that grouting will continue to play a major role in reducing damage from coal mine pollution and subsidence problems.

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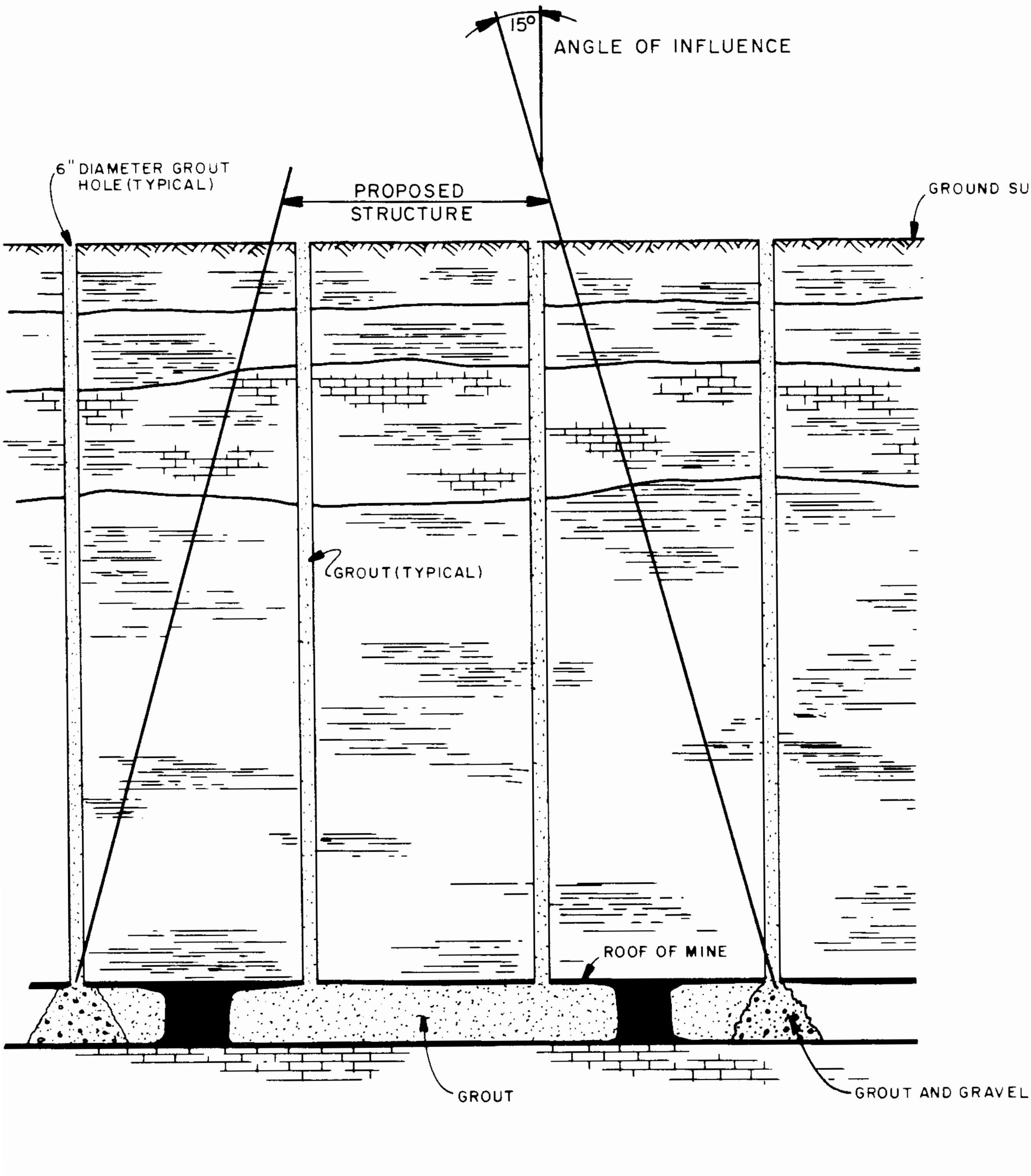


FIGURE 1 - SCHEMATIC OF FLUSH GROUTING FOR MINE SUBSIDENCE CONTROL

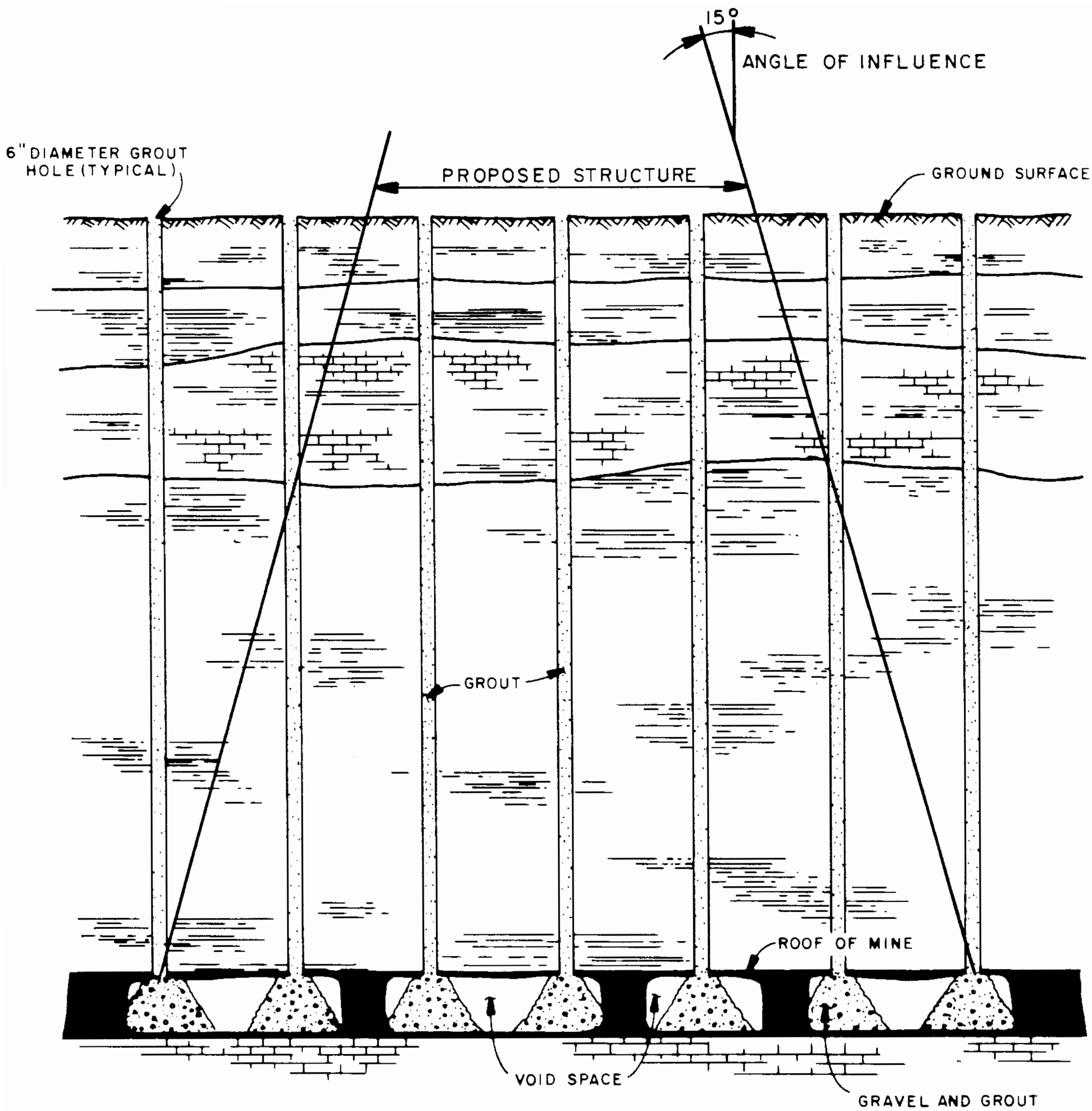


FIGURE 2 - SCHEMATIC OF GROUT COLUMNS FOR MINE SUBSIDENCE CONTROL

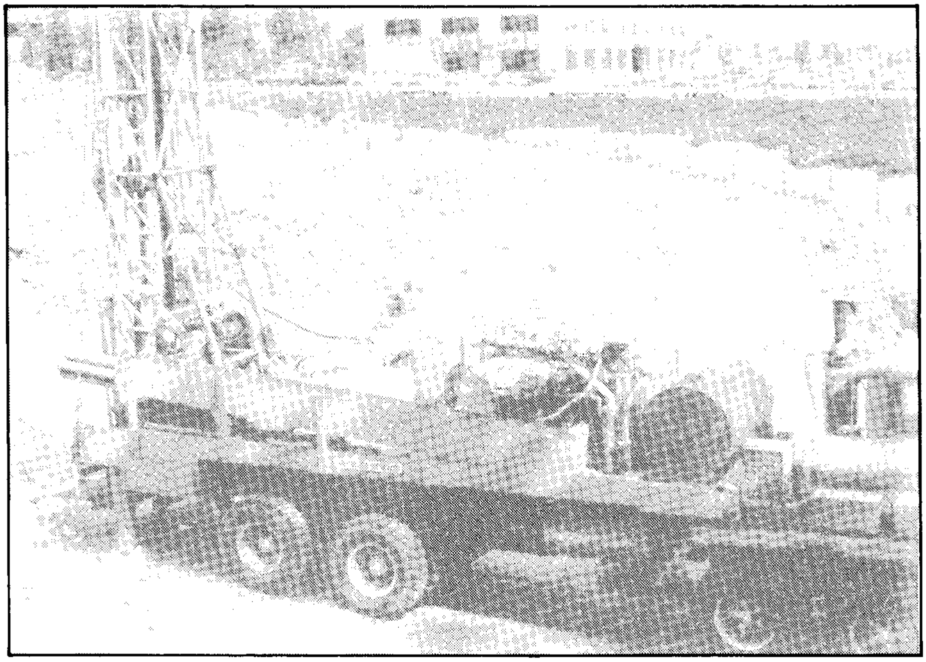


FIGURE 3- AIR-ROTARY DRILL

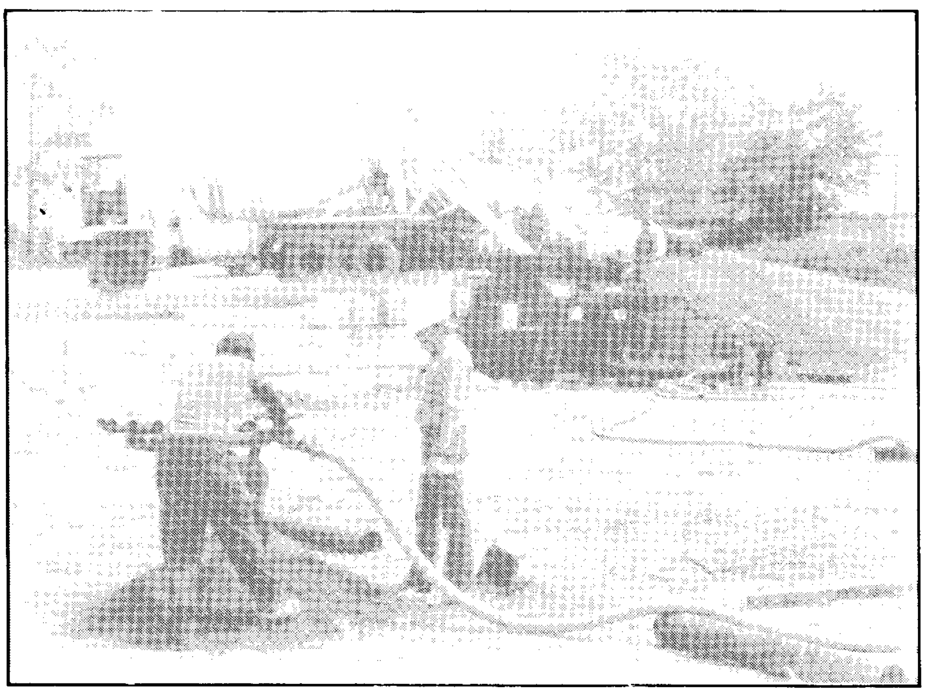


FIGURE 4 - READY MIX GROUT DELIVERY

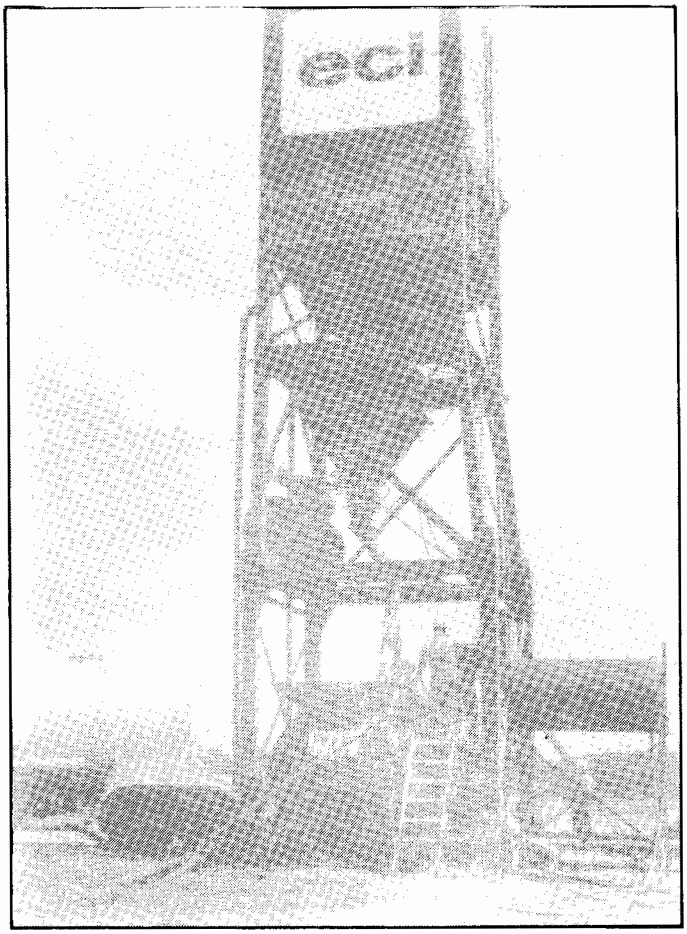


FIGURE 5 - ON SITE MIXING

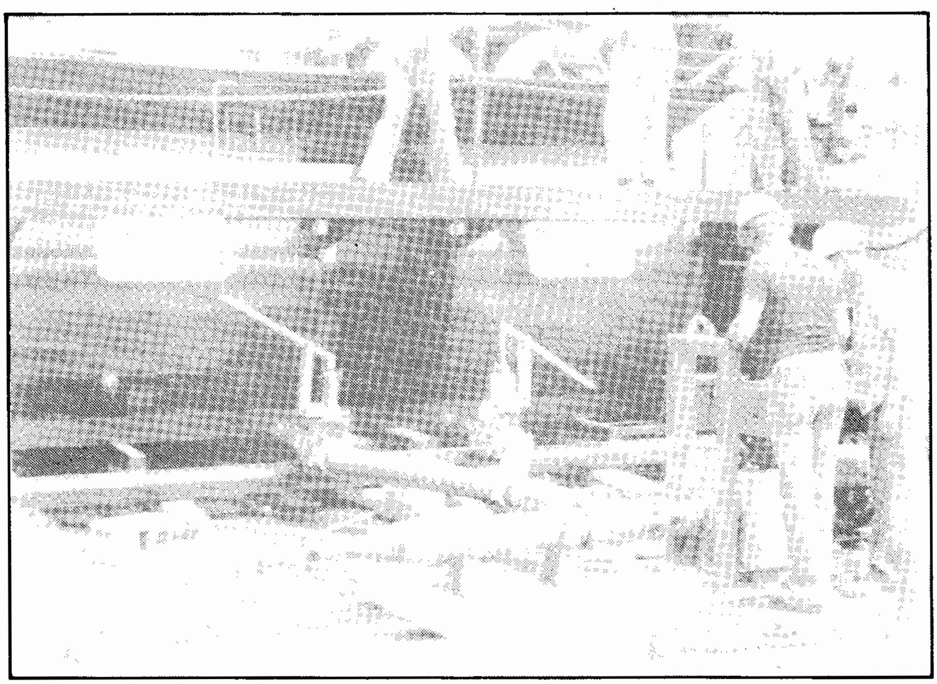


FIGURE 6 - POSITIVE DISPLACEMENT PROGRESSIVE-CAVITY PUMP

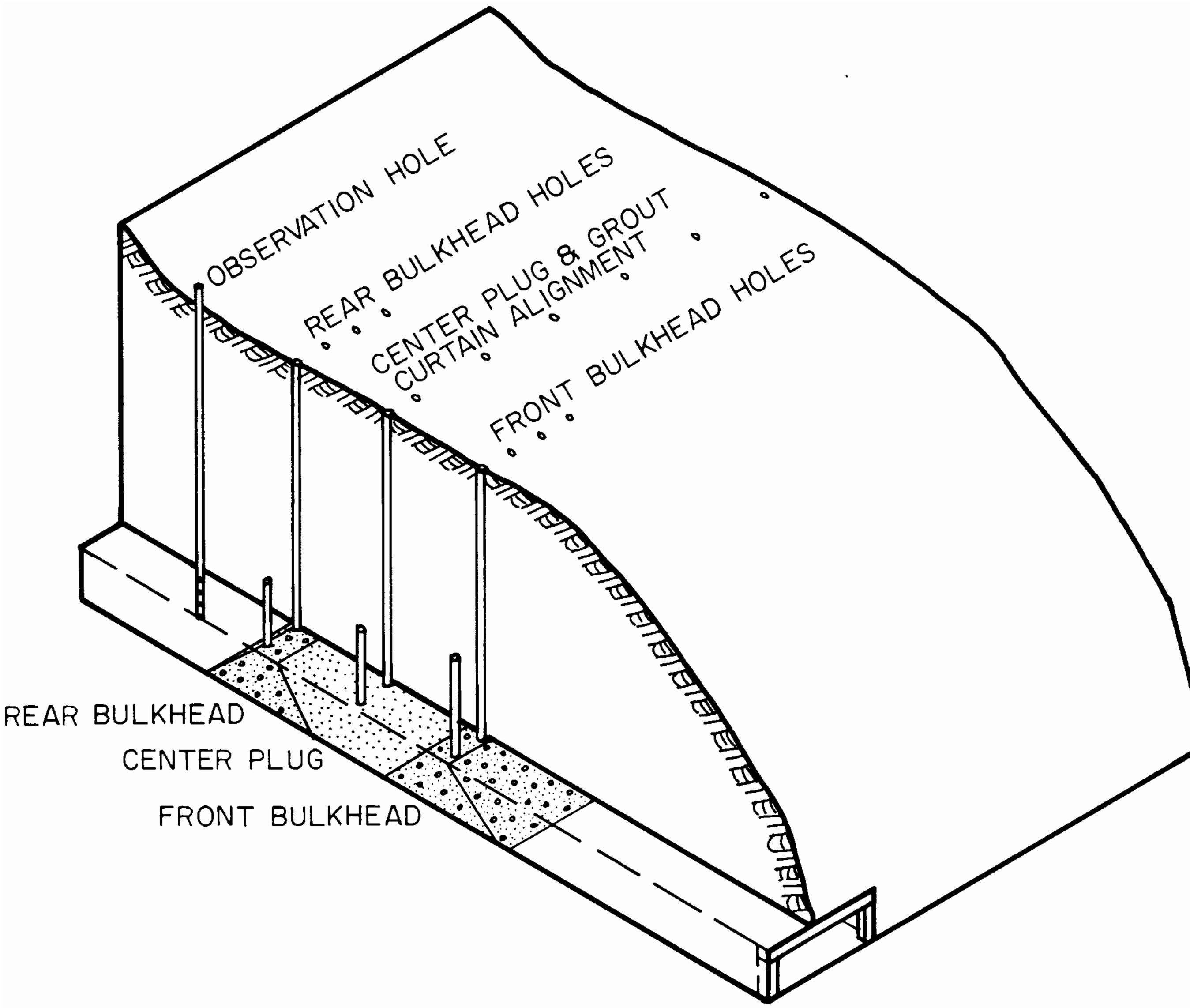


FIGURE 7 - ISOMETRIC DRAWING OF GROUTED MINE SEAL

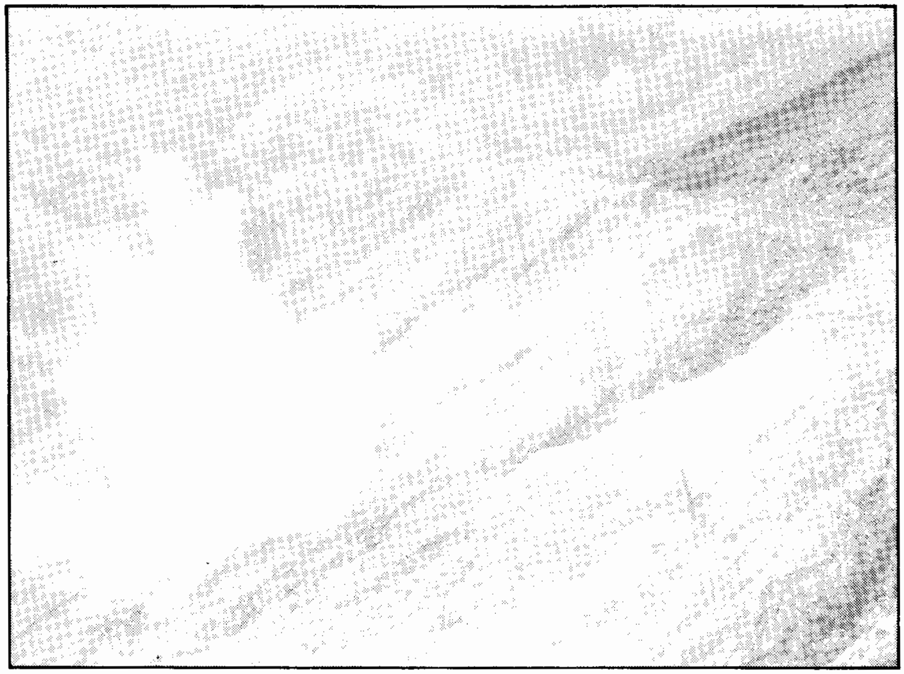


FIGURE 8 - TYPICAL REFUSE PILE FIRE

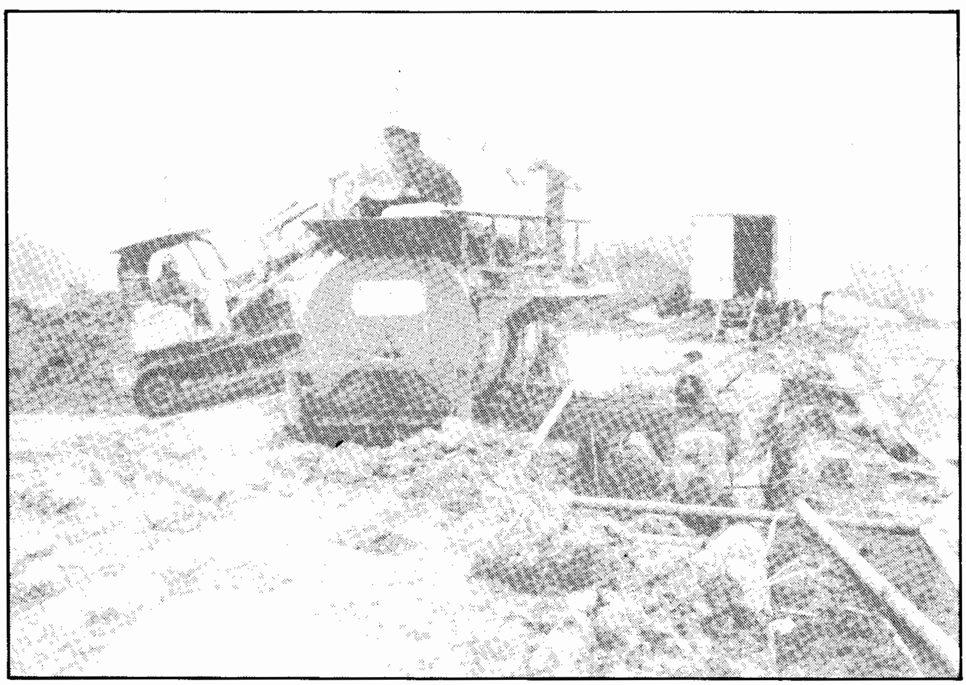
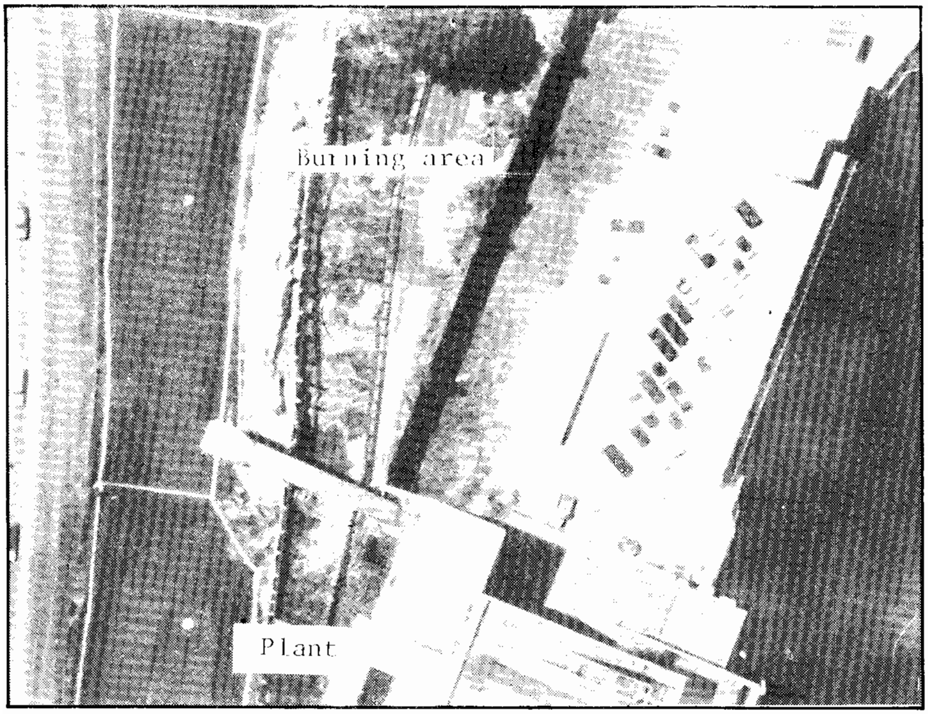
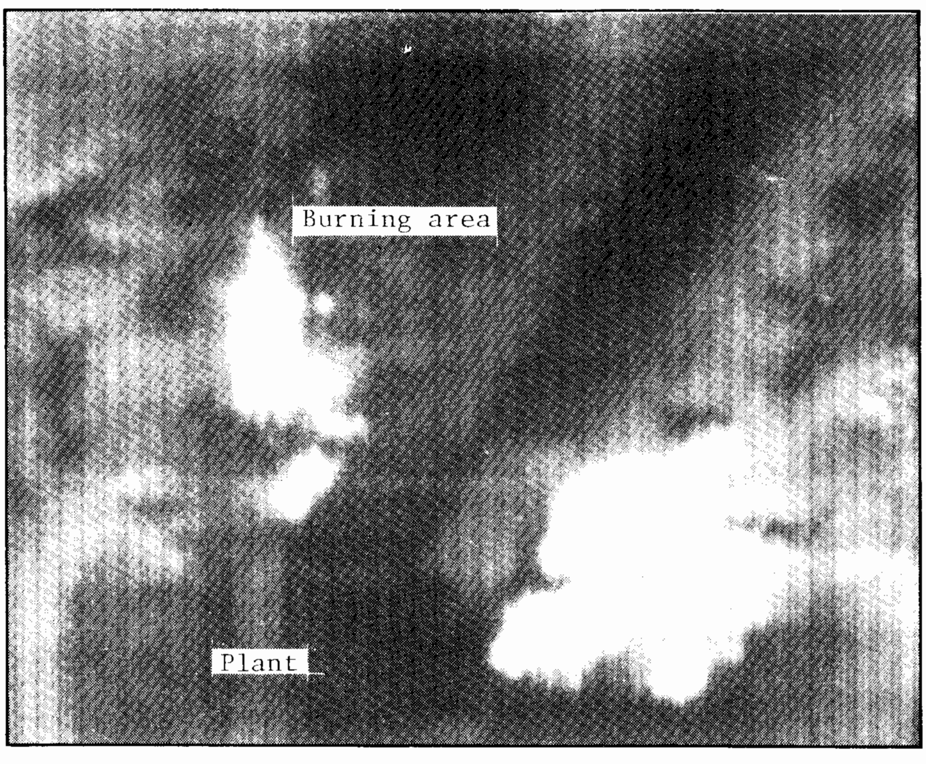


FIGURE 10 - BATCH PLANT



AERIAL PHOTO



THERMAL IMAGE

FIGURE 9 - USE OF AERIAL PHOTOGRAPHY TO LOCATE BURNING ZONES

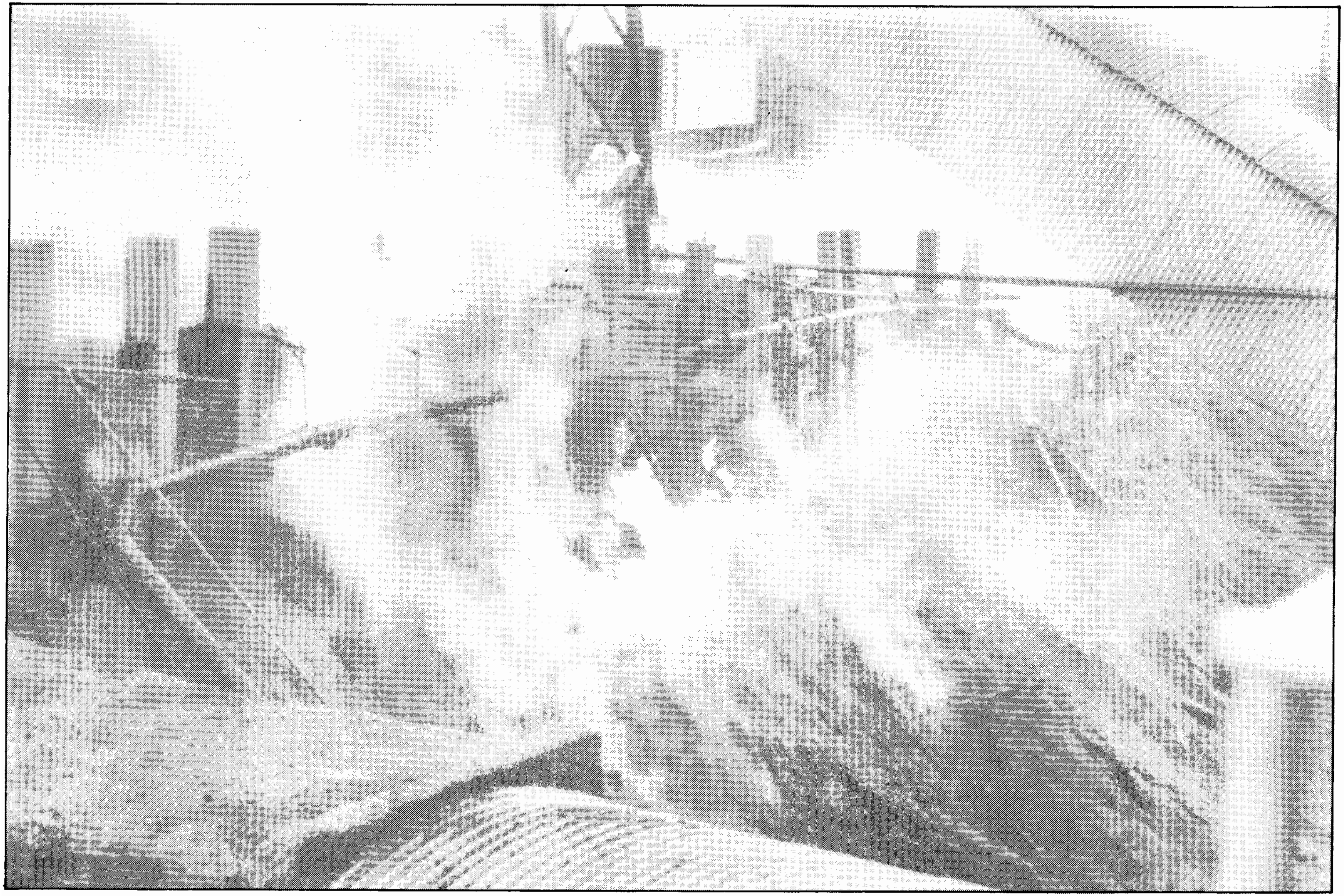


FIGURE 11 – FIRE IN PROCESS OF EXTINGUISHMENT