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A STUDY OF MINE EXAMINATION TECHNIQUES FOR DETECTING AND IDENTIFYING UNDERGROUND NUCLEAR EXPLOSIONS

By the Staff, Bureau of Mines

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

1962

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Marling J. Ankeny, Director

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Preface

This report summarizes the views of a special panel established by the Bureau of Mines under terms of an agreement with the Air Force Technical Applications Center to study mine-examining techniques that might relate to the detection and identification of underground nuclear explosions. The project is part of the VELA-UNIFORM program of the Advanced Research Projects Agency. Specifically, the Bureau of Mines was requested to—

Review previous work directed toward onsite mine examination.
Evaluate suggested techniques and clues, and recommend additional methods.
Determine the feasibility of detection by onsite mine inspection based on existing knowledge.

The study was accomplished through a series of panel discussions, at which time representatives of a number of agencies associated with related phases of the VELA program were interviewed and all available documentation was reviewed. Thereafter, panel members presented their views on all facets of the study together with extensive documentation on subjects with which, as individuals, they had some special knowledge or competence. This report comprises a digest of the products of the study to which the panel members could subscribe.

Members of the panel included: James E. Hill, mining engineer, Washington, D.C., Chairman; Wilbur I. Duvall, physicist, College Park, Md.; William R. Hardwick, mining engineer, Tucson, Ariz.; Scott W. Hazen, mining engineer, Denver, Colo.; Robert B. McCormick, geologist, Washington, D.C.; Constantine C. Popoff, mining engineer, Seattle, Wash.; J. Wade Watkins, petroleum engineer, Bartlesville, Okla.

Consultants to the panel included: E. W. Felegy, health and safety engineer, San Francisco, Calif.; Paul L. Russell, mining engineer, Washington, D.C.; John E. Crawford, nuclear engineer, Washington, D.C., Paul Zinner, Assistant Director—Programs, Washington, D.C.

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By

The Staff, Bureau of Mines

Introduction and Summary

ESTABLISHMENT of an effective inspection system has been held essential to any international agreement that may be designed primarily to curb the testing of nuclear weapons. A number of reports and papers already have described basic inspection concepts and appraised various procedures, techniques, and methods as to their probable effectiveness in detecting and identifying violations under such agreement.

This report results from a study of only one part of the contemplated inspection system, specifically the final phases embracing onsite investigations and mine examination techniques. The results and reports of earlier work were reviewed in detail, and subjects that were found to have been exhaustively evaluated are recognized by reference and not redescribed here. In other instances, previously described techniques, methods, and clues were revaluated to define more clearly their practical value to the final objective of an onsite inspection. Previous documentation does not refer to a number of subjects, techniques, tools, clues, and methods considered by the study; this report treats these in detail, even though when applied singly or collectively their practical value may be questionable.

Finally, the study sought to determine objectively the feasibility of developing valid conclusions by onsite inspection techniques, based wholly upon present knowledge. These findings do not depart substantially from conclusions presented in a report by Foose.[2] Summarized, the present knowledge of methods and application, the total absence of experience that might be gained solely from a practical test, and the obviously wide range of conditions under which clandestine testing might occur preclude establishment of any realistic probability factor. However, under certain conditions, success in locating and identifying such tests could be virtually assured. These conditions would require that the terms of the international agreement authorizing the whole inspection process be liberal and free from prohibitions against the employment of any methods required, and include no inhibiting provisions as to time, techniques, or cost. While international agreements of this nature are rare, a high degree of success might still be achieved under a more restrictive agreement if reasonable examination activity is permitted during the onsite phase of an inspection and if development of related instruments and scientific detection methods is pursued energetically in the immediate future. In addition, a realistic and large-scale exercise involving the planning and conducting of a (perhaps simulated) clandestine test—followed by an exercise involv-

[1] Work on manuscript completed August 1961.
[2] Foose, Richard M., Inspection of Sites of Unidentified Seismic Events: Stanford Res. Inst. Project No. 2 SU-3102, Aug. 19, 1960, p. 4, item 3.

ing both remote and onsite detection and inspection procedures—promises to develop essential experience and to permit a proper appraisal of capabilities. Exercises are seen as the most logical, and perhaps only, means of accomplishing these objectives.

Referring to the onsite phases of a total inspection process, and basing conclusions on existing knowledge and currently available instruments, the success of an investigation at the moment depends more upon applying rare talents for deduction than upon specialized competence in scientific disciplines. This observation is consistent with endorsement of an energetic program for improving or developing new scientific detection devices and techniques. Their improvement is considered not only desirable but mandatory. However, these are merely tools, and their value is, and will be, proportional to the astuteness of the investigators that employ them. In this regard, the study finds some fault with the concept of establishing several substantially self-contained inspection teams stationed at various global points on continuons alert to undertake any type of local or onsite investigation. The infinite variety of conditions under which clandestine testing might occur dictates paralleling flexibility in staffing for investigation. A few hard-core permanent units with access to a wide variety of talents and sources of supply, firmly committed to serve on inspection assignment on short notice, are needed. It seems improbable that the high level of specialized competence demanded by such occasions could be enlisted or retained at many isolated posts on a long-term basis. Global communication and transport being what it is, the concept of a single inspection force, having immediate access to a wide variety of standby talent, merits more consideration. In comparing previous concepts of staff and material support for a typical self-contained inspection team with the variety of problems that such an assembly might be requested to handle, the instance in which a team might be fully adequate was difficult to conceive.

It is questionable that an operating mine or oilfield would be used for a clandestine underground nuclear detonation even though site preparation could be masked reasonably well in an operating area. The deterrents to that choice are a potential loss of production, possible permanent damage, and unfavorable geologic conditions at many mines. However, an operating mine or a well is a possibility, and methods have been discussed for detecting an extensive offshoot excavated from operating mine workings. The detonation site must be located an appropriate distance from any extensive free face, including mine openings, to prevent observable damage and possible venting. Therefore, offset excavation would be necessary even in a deep mine.

Drill holes from the surface seem to be the simplest means of preparing and meeting the minimum requirements for a detonation site. However, there are many problems associated with hiding this type of site, such as casing recovery, drill cuttings, drilling mud, site preparation, and supply and service requirements for roads. Methods have been discussed for detecting these evidences of occupation. If the drill hole were located, evidence of the nuclear detonation would be relatively simple to obtain by drilling, since the test site requires at least an 18-inch-diameter, nearly vertical hole for instrumentation.

Decoupled detonations offer great potential for hiding clandestine tests. However, where to locate such an excavation is a significant problem. Salt domes are readily adapted to solution cavity mining, but because of their relation to oil exploration they are well known and are restricted to certain limited geologic areas. Massive limestones and sandstones and some granites could be excavated by drilling and blasting for decoupled detonation cavities, but these usable formations are scarce. Detailed study of the geology of a country could ascertain potential sites. Judicious selection of stations for the proposed Geneva network could assist in isolating these specially adaptable sites.

Much work needs to be done on assembling specific and exacting background information on geography, geology, technology, economy, and the people of various countries of the world. Several areas of research on earthquakes, seismic monitoring, and rock mechanics have been recommended. All of this information is essential for evaluation of suspected seismic disturbances and will greatly enhance the chances of success.

A number of factors tend to provide limitations on the problem. Some are historical in that their concept has been more or less established by preceding testimony on capabilities of the proposed seismic detection network. Others are factors that the panel considers to be basic requirements for effective operation of an onsite inspection team. Failure to provide any one of the basic requirements would reduce the probability of success for an onsite inspection.

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REVIEW AND EVALUATION OF BACKGROUND INFORMATION

Since the early phases of the Geneva negotiations for cessation of nuclear weapons testing, considerable research in the field of seismology and related subjects has been conducted, with the result that the arts of detecting and identifying nuclear explosions and of conducting and concealing underground nuclear explosions have changed rapidly. With the experimental demonstration that the large-hole-decoupling theory is valid, the art of concealment has advanced ahead of the art of detection and identification. Thus, there is need to reevaluate certain problems stemming from popular concepts of nuclear weapons test ban controls, especially those concerned with the art of identification by means of onsite inspection.

Experiments at the Nevada test site demonstrated the general requirements and advantages of underground sites for nuclear testing. Recent tests in the United States, utilizing high explosives, have demonstrated that decoupling reduces the seismic signal and further enhances the potential for clandestine underground nuclear weapons testing. These demonstrations also emphasize the problems of detecting, locating, and identifying clandestine underground nuclear detonations, even by onsite inspections.

Publication of hearings [3] has made available much of the historical background on the problem. Reports on U.S. Projects Rainier,[4] Hardtack,[5] and Cowboy [6] have provided additional information on the results and implications produced by those nuclear and high explosive tests.

Basically the problem is political, involving treaties, disarmament, and the sovereignty of governments. Attempts to resolve the problem of inspections during nuclear test bans have been founded on available seismic information and on results of known data from past nuclear and high explosive test programs. Negotiators at Geneva attempted to build from these data a system for control of nuclear testing.

SEISMIC DISTURBANCES

Seismic disturbances are detected by vibrations transmitted as waves in the materials of the earth. These disturbances will vary in intensity, and they may originate from a variety of causes other than underground nuclear detonation such as earthquakes; movement of molten rock at depth; abrupt movement of masses of rock, as in rock bursts; natural and manmade explosions; explosive volcanic activity; landslides; meteorites; and collapse of large underground openings.

One of the difficulties in selecting areas for onsite investigations is the inherent uncertainty of distinguishing between earthquakes and subsurface explosions as causes of strong seismic signals. Unfortunately, experience with seismic signals from explosions is limited to a very few large subsurface nuclear and chemical explosions such as the Plumbob (Rainier) and Hardtack II tests and the Cowboy series.[7]

Published data on the detection and location of earthquakes by seismic means are more voluminous. However, differentiation of signals originated by earthquakes from those occasioned by subsurface explosions is a matter only of recent concern. Stations reporting seismic anomalies caused by either class of events have neither been spaced uniformly nor equipped with the same numbers and types of detectors. Standardization has not been available, as it should be if an international teleseismic network were established as has been recently proposed.

Earthquakes

Earthquakes result from stresses in the outer shell of the earth. The origin of these stresses is obscure, but gravitational and thermal forces are thought to be the source of the stresses. With the exception of the small and shallow disturbances generated by volcanism, most earthquakes have a tectonic origin. Tectonic earthquakes are generally believed to result from the release of stress in the rocks of the earth's crust. Rock is elastic, and is known to yield to stresses by slow creep over

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[3] U.S. Congress, Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban: Appendixes to Hearings Before Special Subcommittee on Radiation and Subcommittee on Res. and Development of Joint Committee on Atomic Energy: 86th Cong., 2d sess., pt. 1, 1960, pp. 1–478; pt. 2, pp. 479–951.

[4] Work cited in footnote 3, pp. 238–280.

[5] Foose, R. M., and Hoy, R. B., Identification of Possible Underground Nuclear Explosions by On-Site Inspection: Stanford Res. Inst. and Office of Naval Res., WT–1739, 1959, 93 pp.

[6] Hoy, Robert B., and O'Neill, Bernard J., Jr., Investigation of On-Site Inspection Techniques for High-Explosive Tests in a Salt Mine, Project Cowboy: Stanford Res. Inst. SU–2993, December 1959–March 1960, 76 pp.

[7] Work cited in footnotes 3, pp. 238–280, 5, and 6.

extended periods of time. When the elastic limit of the rock is exceeded at any point, particularly along a fault or plane of weakness, sudden slippage or abrupt movement may occur.

Information as to time and location of earthquakes has been accumulated since 1900. The first seismographs were set up in the United States in 1887. Seismograph records show that there are three general depths where earthquakes originate. The deep earthquakes range in depth from 150 to 400 miles, an intermediate zone occurs from 27 to 150 miles, and the shallow earthquakes occur at depths less than 27 miles. However, the largest number of earthquakes, and the most destructive, occur as shallow disturbances. It is believed that most of these shallow earthquakes have been caused by sudden movements of blocks of the crust along faults.

Information is available on the number, frequency, and severity of earthquakes in most major areas of the earth.[8] Earthquakes have a definite pattern of occurrence and quite frequently are prevalent along mountainous coastal areas.

The limited region in the earth where the energy is initially released is known as the focus of the earthquake. The point on the earth's surface directly above the focus is the epicenter of the earthquake. The epicenters of major earthquakes lie mainly in two belts. One belt passes around the Pacific Ocean and affects countries with coastlines bordering on this ocean, for example, New Zealand, New Guinea, Japan, the Aleutian Islands, Alaska, and the western regions of North and South America. It has been estimated that 80 percent of the energy released in earthquakes comes from this belt. The second belt passes through the Mediterranean region eastward through Asia and joins the first belt in the East Indies. The estimated energy release from this belt is 15 percent of the total. These belts are not uniform in their activity, and there are many branches in each. Also, there is a number of lesser belts of seismic activity, including ones in the Arctic Ocean, the Atlantic Ocean, the Western Indian Ocean, and East Africa. Most parts of the world experience at least occasional small earthquakes.

Earthquake zones are regions of steep continental slopes, deep oceans, volcanic activity, and actively building mountain ranges closely associated with fault structure. The majority of the shallow earthquakes do not produce surface evidence along faults, although nearly all destructive earthquakes result from such movement. Apparently, the points of origin of many of the earthquakes are too deep for the movements to show surface effect.

The effects of earthquakes are numerous and varied and include geological effects, effects on buildings and structures, and effects on human beings. The geological effects include movement along faults; creation of new faults; raising, lowering, or tilting of earth blocks; changes in flow of water; the production of fissure in the ground; landslides; and mud flows.

The effects of earthquakes on buildings and structures are evidenced by varying degrees of damage, depending on the severity of the earthquake. Deep-focus earthquakes of a given magnitude produce more widespread damage than do shallow earthquakes of the same magnitude. Surface structures are affected more than deep underground structures. Little or no damage to mines deeper than 200 feet has ever been reported as due directly to an earthquake.

Earthquakes affect people in various ways. Besides the injuries and deaths from falling buildings, people often see, hear, and smell the vibration of the earth. Such reactions may be real or illusionary due to the hysteria of the moment.

Seismologists have constructed an intensity scale which attempts to relate intensity of the earthquake to the type of damage and/or results of the earthquake. The scale most often used today is the Modified Mercalli Scale.

Seismologists have also tried to rate earthquakes in terms of energy that is released at the focus. This energy is estimated from the amplitude of the recorded seismogram of earthquakes. On this scale earthquake magnitudes range from 0 to 9. Also, seismologists have found that the number of earthquakes of a given magnitude occurring annually increases rapidly with decreasing magnitude. The general relation between earthquake magnitude and energy released and frequency of occurrence is summarized in table 1.[9]

TABLE 1.—*Annual number of earthquakes versus magnitude*

Designation of earthquake	Magnitude	Energy, order of magnitude, ergs	Annual number
Great	8 or more.	2.5×10^{26} or more.	1
Major	7–7.9	4×10^{24}–2×10^{26}	18
Destructive	6–6.9	6×10^{22}–3×10^{24}	120
Damaging	5–5.9	1×10^{21}–4×10^{22}	820
Minor strong	4–4.9	1×10^{19}–6×10^{20}	6,200
Generally felt	3–3.9	2×10^{17}–1×10^{19}	49,000
Perceptible	2–2.9	4×10^{15}–2×10^{17}	300,000

[8] Gutenberg, B., and Richter, C. F., Seismicity of the Earth and Associated Phenomena: Princeton University Press, Princeton, N.J., 1954, 310 pp.

[9] Howell, B. F., Jr., Introduction to Geophysics: McGraw-Hill Book Co., Inc., New York, N.Y., 1959, p. 130.

According to Romney,[10] the relation between nuclear explosion size and equivalent earthquake magnitude is as shown in table 2. The energy equivalent of each size explosion is also given in table 2. These energies were computed on the basis that 1 kt. (kiloton) is equivalent to 10^{12} calories or 4.2×10^{19} ergs.

TABLE 2.—*Earthquake magnitude for various sizes of nuclear detonations*

Size, kt.[1]	Equivalent earthquake magnitude	Energy, ergs
1.7	4.06	7.1×10^{19}
4.0	4.30	1.7×10^{20}
5.0	4.4	2.1×10^{20}
11.0	4.6	4.6×10^{20}
19.0	4.75	8.0×10^{20}
40.0	5.00	1.7×10^{21}
80.0	5.20	3.4×10^{21}

[1] Energies computed on basis that 1 kt. is equivalent to 10^{12} calories or 4.2×10^{19} ergs.

The surface effects resulting from subsurface nuclear tests at the Nevada test site[11] appear to be quite similar to those that might result from an earthquake. It is possible that some differences might be distinguished by skilled seismologists and geologists. A nuclear detonation represents essentially a point source of shock. Reportedly the principal zones of surface rock disturbance at the Nevada test site follow natural planes of weakness. The same might be expected from an earthquake. However, it is likely that the effect of an earthquake of seismic magnitude comparable to that from a 20-kt. nuclear explosion (4.75 Richter scale, coupled under Rainier conditions) would be more widespread. If the shot were decoupled, the yield should be much greater and the effects, perhaps, of much greater magnitude, which might be manifested differently than if an earthquake were responsible for the surface damage.

The State of California has published[12] a complete history of earthquakes which occurred near Tehachapi, Calif., in 1952. This publication gives a most comprehensive discussion of the type of information that is available from careful observation and instrumentation of earthquake phenomena.

The observed pattern of foreshocks, major shock, aftershock, and damage associated with the shocks is of particular interest. The report contains detailed discussion of damage to buildings, oilfields, highways, water-supply systems, agriculture, electrical equipment, and railroads. The report bears out the fact that structural damage caused by earthquakes is greatest in areas underlain by thick unconsolidated sediments and least in areas underlaid by rock. Figure 1 contains photographs of some of the railroad tunnel damage. However, these were virtually surface structures in the sense that they were shallow and along a sidehill.

Field evidence of earthquakes may be either old or new. An earthquake of moderate magnitude might occur on an old fault, but new movement may be so deep that it will not leave surface evidence. Thus, old evidence of faulting is essential for field evaluation of a possible earthquake.

Old fault evidence would be smooth, striated slickensides along a cliff wall; claylike gouge or ground-up rock along a break in the rocks; offsets in rock formations; long, relatively straight alinement of topographic features; cliffs or fault scarps left after one side of a fault has dropped below the other side; excessively steep hillsides or mountainsides; evidence of old landslides, slump evidence of hummocks and depressions; and shattered and broken rock along some evidence of an alinement. Mineralized veins commonly occupy fissures or faults that have remained open.

New fault evidence would be open cracks; small fault scarps; new landslides; horseshoe-shaped cracks and openings in hillsides indicating slumping; small pressure ridges; compression ridges that appear like mole tracks; long, open fractures that aline with old fault traces; new rockfalls; boulders dislodged and rolling down hills; lurch fractures and cracks developing in water wells; increase in stream runoff caused by vibration compaction of and disturbance of unconsolidated water-filled material; increase or decrease of waterflow from springs; or formation of slump or subsidence areas in valleys. Landslides, rockslides, and boulder falls may continue because of aftershock damage and vibration. Small mud volcanoes may form in water-saturated terraces along valleys because of the vibration compaction of the water-filled sediments. The zone of cracking and rupturing may be quite wide and not just along the fault trace. Related movement and fault adjustment on adjacent or transverse faults may occur after the main earthquake shock. Thus, surface damage is not confined to a single area. In major earthquakes involving fault movement where the surface is disturbed, the ground surface may be affected over a considerable distance both along the fault and away from the fault zone.

[10] Work cited in footnote 3, pp. 89–92.
[11] Foose, R. M., and Hoy, R. B., Air and Ground Inspection Techniques for the Detection of Underground Explosive Tests: Office of Naval Res. ITR–1715, Sept. 8, 1959, 124 pp.
[12] State of California Department of Natural Resources, Earthquakes in Kern County, California, During 1952: Division of Mines Bull. 171, 1955, 283 pp.

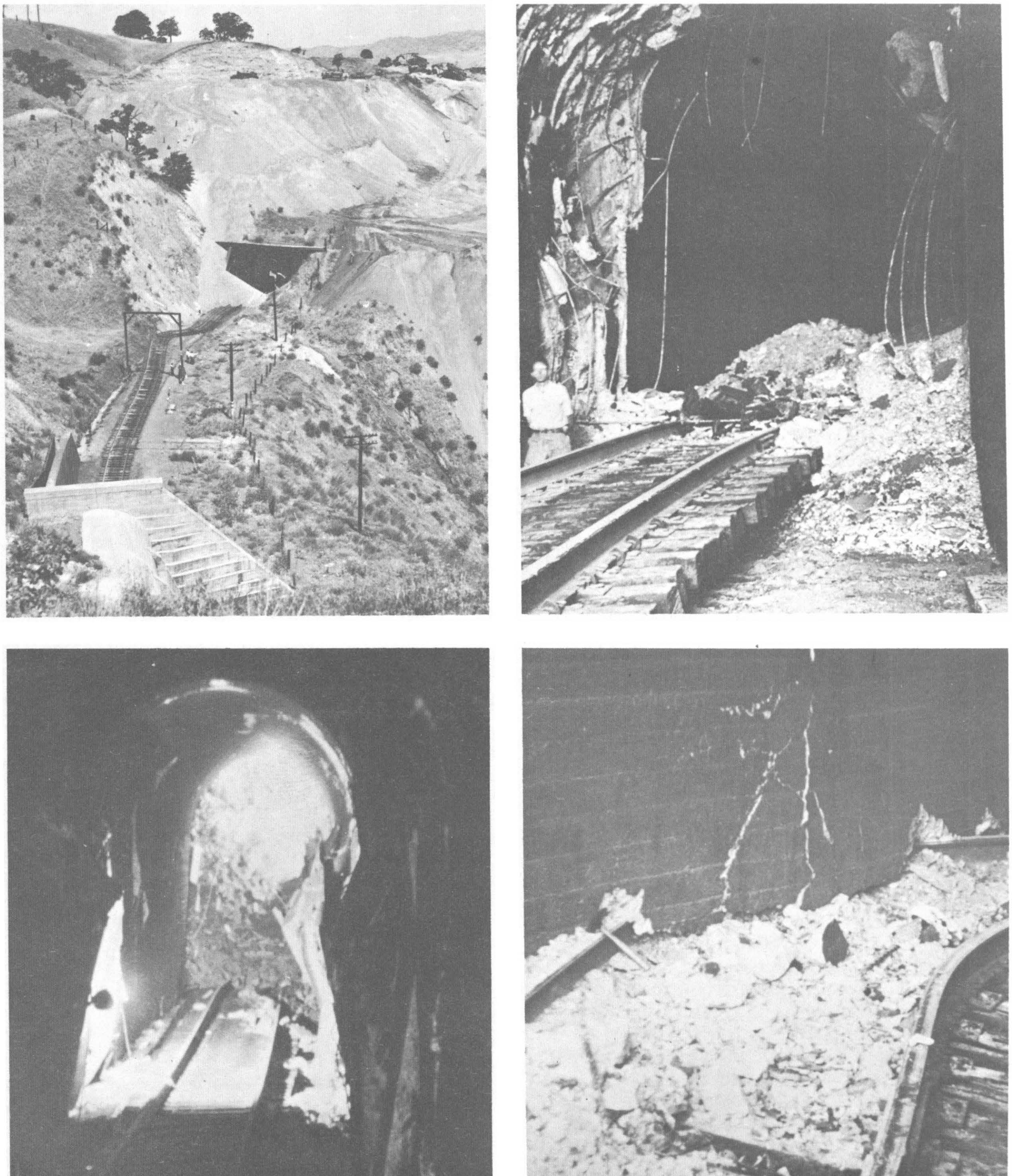

FIGURE 1.—Tunnel Damage From Tehachapi Earthquake, California, 1952.

Flow in many of the streams and springs in the area increased as a result of the Arvin-Tehachapi earthquake.[13] Although this increase in flow appears to have been temporary, there was some evidence remaining a year later. This temporary increase probably was caused by the disturbance of unconsolidated material in the discharge area. It is doubtful that the earthquake had any permanent effect on the recharge areas or the permeability of the aquifers.

There is virtually no information in the literature regarding underground manifestations of earthquakes. Past experience would evidence that underground openings, particularly those several hundred feet below the surface, are not vulnerable to damage by earthquakes. If a mine were very close to the epicenter of an earthquake, there could be some damage to underground installations, such as pipelines. If the mine were on or within the area of a fault movement, there could be damage and loss of workings, depending on the intensity of the earthquakes, but there is no recorded evidence to this effect.

Earthquake information should be assembled country by country and reproduced for evaluation purposes. It was particularly evident in the testimony at the hearings[14] that general information concerning the amount of low-magnitude disturbances is scarce. The onsite investigators should have all available data for differentiating earthquake phenomenology.

Rock Bursts

A rock burst is the sudden failure and collapse of a portion of the solid rock in and around mine openings. Rock bursts are the direct result of the accumulation of stress beyond the ultimate strength of the rock. This accumulation of stress results because of the removal of ore and rock which was originally supporting some of the load on the rock. The rock stresses in and around mine openings continually change as mining progresses. If the mining pattern is such that large stresses are accumulated in a given section of rock, then rock burst conditions are produced. They are relatively common events in some areas and can be a material menace to mine personnel.

Rock bursts are no more than small earthquakes, as both usually involve the sudden release of elastic strain energy. However, the mode of failure associated with rock bursts is generally different from that for earthquakes. For earthquakes, the mode of failure is usually shearing, resulting in elongated fractures or faults. For rock bursts the mode of failure is usually crushing as in compression failure of laboratory test specimens of rock. Because there is space into which the rock can move, the crushed rock is ejected into these openings during a rock burst.

Rock bursts can vary in size and intensity over extremely wide ranges. The spitting of rock fragments from a drift or mine heading is in reality a small rock burst. Such spitting rock is the failure of small pieces of rock on the surface of the opening because of large circumferential rock stresses. Rock bursts may involve only small sections of a mine, such as a pillar, a single drift, or a single stope, or they may involve large sections of a mine including several pillars, stoping areas, or even several levels.

A rock burst generates seismic waves which travel away from the source in all directions. Large rock bursts in deep mines have been known to produce noticeable vibrations at the surface of the earth. For example, houses and buildings vibrate, dishes rattle, and people are often awakened from sleep. Rock bursts have been recorded on distant seismographs in a number of instances.

A rock burst in a mine at Kirkland Lake, Ontario, was recorded by seismographs at Weston, Mass.[15] On October 22, 1937, a rock burst affecting the Champion Reef and Ooregum mines in Kolar, India, was felt by people on the surface in places more than 18 miles from the source of the burst. Local seismograph readings were not obtained on this shock because all three styles were thrown off. A lesser rock burst in 1930 threw off the N.-S. and E.-W. styles but recorded a vertical movement of 31 mm. Three rock bursts occurred in the Galena mine, Wallace, Idaho, on March 24 and 25, 1961. Inquiries by the Bureau of Mines disclosed that two of the three events were recorded by seismograph stations. The first burst was recorded as a primary wave only at Gonzaga University Station in Spokane, 75 miles away. The station reported that the recorded event was more like a rock burst than an earthquake. The second burst was recorded at the U.S. Coast and Geodetic Survey station at Butte, Mont., 190 miles from the mine. The signal was weak but quite clear and was recorded by the station as an earthquake. A Bureau engineer at the site stated that the surface effect was similar to that from an explosion or plane passing through a sound barrier rather than the effect from an earthquake.

[13] Work cited in footnote 12.
[14] Work cited in footnote 3.

[15] Hodgson, Ernest A., Velocity of Elastic Waves and Structure of the Crust in the Vicinity of Ottawa, Canada: Bull., Seismological Soc. of America, vol. 32, No. 4, October 1942, p. 249.

Rock bursts can occur in any mine opening or underground cavity. They are rare in mines with depths less than 3,000 feet below the surface of the earth, but are known to occur at depths of less than 500 feet. Where rock bursts have been reported in shallow mines, there has been evidence always of large tectonic forces in the rock. Thus great horizontal stresses are present, as well as vertical stresses due to the weight of the overlying rock. Hard, brittle rocks are more subject to rock burst than soft, plastic rocks.

For a rock burst to occur, the stress on the rock must exceed the ultimate strength of the rock. Therefore, the probability of rock burst in a given mine can be determined by measuring the compressive strength of the rock and determining the average stress in the rock around the mine openings. The compressive strength of the rock can be determined by testing diamond-drill core samples of the rock in a standard laboratory compression test. The average stress on the rock can be determined by making strain-relief tests in drill holes around a number of mine openings. The method of making these strain-relief measurements in drill holes has been described.[16]

Damage to underground workings resulting from rock bursts could be very similar to that caused by a local underground nuclear detonation. Rock bursts may occur in the bottom as well as sides or top of a mine opening. Complete collapse and floor heaving are not unusual in rock burst damage. Figure 2 shows damage at the Galena mine which included rock spalling, caving of mine openings, heaving of the floor, and distortion of mine supports and ventilation pipes. As indicated by the photographs, underground evidence of rock bursts may be numerous and varied. Usually signs of large stresses in the rock are visible, such as crushing and bending of supports, hourglassing of pillars, and movement along faults. Several reports describe the physical damage produced by rock bursts, methods of measuring pressure in the rocks, and methods of minimizing rock bursts.[17] Identifying rock burst damage will require assessment of mine depth, rock characteristics, history of mine, and previous rock bursts and pressure measurements in the mine.

Because a rock burst generates seismic waves which can be recorded on seismographs, it is very likely that a seismic network designed for monitoring underground nuclear detonations will detect a number of rock bursts. Whether or not these detections can be properly identified from their seismogram is not known. Little or no research work has been done on the subject. Thus, an inspection team would have to be familiar with the characteristics and manifestations of rock bursts.

Large Chemical Explosions

There is always the possibility that some country will detonate large chemical explosions to break a large mass of rock or to remove great quantities of overburden. An inspection team should be familiar with the characteristics of large chemical explosions.

Numerous large chemical explosions have been detonated by various mining and contracting companies. For example, the Ripple Rock blast in Canada on April 5, 1958, involved 2,756,324 pounds of Nitramex 2H, and the Promontory Point, Utah, blast of January 1958 involved a 2,130,000-pound mixture of grained ammonium nitrate and dry carbonaceous material. The Corps of Engineers has made several tests with large volumes of explosives at the Dugway Proving Grounds in Utah.

The size of cavity needed to place a chemical explosion underground is much larger than that required for a nuclear explosive of the same yield. A 1-kt. nuclear explosive could be placed in a cavity smaller than 10 $ft.^3$, whereas 1 kt. of TNT would require a cavity greater than 2.0×10^4 $ft.^3$ Thus, the ratio of the original cavity size is of the order of 2.0×10^3.

The energy density for chemical explosions is much smaller than for nuclear explosions. Thus, the temperature and pressure in the original cavity are much lower for chemical explosions than for nuclear explosions. Consequently, there is little or no vaporization and melting of rock from chemical explosions.

The pressure generated by chemical explosions at the boundary of the original cavity is of the same order of magnitude as the pressure

[16] Merrill, Robert H., Static Stress Determinations in Salt—Site Cowboy: Bureau of Mines Report APRL 38-3.1, July 29, 1960, 13 pp.
Merrill, Robert H., and Hooker, Verne E., Static Stress Determinations and Crushed Zone Measurements—Site Hobo: Bureau of Mines Report APRL E38-7.1, July 1960, 15 pp.
[17] Morrison, R. G. K., Points of View on the Rock-Burst Problem: Canadian Inst. Min. and Met., Trans., vol. 42, 1939, pp. 443–460 (gives a bibliography of 19 references).
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Leeman, E. R., The Measurement of Changes in Rock Stress Due to Mining: Mine and Quarry Eng., July 1959, pp. 300–304 (gives 10 references for recent papers).

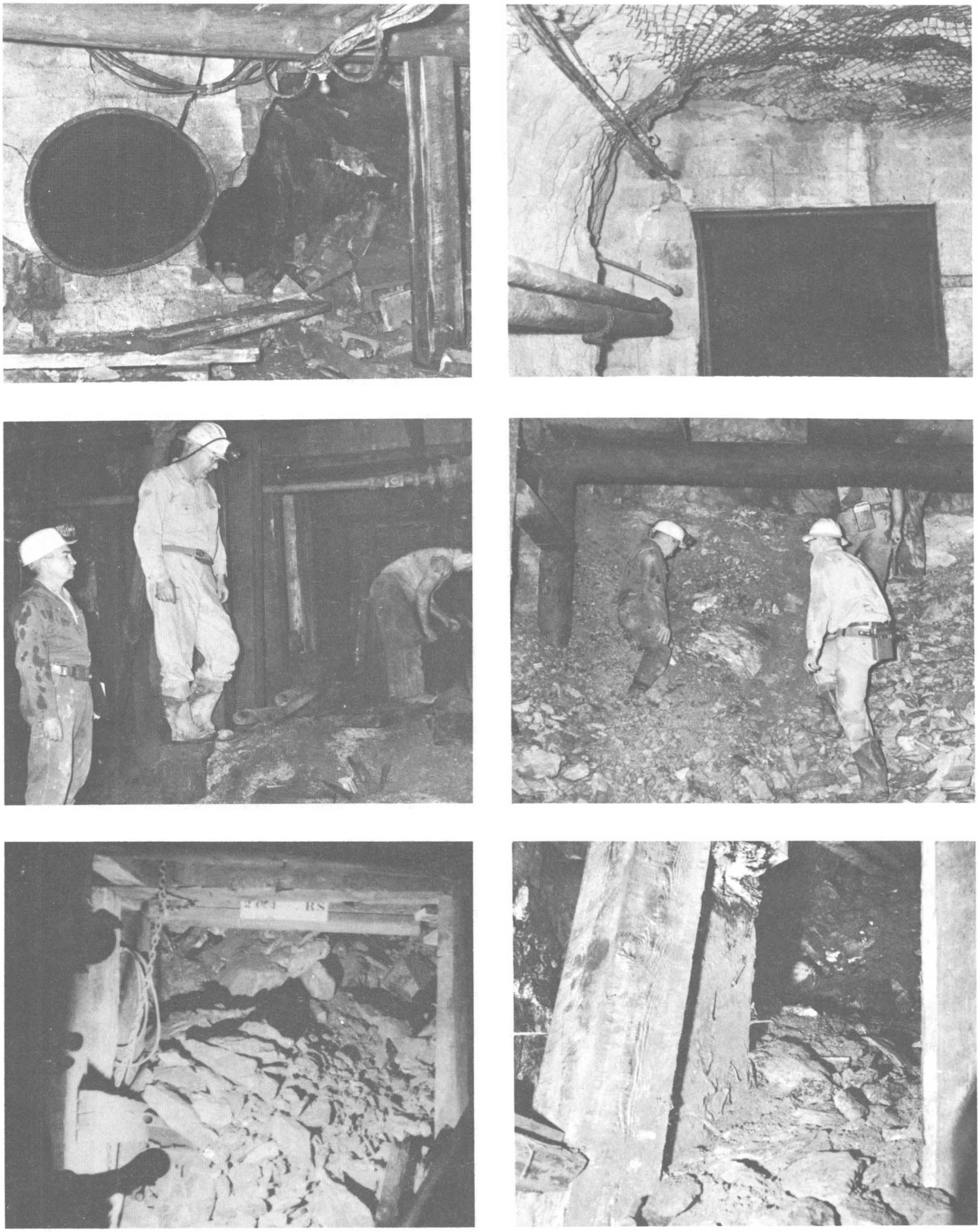

FIGURE 2.—Rock Burst Damage, Galena Mine, Idaho, March 25, 1961.

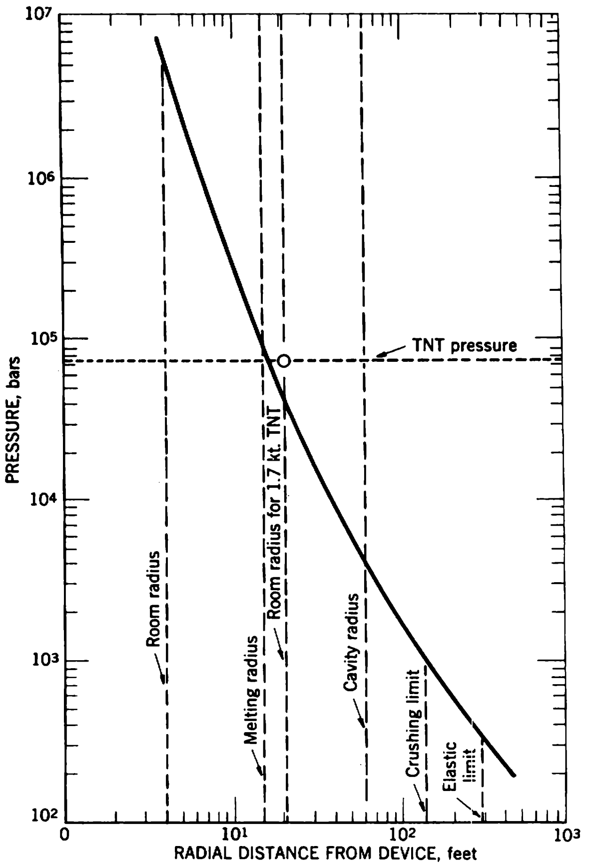

FIGURE 3.—Pressure Versus Distance for the Rainier Event.

generated by nuclear explosions at the same scaled radial distance. Figure 3 shows the pressure as a function of distance for the Rainier event,[18] together with the equivalent cavity necessary to hold 1.7 kt. of TNT at a density of 100 lb./ft.[3] and the explosion pressure generated by the chemical explosive. The plotted point for TNT falls very close to the given pressure curve.

In general, the peak pressure, duration, and shape of the shock wave determine the vibration and damage effects. The shape and duration of the shock wave may not be similiar for nuclear and chemical explosions; however, if their peak pressures at the same scale distance are similar, then one would not expect major differences in the vibration and shock effects. Confining chemical explosions should be more difficult than confining nuclear explosions because of the large gas volume generated in chemical explosions. The biggest difference between chemical explosions and nuclear explosions will be the absence of high temperature and radioactivity in the cavity created by the chemical explosion.

Accidental Disturbances

An accidental disturbance might cause a seismic signal of a magnitude comparable to that caused by a subsurface nuclear detonation. If the seismic signal were caused by an accident in close proximity to a seismic station, it would be identified or otherwise ruled out on the basis of data (or lack of data) from other stations. If, however, it were of appreciable magnitude, it might be detected at several stations and the epicenter might be located by triangulation. In such an instance there should be no particular difficulty in correctly identifying the cause of the seismic signal.

There have been several seismic shocks produced accidentally. The explosion of a ship loaded with ammonium nitrate at Texas City, Tex., was one of the most disastrous in recent years. Although the ship was resting in water, which provided an excellent coupling effect for the explosion, it is doubtful that the seismic effect was more than local in extent. Earthquakes of even minor magnitude develop tremendous energy. Accidental detonations of manmade explosive would seldom produce comparable energy or be felt over very large areas. However, checking times of large dynamite explosions for breaking rock underground at the Climax mine apparently accounts for some of the minor vibrations picked up on the sensitive seismograph at Boulder, Colo., about 100 miles away.

Probably the most energy developed by accidental explosions would be that caused by a large meteorite striking the earth. The Winslow, Ariz., crater and the large crater in Siberia are two examples. It has been estimated that the Winslow crater formation required energy equivalent to nearly 2 megatons of explosives.

Underground Nuclear Detonations

The decision to test nuclear devices underground was originally predicated on the increasing public concern over fallout and the possibility of a resulting limitation on future weapons tests. The Rainier shot was designed to test the feasibility of underground containment of radioactive debris from nuclear explosion. Several possibilities have evolved from the original purpose of underground detonation of nuclear devices, including certain peaceful

[18] Johnson, Gerald W., and Violet, Charles E., Phenomenology of Contained Nuclear Explosions: Univ. California Radiation Laboratory Rept. 5124 Rev. 1, December 1958, 27 pp.

uses, technical knowledge of weapons testing in new medium, and more recently the possibility of clandestine testing.

The principal data available for studying the behavior of underground nuclear explosions were obtained from preshot, transient, and postshot measurements made during experiments at the Atomic Energy Commission's Nevada test site.[19] Some of the characteristics of the underground nuclear explosions that are important to onsite investigators are listed in table 3.

The Rainier test was intensively studied, and subsequent tests were highly instrumented, using data obtained from the Rainier test as a guide to instrumentation and measurements. All of the nuclear devices in these tests were detonated underground in volcanic rock, referred to locally as the Oak Springs tuff.

Reports on these tests indicate that, in all tests, some disturbance of the surface of the earth was detected. With the exception of the Neptune and Blanca tests, radioactivity was confined beneath the surface of the earth.

In considering the physical effects of subsurface nuclear detonations with respect to their detection, it was apparent that radioactive fission products in the atmosphere would not be an effective detection technique and that detection by seismic measurements of the shock wave propagated through the earth would be the first and most important long-range technique.

A natural subsequent consideration was the possibility of reducing the intensity of transmitted shock waves. Latter and associates[20] suggested that if an explosive were detonated in a hole adequately large, without direct contact with the surrounding solid medium, the intensity of the shock wave propagated through the rock would be appreciably reduced by as much as a factor of 300. This theory was tested by detonating chemically high explosives of various yields, both coupled and decoupled in rock salt, during the Cowboy series of tests conducted in a salt dome at Winnfield, La.[21] The basic validity of the decoupling theory was demonstrated by the experiments. Detailed information of the Cowboy tests, Hardtack series, and the Rainier event is available in published reports.

Geological conditions at the Nevada test site are not entirely ideal for all types of underground nuclear testing. The site was established originally to permit isolated tests involving detonations at or above the surface. The geologic considerations were then secondary in importance. Several reports have been written on specific geologic problems at the Nevada test site.[22]

The local geologic setting would be a primary consideration in contemplating underground clandestine nuclear detonations—especially for decoupled tests. The tuff formations at the Nevada test site obviously would not support the required openings for very large decoupled detonations.

[19] U.S. Congress, Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban: Appendixes to Hearings Before Special Subcommittee on Radiation and Subcommittee on Res. and Development of Joint Committee on Atomic Energy: 86th Cong., 2d sess., pt. 1, 1960, pp. 1–478; pt. 2, pp. 479–951.

[20] Latter, A. L., LeLevier, R. P., Martinelli, E. A., and McMillan, W. G., A Method of Concealing Underground Nuclear Explosions: The Rand Corp., Report R–348, 1959.

[21] Herbst, Roland F., Werth, Glenn C., and Springer, Donald L., Use of Large Cavities To Reduce Seismic Waves From Underground Explosions: Univ. California Radiation Laboratory Rept. 6165, Sept. 29, 1960, 55 pp.

[22] Hansen, W. R., and Lemke, R. W., Geology of the USGS and Rainier Tunnel Areas, Nevada Test Site: Geol. Survey, TEI–716, 1958, 111 pp.

Gibbons, A. B., Geological Effects of the Rainier Underground Test. Geol. Survey, TEI–718, July 16, 1959, 35 pp.

Diment, W. H., Geologic Effects of the Rainier Underground Nuclear Explosion: Geol. Survey, TEI–355, January 1959, 143 pp.

Thompson, T. L., and Misz, J. B., Geologic Studies of Underground Nuclear Explosions Rainier and Neptune (Final Report): Univ. California Radiation Laboratory Rept. 5757, Oct. 28, 1959, 58 pp.

TABLE 3.—*Characteristics for six underground nuclear detonations*

Event	Yield (W), kt.	Depth below nearest free surface (D), feet	Scaled depth, of $D/W^{1/3}$	Measured radioactivity on surface (R), percent	Scaled distance for tunnel collapse, of $R/W^{1/3}$	Scaled distance for no tunnel damage, of $R_3/W^{1/3}$	Remarks
Neptune	0. 090	99	220	1–2	--------	340	Cratered from surface to cavity with some venting of gases.
Blanca	19. 0	835	310	0. 5	320	940	Broke up surface badly, cavity caved to surface with some venting.
Logan	5. 0	830	485	0	480	870	Broke and fractured surface.
Rainier	1. 7	790	670	0	167	920	Broke and fractured surface. Cavity caved to a height of 386 feet.
Tamalpais	. 072	330	780	[1] 0	--------	570	
Evans	. 055	840	2, 700	[2] 0	--------	--------	

[1] No breakthrough to surface, but radioactive gases in large quantities leaked into tunnels.
[2] No breakthrough to surface, but stemming failed, reducing gross fission activity into tunnels.

Testing has been held to be essential to development of new nuclear weapons: First, to determine whether the design will work; second, to obtain test data on yield and capability; and third, to obtain data for further development and increased efficiency.

The fact that these advantages and necessary requirements for nuclear weapons development exist points to the potential benefits of clandestine nuclear tests and creates suspicion during any test ban that fails to include adequate controls.

Progress on seismic research has not kept pace with the time, efforts, and funds expended in the decoupling experiments. The need for increased effort was defined in the Berkner Report of the Panel on Seismic Improvement.[23] In general, it was suggested that notable improvement could be made in seismic techniques and in the interpretation of seismic data, and thus in the probability of successfully differentiating between signals from earthquakes and from explosions. The inadequacy of existing world seismic coverage is recognized in the report and associated testimony.

The concept of onsite inspection for purposes of identification of a detected seismic event evolved after the Rainier event and before the Hardtack series. Thus, the first investigation of onsite inspection problems was postshot surveys of the Rainier and Hardtack tests. Some attempt has been made to evaluate the results of these tests as an example of what might be found at the site of a clandestine underground nuclear detonation. Most of this evaluation is a result of postshot instrumented evaluation studies. Some of the postshot evaluation studies, such as those on seismic noise level, were discontinued without definite conclusions. There was no comparative record established for before and after observations.

The idea of documentation for both before- and after-shot records was recognized and practiced at the underground high-explosive tests for Project Cowboy.[24] Some of these observations appear to be useful in the sense that effects can be established that would be valid for any after-detonation inspection.

Obviously, the underground nuclear detonations at the Nevada test site are not typical of conditions likely to surround a deliberate attempt to conceal an underground detonation. As one example, there were hundreds of related scientific experiments and many people involved and associated with the tests that would hardly be essential if concealment was a planned factor.

Published reports by Stanford Research Institute (SRI) [25] review past research on onsite inspection techniques, the proposed program of development work for onsite inspection techniques, and the impact of the latest concepts and information on decoupling. The SRI reports also test proposed inspection schemes by trying them against several theoretical, underground, clandestine nuclear tests and review the equipment and modus operandi of an onsite inspection group, estimating the likelihood that an inspection group can obtain onsite actual samples or other proof giving a high degree of confidence that a clandestine underground nuclear test has occurred.

EVALUATION

Most of the considerations, negotiations, and speculations concerning subsurface nuclear testing are based on Rainier data. This perhaps is unfortunate, as it is possible that weight thereby is given to the probability of concealment, rather than detection. Weight is added to this apparent imbalance by the Cowboy series of decoupling experiments, which were demonstrably successful in proving the decoupling theory.

Many of the present conclusions used as working guides are based on postulated theory and limited test data. In most cases, one rock type has been tested; generally, not more than two rock types provide the instrumented test data. Neither the theory nor the test experience is refined to a point where expected action and results of an underground nuclear detonation are assured. The test literature is replete with wide spreads in instrumental readings and unexpected actions. The scaled depth of burial has had to be increased for planned future shots. It is generally concluded in reports that radioactivity will be contained in the shot cavity, yet this has not actually been obtained in the tests. In general, many of the conclusions are not firm and, therefore, are suspect, particularly when extrapolated to other rock types.

Although large sums of money have been spent for testing and much valuable data have been accumulated, there is still no absolute as-

[23] Work cited in footnote 19. (App. 5, Report of Panel on Seismic Improvement, pp. 643–838.)

[24] Hoy, Robert B., and O'Neill, Bernard J., Jr., Investigation of On-Site Inspection Techniques for High-Explosive Tests in a Salt Mine, Project Cowboy: Stanford Res. Inst. SU–2993, December 1959–March 1960, 76 pp.

[25] Foose, Richard M., Inspection of Sites of Unidentified Seismic Events: Stanford Res. Inst. Project No. 2 SU–3102, Aug. 19, 1960, p. 4.
Foose, R. M., and Hoy, R. B., Identification of Possible Underground Nuclear Explosions by On-Site Inspection: Stanford Res. Inst. and Office of Naval Res., WT–1739, 1959, 93 pp.
———, Air and Ground Inspection Techniques for the Detection of Underground Explosive Tests: Office of Naval Res. ITR–1715, Sept. 8, 1959, 124 pp.

surance that a planned underground nuclear detonation will respond as predicted. This situation is encouraging in one sense, since it suggests a major possibility for detection of clandestine explosions by onsite examination.

A notable example is the apparent discounting of radioactive surveying methods as an investigative tool. It has been stated that the only acceptable proof of an underground nuclear detonation will be positive identification of radioactive fission products in the locality of an onsite inspection. It is generally assumed that the distribution of fission products will be confined within a relatively small radius from ground zero. Available evidence would indicate that the possibility of complete containment of radioactivity is by no means assured at any specific test site. Radioactive surveys must still be considered a powerful potential tool to investigate underground nuclear detonations.

Confinement of radioactivity in underground tests, assuming adequate depths, primarily is a function of the composition and competency of the rock within which the device is detonated and, to a lesser extent, of rocks above and around the test medium. The water content of the medium containing the detonation and the proximity of other rock formations with appreciable contents of ground water that might circulate through the broken rock after detonation also are significant to the distribution of fission products.

All of the underground nuclear tests at the Nevada test site were made in bedded volcanic tuff located stratigraphically so that fracture planes and fault zones within the rock and between it and the surface were minimal. It should be recognized that, in a formation which has appreciable fractures or faults present or adjacent to it, there is a good possibility of fission products being distributed for a considerable distance. It is quite possible that such conducting zones might be present without the knowledge of the party making the test, even though a comprehensive geologic study might have been made before a test was planned and executed.

Furthermore, in reports on the Rainier test,[26] considerable stress was placed upon the fact that a large percentage of the fission and activation products from the detonation were fused in a glass shell which later collapsed to the bottom of the cavity formed by the explosion. The Oak Springs tuff [27] reportedly ranged in SiO_2 content from 60 to 75 percent. The content of Al_2O_3 was 12 to 13 percent. Many rocks that could be chosen for subsurface nuclear tests would have considerably lower contents of silica and alumina. There is some doubt that comparable glass shells would be fused to entrap fission products in many media unless the nuclear device itself were surrounded by fusible material added for the specific purpose of containing radioactivity. For example, rock salt has been considered by some to be a good medium for nuclear tests. However, the silica content of rock salt is so low that no glass shell should be formed.

The effect of circulating ground water in distributing radioactive materials also should not be minimized. The fused glass formed in nuclear detonations in the Oak Springs tuff generally has been considered to be essentially insoluble in water. However, Bond and Clark [28] cite 0.52 percent alpha, 0.54 percent beta, and 0.41 percent gamma radioactivity leached from Rainier debris in 48 hours by ground water at room temperature, with an essentially constant leaching rate at the end of 48 hours of 0.05 percent per hour. For Tamalpais debris under the same physical conditions, these authors [29] reported leaching of 4.1 percent alpha, 13.4 percent beta, and 9.9 percent gamma radioactivity.

Batzel [30] presents a table giving the total radioactivity in curies multiplied by gamma-ray energy per kiloton (fission-products and induced radioactivity), at time in hours after explosion of a nuclear device. Although the fission-products radioactivity and, in particular, the induced radioactivity decay rapidly, approximate values of 10^{16} curies, 2×10^5 curies, and 0.5×10^4 curies per kiloton should remain at the end of 1 week, 1 month, and 1 year, respectively. Similar values are cited by Glasstone.[31] Thus, it is obvious that leaching as little as 0.5 percent of the radioactivity trapped in glass might materially contribute to the radioactivity of circulating ground water and, therefore, be most significant in yielding evidence of a subsurface nuclear test.

In considering the zone within which drilling and logging might detect abnormal radioactivity indicative of a subsurface nuclear test, it generally has been assumed that this would be roughly confined to a sphere with a radius of the original gaseous or fireball zone. For Rainier, this was about 62 feet. There is a high proba-

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[26] Work cited in footnote 19, pp. 238–280.

[27] Warner, Stanley E., and Violet, Charles E., Properties of the Environment of Underground Nuclear Detonations at the Nevada Test Site; Rainier Event: Univ. California Radiation Laboratory Rept. 5542, Rev., April 1959, 127 pp.

[28] Bond, W. D., and Clark, W. E., Leaching of Rainier Debris: Oak Ridge Nat. Laboratory Central Files No. 59–4–30, Apr. 2, 1959.

[29] Bond, W. D., and Clark, W. E., Leaching of Tamalpais Debris: Oak Ridge Nat. Laboratory 2810, Jan. 28, 1960, 11 pp.

[30] Batzel, Roger E., Radioactivity Associated With Underground Nuclear Explosions: Univ. California Radiation Laboratory Rept. 5623, June 23, 1959, fig. 2, p. 12.

[31] Glasstone, Samuel, The Effects of Nuclear Weapons: Department of Defense and Atomic Energy Commission, June 1957, p. 391, sec. 9.5.

bility, however, that the zone of detectable radioactivity might have a considerably larger radius. Johnson and others[32] cite the following radii for various zones in the Rainier experiment: Gas, 0 to 62 feet; liquid, 62 to 62¼ feet; crushed, 62¼ to 130 feet; and fractured, 130 to 280 feet. It should be emphasized that these values apply to the Oak Springs tuff. For other rocks these radii might be either greater or less. In the same presentation, Johnson and others point out, as does Batzel,[33] that some gaseous fission products with half lives adequately long, and some other volatile radioactive substances, escaped from the 62-foot-radius zone of major radioactivity confinement in the Rainier experiment. The gaseous isotopes, principally krypton and xenon, besides being themselves radioactive, are precursors of other isotopes, notably strontium 89, strontium 90, and cesium 137. Johnson and others[34] estimate that 60 to 85 percent of the total radioactivity was contained in the fused glass, allowing for the escape of 15 to 40 percent from the cavity.

Appreciable quantities of radioisotopes might be expected to be distributed throughout zones with adequate permeability to gas, and might be expected either to remain in those zones in the gaseous state or to decay to other radioisotopes that would be absorbed on or precipitated in the crushed or fractured rock. Therefore, for the Rainier test, with a reported yield of 1.7 kt., the zone of potential detectable radioactivity should have been a sphere of as much as 280-foot radius. It is true that abnormal radioactivity was not reported as having been observed from surface measurements or drill holes at a radius of that distance. However, there might have been several reasons for this. If radioactivity surveys, particularly those in drill holes, had been made at an earlier date, the results might have been different. Also, the detection of radioactivity is dependent on the type of detector used and, if beta-logging equipment had been used, the radioactivity from some other substances might have been detectable. Diment[35] says:

> The Rainier explosion was contained in the sense that no anomalous radioactivity was noted either on the surface or in the part of the tunnel that remained after the explosion. However, the radioactivity background due to other tests was so high on the surface at the Rainier site that it is not known whether small but detectable (under normal circumstances) amounts of radioactive products escaped to the surface. The bulk of the radioactive products was confined within a radius of 70 to 80 feet from the point of detonation.

If it is assumed that a coupled shot of 20-kt. yield is the minimum detectable at a seismic signal strength of 4.75 with a Geneva network, extrapolation of the fractured zone to the Blanca test (yield about 19 kt.), for example, would result in the possibility of some radioactive substances being distributed in a zone with a total radius of 630 feet. This would not only increase the extent of detectable radiation but could disperse nuclides of volatile elements that may contaminate ground water and introduce even greater migration of radioactive products.

It has been assumed that airborne radioactivity surveying equipment will be used by an inspection team making surveys of the 13-kilometer-radius area selected for further investigation on the basis of seismic data and other knowledge. Moxham and Bunker[36] describe the manner in which such surveys are made by the Geological Survey and in which they might be made by an inspection team, using scintillation equipment. Surveys on a ¼-mile grid basis are suggested at altitudes as low as practicable (200 to 500 feet with a DC–3 aircraft, depending upon topographic relief). Whether a survey on that grid basis and at those altitudes would detect any radioactivity anomalies of significance is problematical. However, if radioactive fission products have vented to the surface through conductive zones, such a possibility exists. Depending on the terrain, the facilities available, and the time required and available, radioactivity surveys at lower levels and on a closer grid spacing should result in more comprehensive coverage and, consequently, in a much improved chance of detecting vented radioactive material. Therefore, it is suggested that a helicopter or light fixed-wing aircraft equipped with sensitive radiation-detection equipment might be used in making low-altitude aerial radioactivity surveys on a much closer grid spacing. Once smaller areas have been selected so that actual onsite investigations may be started, surface radioactivity surveys, made with scintillation equipment transported in a jeep, boat, or other suitable vehicle, are recommended.

Almost any geologic formation could be used for coupled detonations, but some would be favored over others because of cost considerations in opening and preparing the test site. One of the major problems would be water in the underground openings. The amount of water encountered in penetrating some sandstones and limestones could preclude their selection. Most geologic formations, including the granites, have been faulted, folded, and

[32] Work cited in footnote 19, p. 263, table 14.
[33] Work cited in footnote 30.
[34] Work cited in footnote 19, pp. 238–280.
[35] Diment, W. H., ed., Feasibility of Locating Sites of Underground Nuclear Explosions by Geologic and Geophysical Methods: U.S. Geol. Survey TEM–1106, June 1958, p. 12.

[36] Work cited in footnote 35, pp. 33–36.

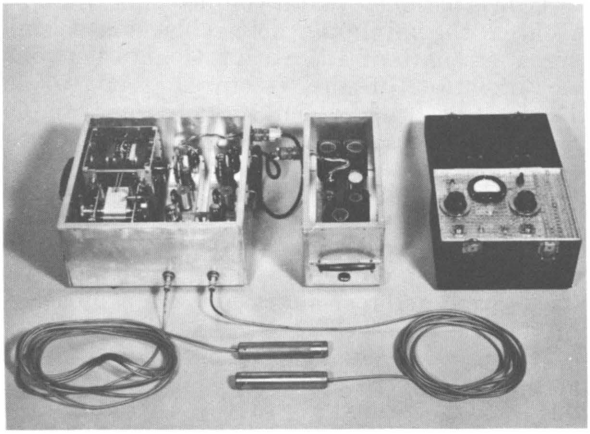

FIGURE 4.—Microseismic Noise-Monitoring Equipment.

fractured. These structural defects will impair their capability to support mine openings without artificial support and tend to channel or give directional effect to the explosion forces. This has been demonstrated in the Nevada test site explosions. Also, this weakness seriously affects their potential as sites for decoupling detonations. Geologic criteria might be established for subsurface nuclear tests, but it is doubtful that any area considered suitable geographically would have beneath its surface ideal geologic features. Therefore, the selection of a geologic structure for testing is likely to represent a compromise.

The tremendous potential for reducing seismic impulses through decoupling seems to present formidable problems in detection of clandestine underground nuclear detonations. However, the history of mining is certainly not marked by the capability of rock to support even relatively small openings, even in terms of tens of feet. Artificial support is a major cost of mining and underground excavation. With the exception of salt domes there is a high probability that few geologic formations will be able to support or maintain sufficiently large openings for large decoupling detonations. There seems to be an area of compromise between the requirement for decoupling and the capability of rock formations.

The Bureau of Mines has done considerable experimental work in the field of competency of rock.[37] More experimental work could be done on this subject. If decoupling were to be limited by the physical characteristics of rocks, then this would limit areas within a country where decoupling could be practical.

In general, the reports by Stanford Research Institute are excellent in that they cover a wide variety of inspection techniques and attempt to evaluate the effectiveness of these techniques. Considerable emphasis has been placed on before-and-after surveys in attempting to evaluate the effectiveness of a given survey technique. This method of approach is certainly necessary in the early research phases of survey techniques. However, the real effectiveness of a given survey technique cannot be fairly judged by before-and-after methods. It should be judged by its effectiveness for postshot application. That is, does the survey give a result when used where a nuclear detonation has occurred that is indicative of an underground nuclear explosion when compared to results obtained where a nuclear detonation has not occurred. Before-and-after surveys minimize the effects of geology, terrain, and so on, whereas comparative postshot surveys tend to maximize these effects. As no before surveys will be possible in any practical case, it seems logical that final evaluations of survey techniques should be based upon such comparative tests.

Past research has emphasized instrumental survey techniques and visual observations. The various techniques have been evaluated for use in the air, on the ground, underground, on water, and in drill holes. Recommendations regarding future research have been made. In general, these evaluations and recommendations appear satisfactory, but concentration on instrumentation and phenomenology tends to minimize other important aspects needed for a logical appraisal of a detected seismic disturbance. Factors of politics, geography, geology, culture, technology, and economics are highly relevant to all phases of the detection and identification process, including onsite investigations.

A review of the literature shows that the concept for seismic-noise-monitoring method has been restricted to low-frequency noise only, that is, less than 100 c.p.s. The Bureau of Mines has developed and used for years a noise-monitoring system for detecting and delineating areas of instability in mines.[38] The process, known as the microseismic method, uses a frequency range from 500 to 2,000 c.p.s. (fig. 4). This method should offer excellent possibilities for detecting underground nuclear detonations; research work to determine its possibilities and extend its range should be undertaken immediately. Further discussion

[37] Obert, Leonard, Duvall, Wilbur I., and Merrill, Robert H., Design of Underground Openings in Competent Rock: Bureau of Mines Bull. 587, 1960, 36 pp.

[38] Obert, Leonard, and Duvall, Wilbur I., Micro-Seismic Method of Determining the Stability of Underground Openings: Bureau of Mines Bull. 573, 1957, 18 pp.

of the microseismic method will be found in another section of this report.

Little consideration seems to have been given to the possibility that a detected seismic disturbance may be neither an earthquake nor an underground nuclear detonation. Rock bursts and large underground chemical explosions will also be detected by the seismic network. From the seismic data alone, these events most likely will not be identified as to cause; thus, onsite inspection of such events should be contemplated. The first observable physical effects, both on the surface and underground, may be quite similar for rock burst, large underground chemical explosions, and underground nuclear explosions. Temperature, radioactivity, and fissionable products will be the only positive method of identification. Strain-relief measurements will be useful (fig. 5).

Insufficient consideration has been given to that phase of onsite inspection concerned with mining technology versus nuclear testing technology. Recognition of this undoubtedly prompted this study.

A most important result of the underground nuclear testing program is the development of scaling laws from test data; the laws have important application to onsite inspection. Considerably more information is needed on the physical effects of underground nuclear detonations and how these effects scale with charge size and vary with distance and depth of burial. A later section of this report discusses scaling laws in more detail.

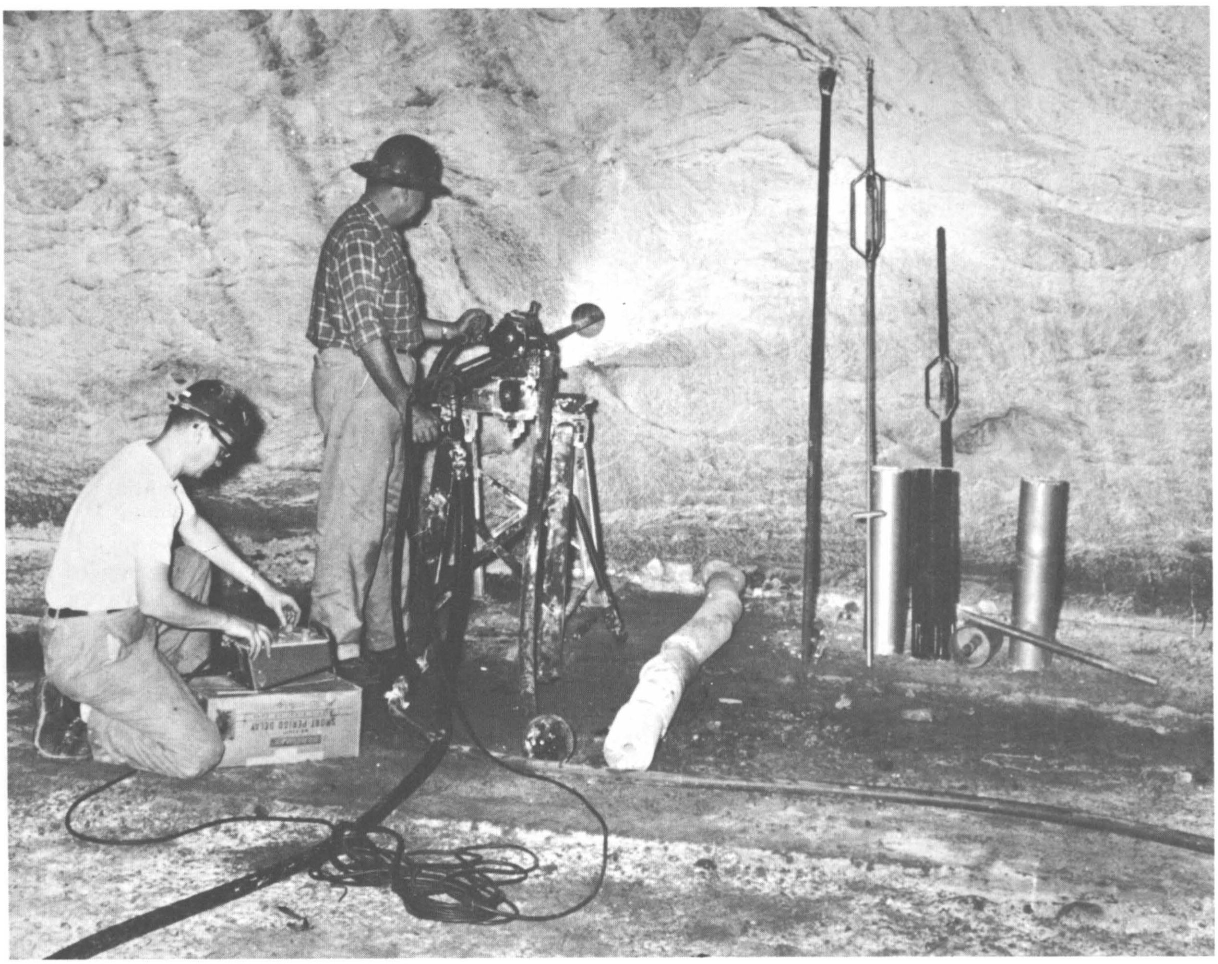

FIGURE 5.—Strain-Relief Measurement.

PRINCIPLES OF INVESTIGATION

The exact processes of evaluation and decision relating to and stemming from any inspection system are certain to be complicated. While every eventuality cannot be anticipated, it is quite clear that at least two parties will continuously employ identical evidence to support opposite interpretations. Moreover, such usage will transpire at every level, possibly culminating with the heads of states. A parallelism is seen in the provisions for appeals to higher bodies in systems of courts of law.

While this study is essentially of onsite findings, the initial tendency to avoid speculation on how local evidence would be weighed in higher "courts" is not quite realistic. For example, the factors used in a determination to authorize an investigation are not too difficult to visualize. Yet the factors influencing decisions to sustain such an investigation to a more detailed phase, or to terminate it, are not so precise. Specifically, what kind of evidence is admissible in presenting one's case? Further, to whom is such evidence presented for judgment? It seems apparent that only the body with authority to initiate an investigation can, in the end, assume the responsibility for terminating it.

The whole investigative process is a continuous balancing of obvious facts against circumstantial evidence to extract conclusions which will require yes-or-no decisions. It is suggested that prescribed periods for decision be defined and then limited to findings at three stages in any single event, including those decisions which determine the initiation and the termination of an investigation, somewhat as follows:

Remote phase:

1. Balancing relationships between: $\frac{\text{Seismic data}}{\text{Inferred nature of the event}}$.
2. Reconciling variation in conclusions.
3. Determining whether evidence justifies local investigation.

Local phase:

4. Balancing relationships between: $\frac{\text{Results of local investigation}}{\text{Inferred nature of the event}}$.
5. Reconciling variation in conclusions.
6. Determining whether evidence justifies onsite (surface and subsurface) investigation.

Onsite phase:

7. Balancing relationships between: $\frac{\text{Results of onsite investigation}}{\text{Inferred nature of the event}}$.
8. Reconciling variation in conclusions.
9. Determination to terminate.

Principal uncertainty attaches to the determination to terminate during onsite phase. The investigative procedure, as well as the types of evidence sought, will be influenced by both the long-range objectives and the specific terms of the international agreement under which inquiry is permitted. The maximum penalty for a proven violation of such an agreement can only be abrogation of the agreement itself, and it is reasonable to assume that no party to the agreement, including the nonviolators, will be particularly pleased with positive proof of a violation.

(The reasoning is for the sole purpose of exploring for the asymptotic limits within which investigations might be conducted. The assumptions should not be interpreted as authorized statements on the U.S. position or as advocated prescriptions for national policy. Specifically, the logic pursued here is the Panel's own. It is based upon reasoning that if a system of international inspection related wholly to nuclear testing can be implemented and sustained over a period of time, a broader and more delicate state of general disarmament might be substantially easier to achieve. This line of reasoning concludes that the establishment of the system itself is the important element, and further, that the products of investigations under the system are less important to the successful achievement of the ultimate objective—as long as some individual product does not destroy the system itself. Accordingly, the Panel felt that it must accept for consideration the possible eventuality of an onsite investigation that would discount all circumstantial evidence even where it is apparent in overwhelming volume).

The question of what constitutes proof of a violation might be governed by terms of the international agreement itself. However, the previous studies cited have all anticipated that final proof of a subsurface nuclear test would develop through drilling specific sites somehow localized first by seismic means and then by local disclosures. Where the recovery of data and samples that can exist only in the presence of a nuclear detonation and that are never occasioned by natural events results from such drilling the proof positive is considered achieved.

(As an academic exercise the Panel considered the question of whether even such products of drilling might in some instances fail as proof in an international arena. The school of thought contends that only confession on the part of the violator will constitute satisfactory proof).

The question that has not been debated is what would happen if drilling failed to produce any condemning products. In this instance, powerful circumstantial evidence would have been the basis for initiating the drilling, yet it is debatable whether any array of the evidence that occasioned drilling would in itself constitute positive proof.

Through a series of exercises, of which the foregoing is but one simple illustration, the objective of an onsite investigation is seen as a variable or perhaps as the apex of a rubber pyramid of evidence and conclusions. The objective certainly governs how an investigation will be pursued and what evidence will be sought. This study is addressed to a single situation—namely, the conduct of an investigation under rules of complete objectivity within the framework of an agreement that in no way inhibits this approach. However, other possible conditions have been recognized, including the one where preservation of the inspection system might be more important than a specific finding under it because of long-range objectives.

The problems and projected capability limits of an initial (remote) identification system, based on the establishment, support, and improvement of a teleseismic net, have been exhaustively reported and debated and were not a primary feature of this study. However, a tendency has been noted to divide the whole investigative process into phases without clearly establishing the important relationship between the nature of the data used to justify an onsite investigation and the techniques employed in the onsite investigation itself. As previously stated, the whole investigative process continuously obligates the participants to seek agreement of an appropriate point for termination. It is inconceivable, for example, that every investigation, once begun, must necessarily and always be carried through all phases of a firmly prescribed sequence that terminates with drilling. Even anticipating significant improvement in seismic equipment, technology, and methods, it seems inevitable that some single local finding might cause reinterpretation of the seismic data, or a prompt termination of the investigation. Further, operating policies that would require an explanation of the initiating seismic event (once an onsite inspection is authorized and underway) would be extremely unwise. Specifically, a reasonable finding that a seismic event probably was not occasioned by a nuclear detonation is a critical point, whereas continuing studies solely for determining the cause of the event is considerably less important, generally unwise, and should not be considered mandatory.

(The foregoing relates to operating policies applied to onsite inspection procedures implemented under terms of an international inspection agreement and not to research undertaken jointly or unilaterally for the specific purposes of improving the science of seismology—and publicly announced as such. The Panel specifically endorsed accelerated and additional research in this area.)

Similarly, the procedures and findings resulting from the conduct of local [39] phases of an authorized inspection strongly influence the direction and extent of onsite studies, and the concept expressed in the preceding paragraph applies equally to this phase.

[39] Some of the reports cited, and some reported discussions stemming from the Geneva negotiations, employ the words "onsite inspection" to describe all work initiated after a seismic event has been detected and a determination has been made to explore for the source. As employed here "onsite" applies to surface and subsurface inspections at a specific site. The words "local inspection" are intended to describe activity within an area delineated only by the capabilities of the teleseismic network, and assumed herein to embrace perhaps 100 square miles. Such inspection, employing both aerial and surface techniques, is visualized as being primarily directed toward localizing smaller areas for more detailed study and ultimately selecting points for "onsite" inspection, and so forth.

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PRELIMINARY INVESTIGATION OF AN AREA

The initial problem of the investigators will be to locate one or more likely areas of 1 to 5 square miles on which to concentrate. The general procedure most likely to produce results in making surveys preliminary to applying special mine examination techniques would be (1) aerial photoreconnaissance of the area, followed by (2) a low-level inspection using helicopters, and (3) a surface examination of suspicious features. Aerial photoreconnaissance of a suspect area before sending in an onsite inspection team for detailed surface examination will expedite the work.

Considerable information has been published [40] on aerial surveys, made to observe the effects of earlier subsurface tests of explosives, and recommendations have been made for aerial inspection techniques that would be useful in detecting evidences of clandestine tests.

Evidence of human activity in aerial photographs of the Nevada test site is abundantly discernible. Roads, rock dumps, tunnel entrances, cleared areas, vehicles, and similar features can easily be distinguished. The value of photoreconnaissance in detecting clandestine underground nuclear explosions that are completely contained (presumably a high percentage would be contained) seems to be mainly the availability of this type of evidence. With every effort being made by the perpetrators of any clandestine program to cover up all traces of surface activity, the chances of detection through high-level photoreconnaissance become greatly reduced. Even though no direct or indirect evidence of nuclear test sites can be developed from aerial photographs, such pictures provide a quick and accurate map guide to the area and probably will be the only maps of sufficiently detailed scale available to the investigating team.

Low-level visual surveys can be made from small observation-type airplanes, but preferably should be made from a helicopter. Preliminary visual surveys from the air should cover most of the suspected area (approximately 100 square miles) because they may pick up many detailed points that cannot be identified from the aerial photographs.

The visual survey crews should carry cameras to take low-level photos, thus permitting a recording of initial evidence that might be damaged or erased by subsequent work. These photographs of specific items or areas will be made before the inspection team actually enters the suspect area on the ground.

Site survey methods have been intensively investigated by Stanford Research Institute in collaboration with other organizations and Government agencies, and the results have been reported.[41] The work included a search for applicable methods and evaluation of their potential.

Most of the methods listed are commonly employed in conventional mineral exploration and mine examination projects and were developed through experience for that purpose. However, to pursue any of these methods successfully, it is necessary to interpret the findings correctly. The validity of interpretation generally improves with more extensive application of the method and with increased experience of the interpreter. Presently, there has been only limited experience in trying to apply the techniques to locate the site of either an underground nuclear detonation or to any conditions that might result from such an event. Improved results would be expected with added experience.

The SRI report suggests three onsite inspection phases: (1) Aerial reconnaissance; (2) intermediate or ground inspection (surface, underground, and water); and (3) drilling. One or all of these phases could be used with the sequence or techniques applied, depending on the requirements for the individual inspection.

Once a decision has been made to investigate a recorded seismic disturbance of unknown origin in a specific locality, preliminary surveys will be necessary before a more detailed inspection of the site. The area to be investigated may possibly be as large as 300 square miles, although it is to be hoped that the seismic records of the event will confine the source to an area half this size, or even smaller.

There should be some means of permanently recording the observations of the visual survey, either by short-range radio to a local base of operations, or with a portable tape or disk made by the observer.

As pointed out by Hoy and O'Neill,[42] it is important to have a qualified observer in a plane, from which aerial photographs are to be made, to select suspicious localities for im-

[40] Work cited in footnote 26.

[41] Foose, Richard M., Inspection of Sites of Unidentified Seismic Events: Stanford Res. Inst. Project No. 2 SU-3102, Aug. 19, 1960, p. 4.

[42] Hoy, Robert B., and O'Neill, Bernard J., Jr., Investigation of On-Site Inspection Techniques for High-Explosive Tests in a Salt Mine, Project Cowboy: Stanford Res. Inst. SU-2993, December 1959–March 1960, 76 pp.

mediate detailed photography. This also should be true for any other kind of aerial survey. Much useful information may be obtained by an observer who is skilled in aerial observations and, in addition, knows the characteristics of the anomalies for which he is looking.

Although radioactivity would not be expected at the surface from a clandestine nuclear detonation, its presence cannot be ruled out entirely. All nuclear tests are experiments, and as such, they are subject to wide variation in results.

Results of the combined aerial observations by high- and low-altitude photography, visual low-level observation, and instrumented surveys will provide the basis for evaluating and determining the specific areas requiring detailed surface examination. Thus, the data so obtained become an essential tool for subsequent mine examinations.

Surface surveys will require photographic record of all evidence, either for or against continuing the inspection. This is necessary for substantiating field decisions to discontinue the inspection, either for lack of evidence, or for finding evidence of an earthquake, or for cause of the disturbance other than nuclear detonation. It is also necessary to support any evidence of clandestine nuclear activity. Since the onsite inspection team would represent some international body, conclusive evidence must be submitted to substantiate its findings.

All available types of photography and film will be used. Color film will be essential. Movies, still photographs, and infrared can be used to produce different emphasis.

Suitable cameras should be standard equipment for each member of an onsite inspection team, as well as for a professional photographer assigned to the team. The photographic lens often detects significant details not noticed through direct visual observation. Furthermore, photographs will be essential as documentary evidence throughout each phase of an investigation. Photographs, made with 35-mm. and larger film, including black and white, color, and infrared (where appropriate), should be taken of any subject that appears to be anomalous or suspicious. Furthermore, probably with less coverage, routine photographs should be made of any and all facilities, openings, and underground workings inspected.

One of the problems will be to substantiate the actual location of the scene that is photographed. The Hollywood movie technicians have become so famous for trick photography and duplicating settings that any film might be suspect as a fake. Some system should be worked out and agreed upon of coding the film used or having neutral observers verify the inspection.

In many instances, photographs should be taken of a suspected ground area before activity of inspection is permitted to disturb the area. For example, helicopter landings and takeoffs will disturb the surface because of the wind from the rotors.

Suitable copies of the aerial photographs should be provided for use of the ground inspection team. The photographs should be tied to appropriate control points so that a working ground grid may be developed if required. The aerial photographs should be designed and prepared for use with available topographic and geologic maps.

In general, the instrumental measurements useful in aerial surveys might be expected to be even more useful in onsite inspections of local areas. This is true of radioactivity measurements and the use of electromagnetic-, magnetic-, and gravity-surveying techniques and instruments. The order of utility is the same for ground as for aerial surveying. Radioactivity measurements should be more useful than electromagnetic and magnetic measurements, which in turn should be more useful than gravity measurements. In onsite inspections, one additional instrumental method, that of seismic-noise surveys, should have considerable potential value.

The decision to use special instrument survey techniques on the surface will have to be made by the investigating team and be based on the situation found in the area. Magnetic and electromagnetic methods may be of value in locating well casing, electrical or coaxial cable, and other below-surface anomalies. Seismic methods possibly could assist in delineating large cavities or other significant below-surface features. Liquid-level surveying for surface subsidence; noise surveys using Geophones to detect excessive noise generated by rock movement in the formation of cavities; and sampling and chemical analysis of the soil, ground water, and vegetation are other surveying methods which should be used by the investigating team in narrowing down the area in which special mine examination techniques need be applied.

There are many factors that could determine selection of a final area (mine) for intensive, detailed investigation. These factors would develop during the preliminary aerial and surface surveys and could be different for each examination site. They must be weighed and evaluated by the onsite inspection team before a site selection is made. Finally, the area or areas to be inspected for final proof should not be limited by prior agreement, nor should the facilities or activities related to the area, and work beyond the immediate confines of a mine be restricted.

MINE EXAMINATION TECHNIQUES

Mining, in the generally accepted sense, is the process by which minerals are removed from the crust of the earth, and a mine is the opening that is required to provide access and remove the minerals. For this report, any access opening in the crust of the earth that could be used for the purpose of placing a nuclear device for underground detonation is considered to be a mine. By this definition, a mine could include drilled holes or wells into the subsurface of the earth, subsurface excavations made expressly for underground nuclear detonation, conventional active mines, abandoned or inactve conventional mines, tunnels, and natural caverns.

A brief discussion of mining activities and technology is given in the appendix to provide a background for the more detailed presentation of specific techniques that may be applied to locating and identifying clandestine underground nuclear detonations.

The same problems could be encountered in preparing a site and detonating an underground clandestine nuclear blast as in operating a mine. Both involve geology, rock mechanics, rock support, engineering, access and transportation, ventilation, water, waste disposal, accounting, and facilities. In many cases special mining techniques have been developed for evaluating and solving these problems. These techniques are discussed in the following section, with particular emphasis on those factors that could indicate the epicenter of an unusual seismic disturbance, such as that caused by exploding a nuclear device.

These examination techniques would be used following (or concurrent with) preliminary areal surveys of the epicenter region of the detected seismic event. The decision for further investigation implies that the detected seismic event has not been identified and that there are good reasons to suspect clandestine operations. There still exists the possibility, however, that the detected seismic event was caused by a natural earthquake, rock burst, or chemical explosion. The purpose of the examination, therefore, is to determine the cause and locate the source of the unidentified detected seismic event.

The first phase of the special mine-examination technique should be to determine whether or not any known mine or mines in the area are producing, are inactive, are exploration developments, or have no apparent practical value except for underground nuclear testing. Such determinations can be obtained by evaluating the geography, geology, economics, mining technology, support, and personnel associated with the site. The evaluations made after these surveys will determine the type of underground mine investigation that needs to be conducted and the order in which it should be conducted.

Rather than attempt to list all possible conditions that might exist and the decisions that would follow, it appears more feasible to discuss in detail the various types of examination techniques and underground investigations that would be useful. Later these are summarized and evaluated with respect to the general subject of onsite examination.

DRILL HOLES AND WELLS

Drill holes and wells are of particular interest to an onsite inspection team for two reasons. First, it will be important to locate, examine, log, and take samples of gases, liquids, or solids from existing holes. Second, the drilling of exploratory boreholes for logging and sampling will be a significant technique in the final phases of an investigation. Fortunately, drilling, logging, and sampling are such indispensable techniques in mining and petroleum exploration and production that tools and techniques used for these purposes are highly developed.

Drilling, logging, and coring equipment adequate for any conceivable onsite use may be obtained as essentially packaged units. Such equipment is compact and self-powered, and may be transported by land, water, or air to essentially any site, regardless of terrain and geographic location. Rotary units are available capable of drilling holes to depths greater than 5,000 feet with conventional drill pipe and slim holes as deep as 10,000 feet with small-diameter (2⅜-inch) drill pipe. These units may be completely transported on a single truck or trailer with all accessory equipment except drill pipe and even may be transported in sections by helicopter.

If an effort has been made to conduct a clandestine nuclear test, it may be assumed that much attention will have been given to eradicating all traces of, or disguising, existing holes. Evidences of recent drilling might be obliterated; however, it would be difficult to obliterate the evidence of having done so. In drilling a well, some kind of drilling fluid must be used to remove drill cuttings from the hole. Power and other facilities are required. The drilling fluid itself, whether it be gas or liquid, must be supplied. Pieces of cores or drill cuttings, scraps of metal, drilling mud, general disturbance of the earth's surface required to cover up drill cuttings or mud pits, oil stains from equipment, access roads, and many other evidences necessarily are associated with drilling on land. Evidences of drilling from a barge or other platform in water would be much easier to disguise. However, even in such an instance, if other evidence pointed to small local areas for investigation, it would be difficult to eliminate all traces of fairly recent drilling activity.

If decoupling is a part of concealment techniques, a large underground opening will have been required. This means that a great quantity of rock or some mineral substance will have been removed. This might be done either by mining at the bottom of a shaft or large-diameter drill hole, or by solution mining in rock salt. Concealment in a salt formation lying below a water body perhaps would be the easiest form of drilling and hole enlargement to conceal. Even so, concealment would be a problem, as it would be necessary to dispose of vast quantities of brine essentially saturated with sodium chloride. If such brine were discharged at the bottom of a body of water for concealment, the heavy, salt-saturated brine should remain detectable because of differences in its gravity and resistivity as compared with the surrounding water. Therefore, if suspected, such a procedure might be detectable by sampling or logging.

If a nuclear device were detonated in a drill hole without decoupling, it may be assumed that, after the experiment was completed, the surface pipe would be cut off and removed, the hole would be plugged, and the surface would be covered. This procedure should leave evidence of recent earth disturbance, if on land, and would make it more difficult but not impossible to locate the hole. Experience in finding old, abandoned, and uncharted oil wells[43] has shown that a variety of methods may be used. Generally, the procedures used parallel the recommended procedures for detection of clandestine nuclear explosions, involving the following general steps: (1) Collection of all available information, (2) general survey of the property, (3) localizing the probable area in which the well may be found, and (4) detailed search of the localized area (using a variety of tools and techniques) to find the exact location of the well.

[43] Hamontre, H. C., Locating Abandoned Wells: World Oil, vol. 134, No. 4, March 1953, pp. 184–192.

Among the techniques successfully used in combination to search localized areas were: (1) Inductive coupling of electrical signals by using separate transmitters and receivers for locating and tracing buried steel lines; (2) localized inductive coupling (mine detectors) for locating scraps of metal or metal-bearing waste materials, such as cinders from coal-fired boilers; (3) locating buried, magnetized, vertical pipe (well casings) through using compasses and dip needles; (4) detecting air chambers by sonic means within incompletely plugged drill holes; (5) earth probing with steel rods; and (6) stripping surface earth in suspect local areas with bulldozers. In many instances, no one technique was successful in itself. However, the combination of tools and techniques with logical reasoning as to the importance of many bits of evidence resulted in a surprisingly high success ratio when used on many oil leases in the midcontinent area (57 percent exactly located; an additional 30 percent approximately located, then exactly located by stripping surface earth with a bulldozer).

DRILLING

It is probable that drilling exploratory holes will be a final integral part of an onsite investigation. The size of the holes required will depend on the information necessary, the depth will be governed by the expected depth of burial, and the grid spacing on which holes should be drilled will depend on the probable yield of the explosion and the consequent radial distribution of detectable radioactivity, fractures, or thermal zones.

The diameter of exploratory drill holes need only be adequate to permit making the desired instrumental measurements in the holes and to obtain such samples of fluids or rocks as may be required. No hard-and-fast rules may be established for this, as it is possible that hole diameters will differ, dependent on the information required. However, it is probable that a nominal 8-inch-diameter hole will be the maximum that might be needed. Holes of much smaller diameter (up to 4 inches, for example) that might be drilled with a portable shot- or diamond-drill rig probably would suffice for most purposes.

Inasmuch as radioactivity from fission products is accepted as final conclusive proof of a subsurface nuclear detonation, this should be the governing factor in determining the spacing on which holes need to be drilled. Some radioactivity from a coupled 1.7-kt. device under the Rainier test conditions might be distributed to a maximum radial distance of 280 feet from ground zero. For a 20-kt. device, under similar conditions, the maximum radial distance might be as great as 630 feet. If these values are approximate for the subsurface detonation of a nuclear device in other rock types, the drilling of exploratory boreholes on spacing somewhat smaller than 10 acres (660 feet between wells) might be expected to yield information concerning the detonation of 1.7-kt. shot, while wells drilled on a spacing somewhat smaller than 40 acres (1,320 feet between wells) might be expected to yield similar results for a 20-kt. shot. It is possible that the zone of fractured rock within which some radioactive fission products might be deposited as decay products of vented gases will have a somewhat greater radius for other rock types and that less of the radioactivity will be trapped in a fused substance. It is probable that the yield of a device determined by seismic measurements will be at least 20 kt. and perhaps greater, especially if the device is decoupled. Therefore, the number of holes required to search for anomalous radioactivity or other anomalies indicative of a subsurface nuclear explosion will not be so great as to be impractical with respect to time and cost.

The time element itself, if drilling equipment is selected judiciously, should not prove to be prohibitive under any reasonable international agreement. Portable rotary rigs, using compressed air as a drilling fluid, have been reported [44] to be capable of drilling a 6¼-inch hole to depths of 400 feet in an average time of 24 hours per hole. This time includes moving in, rigging up, spudding in, setting surface pipe, drilling, chip sampling, shooting, cleaning out, and moving to the next location. With a portable pulling unit the same company set and cemented pipe in the wells in an average additional time of 6 hours. An average of 100 feet per 24 hours would be expected for exploratory diamond core drilling.

Sampling of existing and exploratory drill holes or wells will be a desirable inspection technique. The methods of sampling used, however, may vary considerably and will depend upon circumstances and the information desired.

It may be desirable to obtain samples of fluids from existing holes by the use of a bottom-hole sampler, thief, or bailer-type device. Gas samples also may be desired and, if so, may be obtained by the use of a bottom-hole sampler or a suction device for drawing gas from the wellhead. If rock samples are required, a sidewall coring barrel or chip-coring device may be used.

Obviously, it will be desirable to take samples from exploratory drill holes. Much geologic information may be obtained through the macroscopic and microscopic examination of drill cuttings. It is possible that at least part of each drill hole should be cored. Dependent upon circumstances, it may be desirable to core all of some drill holes. When fluids are encountered in drilling operations, it probably will be helpful to obtain samples of them for analysis to determine radioactivity, mineral constituents, and other properties. Coring tools and other sampling devices should be available to any onsite inspection team. Facilities for determining radioactive, physical, and chemical properties of rocks and fluids should be provided. Preferably, such analytical equipment should be designed for field use.

In addition to radioactivity logging, other types of logs might be made to determine geologic and physical properties of borehole walls and the surrounding rock medium.

Electric logs, through the determination of spontaneous potentials and resistivities, yield information on lithology and the nature of fluids in the rock pores surrounding uncased holes.

Sonic logs may be used to determine hole diameters, especially in caverns or enlarged holes. Mechanical calipers [45] may be used to measure the diameters of drill holes.

Density logs, through determination of the absorption of gamma radiation from a source in the logging probe, may reveal changes in density of rock medium caused by fracturing due to an explosion.

Thermal profiles, obtained by the use of appropriate logging devices, will detect anomalous temperature gradients such as might be caused by the distribution of heat from a nuclear explosion.

Photographic logs, using a borehole camera,[46] may reveal the presence and nature of fractures intersected by drill holes.

In addition to the types of logs mentioned, numerous modifications of them and several other logging methods now are in routine use. Hamilton [47] describes about 40 logging techniques used in the petroleum industry for determining more than 30 properties of productive formations.

The judicious selection of logging tools and methods must play a large part in planning for an onsite inspection.

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[44] Brundred, L. L., Rotary Drilling With Air in Shallow Waterflood Development: API Drilling and Production Practices, 1956, pp. 448–449.

[45] Hamontre, H. C., Armstrong, F. E., and Mueller, F. G., Bureau of Mines Well-Bore Caliper: Bureau of Mines Rept. of Investigation 5092, 1954. 18 pp.

[46] Dempsey, J. C., and Hickey, J. R., Use of a Bore-Hole Camera for Visual Inspection of Hydraulically Induced Fractures: Producers Monthly, vol. 22, No. 6, April 1958, pp. 18–21.

[47] Hamilton, R. G., The Revolution in Well Logging: Oil & Gas Jour., vol. 58, No. 26, June 27, 1960, pp. 187–188.

ROCK MECHANICS

Although the science of rock mechanics is relatively young and still in the development stage, the known data offer excellent opportunities for locating and identifying underground nuclear detonations. Knowledge of rock mechanics has already been applied to determine parameters for underground explosions, and many of the scaling laws used in conducting an underground nuclear test are based on these parameters. Application of these principles in reverse to determine the site of a nuclear detonation is, therefore, logical and a paramount inspection technique.

Analysis of the results from the six underground nuclear detonations in tuff (table 3) has shown that scaled equations of the form $R=kw^{1/3}$ can be used to predict the distance from the source where certain phenomena occur. Thus, for example, the ultimate size of the cavity is given by

$$R=50W^{1/3}$$

where

R is a radial distance from source in feet.
W is size of detonation in kilotons of TNT equivalent.

TABLE 4.—*Scale distance for various phenomena associated with underground nuclear detonations in tuff* [1]

Radius of cavity and major radioactivity.	$R_r=50W^{1/3}$
Radius of crushing	$R_c=110W^{1/3}$
Radius of cracking or start of elastic propagation.	$R_e=230W^{1/3}$
Radius for 3° C. temperature rise	$R_t=125W^{1/3}$
Depth of burial for containment of radioactivity.	$D_c=400W^{1/3}$
Depth of burial for no visible surface evidence.	$D_v=1{,}000W^{1/3}$
Distance for total tunnel collapse	$D_t=330W^{1/3}$
Distance for no tunnel damage	$D_n=700W^{1/3}$

[1] Derived from U.S. Congress, Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban: Appendixes to Hearings Before Special Subcommittee on Radiation and Subcommittee on Research and Development of Joint Committee on Atomic Energy: 86th Cong., 2d sess., 1960, pt. 1, pp. 222–280.

A list of useful scaled distances is given in table 4. These values apply only to bedded tuffs. Different rock types should have different constants. How these constants vary with rock type is not known; however, one would not expect changes of order of magnitude.

From the seismic data that detect the suspicious event, the epicenter of the event will be located within an area of radius of approximately 13 kilometers. Also, the size of the event will be estimated from the amplitude of the recorded waves. From the size of the event the data given in tables 3 and 4 can be used to estimate the target size and depth. If damage to underground openings is found during onsite inspection, the average scaled distance for tunnel collapse and for no tunnel damage will be useful in determining the source of the explosion.

The seismic waves generated by the detonations at the Nevada test site have been measured over wide ranges of distances, both in the medium and on the surface. A review of the literature shows that there is a large quantity of acceleration and velocity data obtained from surface measurements.[48]

The acceleration data have been scaled and plotted on log-log coordinates and found to fall on approximately a straight line between scaled distances of 8×10^2 to 5×10^4 ft./(kt.)/$^{1/3}$. All three components of acceleration have been used, and very little difference between the various components exists. The equation for these data determined by the method of least squares is:

$$A\,W^{1/3}=1.25\times10^3\left[\frac{D}{W^{1/3}}\right]^{-2.54}$$

where

A=acceleration in units of gravity,
D=slant distance in feet, and
W=charge size in kilotons.

The spread of the data about this equation has a standard deviation of approximately 300 percent. Thus, from these data the acceleration can be estimated within only a factor of ±3 fold.

The velocity data have been handled in the same manner as the acceleration data. The equation for the particle velocity is:

$$V=2.03\times10^7\left[\frac{D}{W^{1/3}}\right]^{-2.04}$$

where

V=particle velocity in inches per second,
D=slant distance in feet, and
W=charge size in kilotons.

The standard deviation of the data about this equation is approximately ±50 percent, and the data cover a scaled distance range from 8×10^2 to 5×10^4 ft./(kt.)$^{1/3}$.

The two equations should be useful for estimating the source of an event that has produced damage to surface structures. Structural damage can be expected for particle velocity in excess of 2 in./sec. or particle acceleration in excess of 0.1 g. (the acceleration of gravity).

[48] Swift, L. M., Sachs, D. C., Bremer, J. L., and Wells, W. M., Surface Motion From an Underground Detonation: Interim Test Rept. 1528, Project 26.4a, 1959, 59 pp.
Perret, W. R., Subsurface Motion From a Confined Underground Detonation—Pt. 2: Interim Test Rept. 1529, Project 26.4b, October 1957, 65 pp.
Adams, W. M., Flanders, P. L., Perret, W. L., Preston, R. G., and Sachs, D. C., Summary Report of Strong Motion Measurements, Underground Nuclear Detonations: Interim Test Rept. 1711, Project 26.0, April–October 1958, 80 pp.

Rock, in general, is a poor conductor of heat. Therefore, the heat liberated by the detonation of an underground nuclear device is confined mainly to the cavity and surrounding rock unless breakthrough to the surface or tunnels occurs. Under complete confinement of the explosion, this heat remains in the vicinity of the source for long periods of time. The scaled distance for a sharp rise in temperature as the source is approached is only about 80 ft./(kt.)$^{1/3}$ even after several months following detonation.

Even though this heat source is relatively small in volume, it should have an effect on the static stress distribution existing around the cavity. As this heat slowly conducts out through the rock there should be produced a steady readjustment of stresses in the rock. Such readjustment of stress might well be detected by means of the microseismic method of detecting rock instability. The possibilities of this method for use by an inspection team should be investigated immediately by comparing the microseismic noise levels around the six Nevada test sites with other locations in the same tunnels. Even at the writing of this report these tests could be conducted, as elevated temperatures still exist in the vicinity of these shots.

In the course of conducting onsite and underground mine investigations there will arise most likely a number of questions which can be answered only if the stresses in the mine structures and the strength of the rocks in the structures can be estimated or measured. The type of rock, its physical and geological characteristics, and the stress field before mining, determine, in general, the size and shape of underground openings that can be used and the amount of artificial support that must be installed.

For this discussion, rocks will be divided into two main divisions: (1) Competent rock, and (2) incompetent rock. Competent rock is defined as rock which, because of its physical and geological characteristics, is capable of sustaining openings without any structural support except pillars and walls left during mining (stulls, light props, and roof bolts are not considered structural support). Incompetent rock is defined as rock which, because of its physical and geological characteristics, is not capable of sustaining openings without the use of artificial support, such as steel sets, square sets, and so forth. From these definitions it seems most unlikely that any clandestine tests would be conducted in incompetent rock. Only small openings could be employed in incompetent rock and after detonation of a nuclear device the possibility of cavity failure, collapse, and caving to surface is very great. Thus, the escape of some radioactivity to the surface or to other underground openings is highly probable.

For this report, only competent rock will be considered. Also, competent rock will be further subdivided into three classes: (1) Massive-elastic; (2) bedded-elastic; and (3) massive-plastic. Massive-elastic rock is considered to be elastically perfect, isotropic, and homogeneous, and to possess a strength that does not vary appreciably from point to point. Typical examples are massive-igneous rocks such as granite, diorite, basalt, and rhyolite; some massive metamorphic rocks such as marble and quartzite; and some sedimentary rocks. For sedimentary rocks to be included in this class, either the bed thickness must be large compared with the roof span or the bonds between thinly bedded rocks must not be planes of weakness.

To be classed as bedded-elastic, the rock within each bed, in addition to being elastically perfect, isotropic, and homogeneous, must have a bed thickness that is small compared with the roof span, and the bond between beds must be weak. Most sedimentary rocks and some stratified metamorphic rocks fall in this group.

Massive plastic rocks are those that flow slowly under relatively small applied static stresses. Most salt deposits and other massive soft rocks can be placed in this class.

Identification of the rock and its classification as to massive-elastic, bedded-elastic, or massive-plastic can be made by examining rock exposures in underground mines and performing physical property tests on samples of the rock.

All underground rock is in a state of stress as a result of the weight of the overlying rock and possible tectonic forces. Any underground opening produces additional stresses in the rock surrounding the opening. The stresses in rock produced as a result of the weight of the overlying rock only can be estimated from the following:

$$S_v = pgZ,$$

$$S_h = \left[\frac{\nu}{1-\nu}\right] S_v$$

where

S_v = vertical stress,
S_h = horizontal stress,
pg = weight density,
ν = Poisson's ratio, and
Z = depth below surface.

Theoretically, tectonic stresses cannot be estimated accurately. Their magnitude can be determined only by measurement using techniques of strain relief.

Given the state of stress before mining, methods for estimating the stress distribution around mine openings in massive-elastic and bedded-elastic rocks have been described in detail.[49] Methods for determining the physical properties of rock for use with the above design methods have also been reported.[50]

Methods for determining the physical properties of plastic rocks and the principles to use in estimating the structural stability of mine openings in massive plastic rocks have been reported recently.[51]

The information contained in the above three reports is useful for estimating the stresses around mine openings and determining their structural stability, provided the state of stress before mining is known accurately. More recently there have been developed methods for determining the absolute state of stress in rock by means of strain-relief measurements.[52] [53]

The microseismic method can be used for determining the order of magnitude of stresses in mine rocks, and for locating zones of high stress concentration and rock instability. This method is based upon the fact that rocks under stress generate small seismic noises which can be detected by means of sensitive high-frequency Geophones. The amount of noise generated and its intensity increase as the rock stress approaches the ultimate strength of the rock and, also, during periods of readjustment of stress.[54]

Of all the techniques used in the field of rock mechanics, the microseismic method and strain-relief method appear to offer the best solutions to the problem of determining the cause and locating the source of an unidentified detected seismic event. The microseismic method should be useful in locating the source, provided there are underground openings within a few thousand feet of the zero point. The microseismic method also should be useful for determining the cause as a rock burst or for eliminating a given mine as a possible location for the source. The strain-relief method should be useful in determining that the cause was a rock burst.

The detonation of a nuclear device in an underground opening can be expected to create a cavity that has a radius of $50(W)^{1/3}$ feet; to crush rock for a distance of $100(W)^{1/3}$ feet; and produce scabbing, spalling, and fractures in tunnels to a distance of $700(W)^{1/3}$ feet. Also, temperatures in excess of 100° C. can be expected to exist in the cavity after detonation.

Except under the most ideal situations, the cavity cannot be stable; thus, collapse of the opening and some caving should follow. This caving would be expected to occur for days or weeks depending on the nature of the rock overlying the cavity. Also, the high temperatures existing in the cavity would produce a steadily changing local stress distribution. Consideration of the preceding disturbances, taking place in the rock surrounding a nuclear detonation, leads to the conclusion that there should be a relatively high microseismic noise level in the rock following detonation. If such is the case, then the microseismic method should be able to locate the source.

If the noise generated in the rock surrounding the cavity can be picked up in solid rock with sensitive Geophones for distances of 500 to 2,000 feet, then the method has practical value. By using several Geophones at known distances apart and recording the differences in arrival time, the origin of the recorded noises can be determined. From a large number of such measurements, the source of the rock noises can be located, which should be helpful in delineating a relatively small area into which to drill to obtain radioactive material.

The microseismic method would also be useful in ascertaining if observed damage to underground structures could have been caused by a rock burst. If rock burst conditions exist in a mine, then the average stress on the rock is approaching the ultimate strength of the rock, and rock bursts occur when the maximum stress exceeds the ultimate strength. In general, the noise level of the rock in a mine subject to rock burst is very high at all times and in most areas of the mine. Also, areas of high stress concentration show large increases in noise level. Thus, by making a general microseismic noise level survey of a mine, one can usually determine whether or not rock burst conditions are imminent.

A more quantitative determination can be made of the probability of rock burst by the strain-relief method and physical-property testing. If strain-relief measurements show that the absolute stress in the rock is nearly equal to the ultimate strength of the rock, and laboratory compressive strength tests have indicated no tendency toward plastic yielding at rupture, then rock burst conditions are indicated.

The decoupling theory states that the amount of low-frequency seismic energy received at a distant seismographic station is much less for

[49] Obert, Leonard, Duvall, Wilbur I., and Merrill, Robert H., Design of Underground Openings in Competent Rock: Bureau of Mines Bull. 587, 1960, 36 pp.

[50] Obert, Leonard, Windes, S. L., and Duvall, Wilbur I., Standardized Tests for Determining the Physical Properties of Mine Rock: Bureau of Mines Rept. of Investigations 3891, 1946, 67 pp.

[51] Serata, Shosei, and Gloyma, E. F., Principles of Structural Stability of Underground Salt Cavities: Jour. of Geophysical Res., vol. 65. No. 9, September 1960, pp. 2979–2987.

[52] Merrill, Robert H., Static Stress Determinations in Salt—Site Cowboy: Bureau of Mines Report APRL 38–3.1, July 29, 1960, 13 pp.

Merrill, Robert H., and Hooker, Verne E., Static Stress Determinations and Crushed Zone Measurements—Site Hobo: Bureau of Mines Report APRL E38–7.1, July 1960, 15 pp.

[53] Hast, Nils, The Measurement of Rock Pressures in Mines: Sveriges Geologiska Undersohning Ser C., No. 560, Stockholm, 1958, 183 pp.

[54] Obert, Leonard, and Duvall, Wilbur I., Microseismic Method of Determining the Stability of Underground Openings: Bureau of Mines Bull. 573, 1957, 18 pp.

a nuclear explosion detonated in a large cavity than for one detonated in a small cavity. The decoupling increases with cavity size until the cavity size becomes large enough to reduce the pressure in the cavity below the elastic limit of the rock. Any further increase in cavity size does not result in further decoupling.

The radius of a cavity necessary to achieve appreciable decoupling (300 in salt or 50 in tuff) is $170(W)^{1/3}$ feet, and to achieve small decoupling (30 in salt or 5 in tuff) is $55(W)^{1/3}$ feet.[55]

Thus, even for small decoupling fairly large cavities are required for detonations exceeding 1 kt. There are very few rock types that can support openings 200 feet in diameter or more. Only those rocks that are massive in structure and that are devoid of structural defects will support openings of this size. As jointing and faulting usually result in structural defects, large cavities in badly faulted and jointed rock types would not be possible. Plastic rocks such as salt would be most suitable for the construction of large cavities.

GEOLOGY

Surface and subsurface geologic conditions are important factors to be considered when attempting any extensive underground excavations. This holds true whether the purpose be mining, oil production, tunnel driving, or underground nuclear testing. Geologic conditions will govern the choice of the site, influence the design and plans for an underground excavation, affect the method of excavation, and determine the rate of production or effects of a test shot. Usually the geologic factors have a direct and logical relationship to the individual underground excavation that should be apparent upon inspection. The consideration of salt beds for underground nuclear testing is a case in point.

The existence of a conventional mine depends on geologic factors. The combination of topographic and geologic conditions largely determines the location and method of access into a mine. Because geology is such an important factor in relation to an underground excavation, much attention is given to the geology of a mine, which is usually well documented.

Geologic conditions influence the seismic signal generating from an underground explosion. The amplitude and frequency of the waves depend on the combination of yield of the explosion, size and shape of the shot chamber, depth of burial, physical properties of the surrounding medium, and local and distant geologic conditions. Analysis of a seismogram would not necessarily reveal these factors, but a knowledge of local geology and general geologic conditions of the path of the transmitted wave may lend itself to interpretations helpful for orientation of the onsite inspection of mines. Compatibility of the seismic signal with known local geology may be determinable, and compatibility of the local geology as a possible seismic or aseismic area may be evident. Geologic knowledge will be important in assessing the probable maximum size of unsupported underground opening that can be mined and approximate locations of such areas.

As soon as a seismic disturbance has been recorded and located, it is necessary to study the earthquake history and the geology of the location to evaluate whether or not the disturbance could have been an earthquake. If the disturbance were located in an earthquake belt and in an area that was known to be earthquake prone, such as in the vicinity of the San Andreas fault in California, the disturbance undoubtedly would be classed as an earthquake. There would have to be very definite differences in the seismic record to classify the disturbance as something other than an earthquake.

Comparison of compatibility of the geology and underground excavations at the Nevada test site would show little logical reason for a mineral production operation. There are a number of possibilities for evaluating geologic compatibility with a mine and its probable use for underground nuclear testing. One interesting aspect is the relationship of mines and earthquakes.

California, in the most active earthquake area of the United States, has many gold and mercury mines, yet there are virtually no records of earthquake damage to these mines. The mercury mines are associated with faults and structures that are related to the San Andreas fault.

Mineral deposits, especially in igneous rocks, are related to faulting and fracturing. There are many vein deposits that occupy old faults and fissures. Many of these deposits show postmineral faulting along the veins as well as offsetting of the deposits. Apparently these ore deposits are of sufficient age to have reached a state of equilibrium.

Although earthquake-magnitude movements are rare around mines, this does not mean that the rocks are stress free. Rock bursts that occur in many mines indicate the tremendous residual stresses that are still present in rocks that are apparently in equilibrium. As soon as

[55] U.S. Congress, Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban: Appendixes to Hearings Before Special Subcommittee on Radiation and Subcommittee on Res. and Development of Joint Committee on Atomic Energy: 86th Cong., 2d sess., pt. 1, 1960, p. 131.

a mine opening introduces changes in the stress conditions, the rocks under stress try to relieve this residual stress.

Most countries have some agency that reports on the geology of the country. Some countries hire outside groups to perform at least reconnaissance surveys for minerals and oil. Results of the work are usually published. Private companies obtain concessions to explore and prospect for oil and/or minerals in many countries. Although reports on these activities would be confidential with the companies, Government usage should be permitted.

Good aerial photographs provide much information on the geology of an area. Most countries have been photographed on a systematic basis.

Technical schools in many countries teach geology and mining engineering. Students and professors do detailed studies on local areas for thesis requirements. These are available and on file at the schools.

Often there is more than a single government agency that acquires geologic and geographic data on a country; for example, in the United States the Federal Geological Survey, Bureau of Mines, Department of Agriculture, Forest Service, Bureau of Land Management, Department of Defense, and many others perform these services. Many secondary governments, such as States, also carry on geological studies. All of these could be sources for compiling detailed information on the geology of a country.

In the field, the geology and its influence on any activity in the area is determined by detailed study and mapping of the rocks. The source, formation, composition, and structural history of rocks have a direct bearing on the characteristics, competency, mineralization, and surface form of rock structures. Interpretation of existing surface rocks and land forms permits a good idea of what can be expected below the earth's surface.

Most of the branches of geological science concerned with both surface and subsurface phenomena are important facets of mining, mine examination, and the present problem of underground nuclear detonation. Implications of geology and gelogical science to underground nuclear testing are given in detail in the hearings.[56] A vast library of their relationship to mining has been published since the earliest printed reference in Agricola's "De Re Metallica," published in 1556.

Geophysical science and techniques are basic to both the detection of underground nuclear detonations and exploration for mineral deposits. The former aspect has been extensively investigated by various research groups connected with the program. The onsite investigators should obtain any information on geophysical mineral exploration in the area, to evaluate both the possible effectiveness of geophysical techniques for detection purposes and the possible implications of the geophysical data in regard to location of a probable test site.

Mineralogic and petrographic characteristics of rocks are frequently used in geologic, mining, and processing studies of a mineral deposit. These characteristics could influence also the choice of a site for an underground nuclear detonation. They could be used as a tool in several of the mine-examination techniques applied to detection, such as dust analysis, waste disposal, and mine water investigations. The nuclear detonation may introduce physical and chemical changes in rock characteristics that would be a clue to the detonation site. Wilmarth[57] describes some of these effects. Stratigraphic, lithologic, and structural geologic features have important relationships to mining, selection of test sites, and probable effects resulting from an underground explosive detonation. Geologic requirements for nuclear testing would generally favor horizontal rather than vertical strata; thick rather than thin strata; rock constitution that would favor confinement of radioactivity; and structurally intact and competent formations rather than badly folded, faulted, and jointed structure.

Source material for these data is generally available, particularly for active mining regions. Detailed geology of individual mines and mining districts is published in technical journals and government and university reports. The mines have maps, drawings, reports, models, and frequently rock samples and cores from exploratory drilling.

WATER

A clandestine underground nuclear detonation can be influenced by water in two ways—first, through the potential capability of water to produce evidence of the detonation or its products, and second, because of this potential trying to obtain an underground test site that will not be affected by water. This was a contributing factor in selecting the underground test sites in Nevada. Precipitation falling into the cloud of nuclear contamination arising from a surface detonation will pick up radioactivity and contaminate the ground surface.

[56] Work cited in footnote 55, pt. 1, pp. 1–478; pt. 2, pp. 479–951.

[57] Wilmarth, V. R., Some Effects of Underground Nuclear Explosions in Tuff: Geol. Survey, TEI–756, December 1959, 34 pp.

Ground water can do the same for an underground nuclear detonation.

If an underground detonation were completely confined (fracture area and caving above site) in a single geologic formation, the ground water present in the formation could absorb radioactivity (after the temperature was reduced below boiling). This radioactivity in the water would be detectable if the water were to reach the surface or be a source of supply for a well. The time of emergence of the radioactive water would be a function of the permeabality and depth of the formation. Some formations are virtually impermeable and the radioactive water would not circulate. Geologic formations can contain considerable water in the interstices between mineral grains, but the water cannot flow unless the interstices are interconected to permit circulation under the influence of a hydraulic gradient. Some limestones are permeable not only because of interconnected interstices but because of the highly jointed character of the beds in the formation. Some formations are so permeable that large pumps cannot draw down appreciably the water level in a well.

An onsite inspection team should make a careful study of the geologic formations in a suspect area and determine their relationship to the hydrologic cycle. The geologic structure of a catchment area is always important and must be considered in estimating surface water. Surface water originates not only from the runoff but from the reemergence of free ground water as well.

It would be advisable to make immediate radiological surveys of any water source—well, spring, stream, or river—that might be supplied by ground water emerging from suspect areas. These surveys should then be made at periodic intervals, as long as the possibility exists that they may furnish evidence. In making these surveys consideration must be given to the possibility of natural occurrence of radioactive minerals in the area.

If the detonation site were wet, or even damp, the device would have to be waterproofed along with the other elements of instrumentation and wiring. The waterproofing material would be vaporized in the detonation. These vaporized products could be precipiated by water and be soluble. All water samples should be tested for all foreign products and gases.

The seismic shock caused by an underground nuclear detonation will be rather severe close to the detonation site. An empirical scaling of $A=0.6W^{0.8}/D^2$ has been given,[58] where A is in units of gravity, W is in kilotons of yield, and D is in kilometers. The shock will disturb the underground water and springs. This phenomenon was observed and recorded after the recent Chilean earthquake. Within a day or two after the Japanese earthquake, the large mineral hot spring at Thermopolis, Wyo., became very turbid and laden with gray silt.[59] This condition continued for 3 weeks as the water gradually returned to normal.

The detonation shock also should compact unconsolidated sediments in local streams and rivers, which could cause roiling of streams, springs, and wells. It also should produce an increase in the flow of surface water. In the winter this could cause overflowing on ice covering the normal flow of water. The shock could crack and break up ice covering a river or lake. If a frozen lake were used as a cover for a drill hole test site, the ice could fracture in a radial and concentric pattern.

The seismic shock also could produce changes in the elevations of water in wells. Records of the Arvin-Tehachapi earthquake in Kern County, Calif., showed stream and well fluctuations. A well 20 miles from the epicenter recorded a fluctuation of 7.34 feet. Another well 180 miles away showed a fluctation of 0.12 foot. Unless permanent fluctuation recorders are installed in wells, this record would not be available. Some temporary changes in well levels occurred that could be related to the compressional effect of the shock on both confined and unconfined aquifers. Also, it is possible that the shock could be severe enough to disrupt the water table through fracturing or compaction.

Often the mineral content of water samples from springs will provide clues to the nature of sediments through which the water has moved. This may be useful in correlating geologic formations and depth of the aquifer supplying a spring and might be matched with expected depth of the detonation for potential evidence of radioactivity or sediments.

Virtually all deep mining operations and most shallow mines have a water problem from flow of water into the workings. Sedimentary rocks such as sandstones and limestones are known to be good aquifers and to support large reservoirs of circulating ground water. In many mining districts, located in igneous as well as in sedimentary rock areas, it has been necessary to drive tunnels or to install pumping facilities to provide drainage (fig. 6). Sealing off waterflow into mined openings and drill holes is often necessary.

Surface runoff from heavy rainfall or spring flooding can overflow normal water barriers and flow directly into mines that have open-

[58] Diment, W. H., Stewart, S. W., and Roller, J. C., Maximum Ground Accelerations Caused by Nuclear Explosions at Distances of 5 to 300 Kilometers: Geol. Survey Prof. Paper 400(b), paper No. 70, 1960, pp. B 160–161.

[59] Personal observation.

FIGURE 6.—Waterflow Into Mine Drainage Tunnel.

ings in an outcrop that is crossed by a natural drainage system. It is customary to leave barrier pillars between the upper workings and the surface where there is a possibility of flooding. In time these barrier pillars become cracked and broken, permitting an increasing water drainage from the surface into the mine workings. Coal mines have a history of many floodings.

Veins of ore are often leached and altered so that they are more easily eroded and form depressions that are natural water traps. If the vein were porous or fractured, water could work down through the vein into lower mine workings.

In shallow mine workings, free ground water may be as much of a problem as surface water. Deeper mines encounter confined ground water that may be under high pressure.

Mine openings are usually driven on a slight upgrade to provide a natural gradient for drainage of mine water. However, some coal mines are driven down the dip of the beds and are an exception to the natural drainage gradient. Constructing and maintaining drainage ditches, pumping, and disposal of mine water can become a significant expense in mining operations.

Most mines also introduce water into the mine for wet machine drilling and for spraying to reduce dust. In many metal mines, mill tailings are remixed with water and run into stopes and other openings to support the walls after the ore has been removed. Proper mixing of tailings (as to clay content and particle size) with the water will permit the water to filter out and leave the filter-compacted tailings in the opening. The tailings backfill program can be quite large at some mines and contribute appreciably to the water problem.

The first confining layer that is the lower boundary for free ground water is seldom very far below the surface of the ground. Free ground water (or surface water) is seldom a real problem for most mines unless they have shallow workings that have been opened either directly or through fractures to the free ground water horizon. However, the free ground water area may be cut by faults and fractures that permit the water to flow into shallow workings and down into deeper workings.

Surface and free ground water probably are not serious problems for consideration in the preparation of a clandestine underground nuclear detonation site. If a shaft or drill hole were being put down to depths needed for a detonation site, the surface or free ground water could be blocked or dammed off by cementing or casing. Mine shafts in wet formations are usually lined with cement to eliminate waterflow. Unless unusual geologic conditions of faulting, folding, or uplift and dissection were present, it is doubtful that surface or free ground water would reach the depths needed for a detonation site.

If the drill water supply is piped from a surface source it will introduce surface water into the underground areas. Any underground mine water sampling for mineral content, radioactivity, or other contaminants must consider the origin of the drilling water, because it could be the source of some foreign materials.

Water confined in capillary openings in buried sediments is under hydrostatic head. When these sediments are cut by a mine opening, the water will flow to this opening. Water will continue to flow as long as the sediments remain permeable and are under a hydrostatic gradient.

Exploration drill holes often encounter heavy waterflow. Cement and heavy drilling mud are used to seal off water-bearing formations and openings. Casing is used when these fail to cut off the flow of water.

Sinking mine shafts in water-laden sediments can present many problems. Deep shafts, sunk to develop the potash deposits east of Regina, Canada, have encountered large waterflows in the alluvium and in the sediments. Freezing, cementation, and shaft lining are used to control or stop the waterflow.

Limestones are soluble, particularly with slightly acid water that is often associated with mineral deposits. Water-filled cavities and channels in limestones can pour tremendous volumes of water into mine workings when they are tapped by blasting. Some limestone formations may be competent and solid enough to support mine openings sufficiently large for small-yield, decoupled detonations. However, the problem of ground water could be quite serious in opening a large detonation chamber in many limestones. Many sandstone formations are highly permeable and contain huge volumes of confined ground water under hydrostatic head. Mines developed along vein ore deposits in igneous rocks usually encounter considerable ground water. Veins often have open watercourses that produce large inflows of water. Some of these flows are temporary and are reduced appreciably in a few days. Other openings seem to have no bottom and flow on uninterrupted for years.

Virtually any mine opening driven out from existing mine workings into barren ground for some distance to provide a detonation site will encounter ground water. If the mine is in hard rock that requires blasting, the shock of blasting would fracture the rock surrounding the opening. This fracturing may extend for several feet out in all directions. Any attempt to seal off water draining from an opening would have to extend the seal beyond the fracturing pattern. Inherent pressures in the rock may be such that they will cause further fracturing to occur as the blast-fractured rock is removed. Thus, it may be difficult to seal off permanently water draining out of a mine opening. An opening could be sealed adequately to keep mine water backed up until the hydrostatic pressure forced the water out of the fractures around the seal. It may take some time for the mine water to build up enough pressure to start leaking out around a seal, perhaps longer than an onsite inspection.

A water seal placed to contain and hide drainage of water from an underground detonation site would have to be hidden from inspection. The seal probably would be hidden by blasting down the mine opening some distance out from the seal. Instrumentation for the detonation and recordings would have to be removed (after the detonation) through the seal and past the proposed caved area. Then the water seal would be completed, and the opening would be caved by blasting. A large muck pile will retain gases from the blasting agent for several days. If a caved opening were suspect as a hidden access to a detonation site, gas samples could be taken to determine if the caving was natural or the opening had been blasted to cave it.

During an onsite inspection of a mine, any out-of-the-way mine opening that appears to have inadequate drainage of mine water compared to the rest of the mine should be treated with suspicion.

Mine drainage is dirty and often full of sludge from drilling holes for blasting. Drainage ditches are usually stained by the mine water. The sludge is composed of fine rock cuttings, and careful sampling and analysis should reveal the nature of the rocks that were penetrated. Geologic maps of the known workings will check out the rocks that have been penetrated in mining. Comparison of these findings may show sludges from strange rocks. Surface geology could be used to determine where the strange rocks could be found in the area. This is very similar to the study and logging of oil-well drill hole cuttings to identify the formations penetrated by the drill hole.

There is the possibility that a mine opening could be hidden behind timber and lagging placed in the regular mine opening where the hidden opening branched off toward the detonation site. During the driving of the hidden opening to the detonation site, mine water would be drained out into the regular opening and drainage system. Careful sampling of the sludges and water in the ditch along the regular mine opening might reveal a distinct change in drill cuttings at some place in the heavily timbered section. Even if special precautions had been taken to wash away all traces of sludge, the lack of dirt and sludge in the mine water drainage would be suspicious.

In the mines that have even a small amount of mine water drainage, the humidity is high. This causes dampness in the walls of the openings. Dust from passing cars of rock and from the ventilation system tends to collect on the damp walls. Samples of the dust accumulated on the walls could show up strange rock dust. This would follow the ventilation and transportation pattern and could be traced.

In vein deposits in igneous rocks, water flowing from the vein is often almost completely devoid of oxygen because the original oxygen content has been used up in oxidizing minerals in the vein. When the vein water encounters air in the mine workings, it absorbs oxygen. As a result the mine air quickly develops an oxygen deficiency. Active mine workings usually have adequate ventilation to replace and maintain oxygen losses. Air in old workings or sealed-off workings could be depleted of oxygen quite rapidly. If a detonation site were sealed off in a long out-of-the-way mine opening, all of the water would not be sealed out since some water would normally be in front of the seal. If the entire working is hidden by timbering at the branch point from the regular mine workings, then some water may be leaking out at this hidden timbered junction. Extra water inflow can be hidden with the regular mine flow rather easily unless volume measurements should be taken. However, an oxygen-content survey of the drainage water might show differences above and below the hidden opening. This could be vein water entering the regular mine working or it could be oxygen-deficient water from a closed-off working. The deficiency might not show up quickly because the hidden area would not have been out of service very long, although some workings lose oxygen in a few days.

Most mine water will assume the rock temperature. Some mine water is very warm, particularly if it is around sulfide ores that are being oxidized. If ground water were to flow through or near a nuclear detonation site, the water might be heated. Should heated water reach the regular mine workings, it could be differentiated by temperature sampling of the water.

Interpretation of radioactivity surveys of mine water, air, or dust must be carefully considered. Broken rock tends to produce or liberate trapped radon gas. Also, many mines contain radioactive minerals in small quantities.

Mines that have been shut down or abandoned often fill up with water. They will remain open and uncaved longer when filled with water than when open to air slacking of rock and the usual rapid decay of timber in moist air. Old abandoned mines filled with water could be potential detonation sites. However, pumping water out of a mine deep enough for nuclear detonations would require a large pumping installation. Most mines tend to produce iron oxide in the mine water, and this will stain the sides of openings and water drainage areas. Many streams that have received mine water discharge for years have stained boulders, sand, and dirt for miles downstream from the discharge point. Pumping from old workings would show new staining of the discharge runoff area.

In some countries, mine water and mill tailings must be retained in settling ponds to allow precipitation of the sediments. In places treatment is required to remove certain chemicals in the water.

When a mine is developed by a tunnel, the opening is driven on a slight upgrade to permit the mine water to drain out by gravity flow. Drain ditches are carried along one side of the opening. The water gradient is not steep, because the rock transportation system must operate against this grade in delivering empty cars to the working face. There is a tendency to compromise and use a minimum water gradient. This grade is usually too shallow and too carelessly maintained to carry effectively much sludge along with the water unless there is a large volume of flow.

Mines developed by vertical or inclined shafts drive their openings on an upgrade from the shaft to provide drainage to the shaft. Pumps are installed temporarily during shaft sinking. Permanent pump stations are installed at the bottom of the shaft when the shaft is completed. Usually the shaft is sunk some distance below the pump station to provide a water storage sump. Mine water drains into the sump, which acts as a settling pond.

Mine water can be highly acid in some mines. This may necessitate special pumps, liners, and pump column. Each installation is a special problem, and its design and adequacy will have to be judged and evaluated on the site. Permanent installations are larger, more complex, and better planned and installed than temporary pumping plants. Any good installation should have maps and plans available at the mine office. Supply parts should be available and on inventory records. There should be records of performance and running time of pumps for each shift. Most pumps are electrically driven if power is available. Compressed-air-driven pumps are used occasionally, particularly in small mines that do not have much water or electric power or where explosive gases prohibit electric pumps.

A permanent mine installation for pumping would have an adequate sump to take care of the expected mine water for periods of 8 to 24 hours while pump repairs were being made. A temporary operation might not make adequate provision for a sump capacity because it does not expect to operate long enough for the pumps to break down and need repairing. Permanent sumps are planned so they can be cleaned out; temporary installations may disregard this feature.

It is usually assumed in the United States that any pumping installation would be specifically designed for the mine and water problem. This may not be true in other countries where it is difficult to obtain equipment. Under these conditions the best, and sometimes only, available equipment is used. It would be helpful for evaluation to know what conditions exist with regard to mine equipment in regular mine installations in the suspect country. If it were difficult to obtain new equipment for a mine then a special installation with new pumps would be suspect.

A complete survey of the volume of underground mine waterflow might be advisable in an onsite examination of a mine. This would establish a base for later surveys. Small portable weirs could be used to determine the source and location of the water supply. With this survey, sampling of acidity, mineral content, sludge content, and radioactivity could be made and plotted on mine maps with the volumes of flow.

Surface water in streams, wells, and springs should be surveyed for location and sampled for flow, acidity, gases, radioactivity, mineral content, sedimentation content, and temperature. These sources could be plotted on the area map and related to the mine workings.

If the mine water or surface water were a critical factor, these surveys would be repeated as often as necessary.

Ground water in drill holes could be sampled by pumping after cleaning out the hole to remove drilling contaminants. If specific formations were of interest, casing could be placed in the drill holes and perforated at the desired position.

Wherever possible, samples of water should be obtained and analyzed to determine radioactivity, suspended solids, and minerals present as dissolved solids in major, minor, and trace concentrations. Such samples might be taken from within mines, or from existing drill holes or other openings.

The first and most significant measurement that should be made on such samples is gross radioactivity. If abnormal, gamma-spectral analyses should be made to determine whether the high radioactivity is caused by dissolved or suspended fission products or by natural radioactive salts. Spectral analyses might be supplemented further by radiochemical assay to determine the radioactive species present.

The removal, analysis, and identification of suspended solids may indicate unusual quantities or kinds of minerals that may have been deposited in water as debris from a subsurface explosion. Analysis of water samples may also indicate substances in solution that are not indigenous to water in the particular area.

Drilling holes or wells requires a source of drill water. Frequently it is necessary to impound a source of water to supply the quantity required, which is pumped through a pipeline to drill site. Evidence of an impounded water source, pump site, or pipeline could indicate a drill site.

VENTILATION

Underground mine openings require some form of ventilation both to provide fresh air and to remove dust and fumes generated by mining. The circulation of air may be natural, forced, or a combination of these, usually provided on a systematic basis to meet the requirements of the particular mine. The ventilation system usually consists of a normal or main system and an auxiliary system.

The implication of ventilation to reactivating an idle or abandoned mine for a test site is obvious; it may be also an important factor for onsite investigation on an active mine.

Normal System

Ventilation records at the mine, if any are kept, may reveal significant anomalies for the period before the suspected nuclear shot.

Ventilation must be provided for excavation of the shot chamber and the access to the chamber, and during emplacement of the device. It is improbable that records will be kept of ventilation measurements in the special area, but the effect of supplying air to that area may be reflected in ventilation measurements in other parts of the mine.

Exact effects on normal measurements caused by ventilation of a special project area are difficult to predict. They depend on such factors as the number of working levels, the extent of the different levels, the simplicity or complexity of the normal ventilation system, the total quantity of air normally supplied, and the particular section of the mine in which the special project was developed. The most probable effects may be—

1. Decreased total air quantity supplied, or increased total fan pressure. The special area always is a dead end during excavation, resulting in increased total resistance to airflow, or increased total pressure required to maintain some total flow.
2. Decreased air velocity in main return, if total quantity was decreased and total pressure remained constant.
3. Decreased air quantity and velocity at all points along one particular split of air (that which included the special project) but no change in other splits, if total quantity was decreased and total pressure remained constant.
4. Increased air quantity and velocity in all splits other than that which included the special project, if total pressure was increased and total quantity remained constant; air quantity and velocity in split that contained special project still decreased.

Changes in characteristics in splits of air may differ from those suggested in items 2 and 3 depending on the increments of change in total pressure and quantity. If the mine is relatively small and the extent of the special project excavation represents an appreciable portion of the whole, changes in ventilation characteristics also will be appreciable. If the mine is relatively large and the extent of the special project excavation represents only a small portion of the whole, changes in ventilation characteristics also will be generally small, although they still may be marked in the one particular split that included the special project.

Ventilation characteristics always exhibit some changes in normal operations, and it is possible that the effect of ventilating a special project may be concealed in the normal fluctuations. Nevertheless, if the records show that a normal pattern changed for a period of time and then reverted to the original pattern, an explanation for the change should be sought. If it cannot be proved that the change was caused by an unconcealed development program subsequently abandoned, a concealed special project should be suspected.

Ventilation of a special project may have been continuous from its inception to the time of detonation of a device, and a ventilation survey may not have been conducted after that time and before the arrival of the inspection team. If ventilation records are maintained, they may show a normal pattern that changed but did not revert. The inspection team then should request a ventilation survey identical to that customarily conducted at the mine. A single survey may not suffice to prove reversion to normal conditions, but any marked changes from the most recent surveys should be suspect.

A ventilation survey conducted in accordance with customary routine procedures should be requested by an inspection team at any suspect mine where ventilation records are kept. Examination of the records may not disclose a suspicious pattern, but the effects of the explosion may have altered normal airways in some fashion, with or without escape of radioactivity. A ventilation survey then might show marked changes from those on record, and this condition should automatically be considered suspect.

Auxiliary System

Ventilation of a special-project excavation of any extent requires installation of a fan or fans underground to insure air circulation throughout that project. It can be assumed that the fans will not be installed in normal travelways if concealment is intended. The fans most probably will be powered electrically, although compressed-air-operated fans may be used. The latter normally are distinctively noisy, but it might be possible to overcome this problem. In either event, connections must be made to a source of power unless a diesel-operated generating unit is employed.

A diesel-operated generator would create additional but not insuperable problems of additional air contamination. It could be removed, after it had served its purpose, without leaving any discoverable evidence of its use. Indications of electrical or compressed-air connections overlooked by those attempting to conceal their activities might be discovered by the inspection team. The connections might be the same as those required for power for mining operations if power is used for that purpose.

Indications of auxiliary fan power connections may be a possible cause for suspicion of surreptitious mining activities. This cannot logically be considered to be a strong factor; such indications will be relatively easy to conceal and lack of concealment will result almost solely from carelessness. Alternatively, they need not be concealed but can be used for and explained by other purposes.

Gas

Analyses of gas samples collected underground at the time of the inspection may be expected to yield positive indications of a nuclear explosion only if complete containment is not achieved and radioactive products escape into the mine atmosphere. If containment is not complete, radioactivity-monitoring devices will make gas sampling by other methods unnecessary.

Determination of radon and its daughters in the mine atmosphere offers a slight possibility of indicating a concealed nuclear explosion under certain special conditions. If a radioactive substance is being mined, this technique is hopeless. Slight but measurable radon daughter concentrations have been detected in mines and tunnels where no radioactive ores are mined. The U.S. Geological Survey has reported observing anomalous radon concentration near recent excavations subsequent to large quarry explosions.

The presence of radon and its daughter products might be considered suspicious, and the higher the concentration, the higher the degree of suspicion. Slight concentrations also may be natural and usual and may mean nothing. Alternatively, they may be indicative of rock disturbances caused by shock resulting from an explosion. If they cannot be proved to be customary or explained satisfactorily by recent detonations of large charges of chemical explosives, or by natural earth movements, a contained nuclear explosion may be suspected as the causative factor.

Analyses of gas samples by mass spectrometry or gas chromatography may indicate traces of foreign substances too slight to be detected by other means. This may be suspicious within the limits of accuracy of the analysis. Adequate normal ventilation, or extra ventilation induced after an explosion and before the inspection team arrives, most probably will result in a normal mine atmosphere, so that this technique also presents only minor possibilities. However, the presence of ventilation facilities greater than needed for normal ventilation would be suspicious.

Records of periodic air analyses, if any are maintained, also offer a slight possibility of detecting unusual activities. It should not be expected that records of air analyses in a special excavation project will be available, but unusual conditions in the special activity (that is, outbursts of methane, carbon dioxide, or other gases) may be reflected in air samples obtained elsewhere in the mine.

Additionally, if methane or other gas emissions are commonly found in the normal working areas, ventilation pressure change caused by the special project excavation may increase or decrease the rate of liberation. Gas liberation rates are not usually precisely constant, but vary irregularly. If over a certain period of time the rate of liberation is consistently either greater or less, or if the fluctuations are greater than normal, this condition may be considered suspicious.

Omission of gas sample records for a period of time may indicate that analyses during that time were abnormal and were not recorded intentionally in order not to draw attention to the abnormalities. The absence of records for a given time interval only, or a sudden termination of records, may be as suspicious as abnormal records.

The explosion might result in liberation of methane, carbon dioxide, or other gases in other areas of the mine, and the possibility exists that these conditions might not be cleared by ventilation before arrival of the inspection team. Analyses of samples, collected by the inspection team, that differ from recorded sample analyses should be suspect.

Dust

If records are kept of periodic dust surveys, examination of the records may disclose anomalies indicative of unusual mining activities over a certain period of time. Dust counts are reported as millions of particles per cubic foot of air in this country. Presumably similar counts in some units are recorded in other countries. Changes that might be detected are:

1. Higher counts in the particular air split that includes the special excavation. These will be particularly noticeable if little or no other mining is done in that air split.

2. Consistently higher, consistently lower, or markedly erratic higher and lower counts in other air splits. Changes in counts in these splits will depend on the extent of mining in each and the effect of increased or decreased air velocities suggested in the section of ventilation. The character of changes in counts is difficult to predict, but any abnormal changes will indicate abnormal conditions.

A distinct pattern change may not be discernible for the same reasons that distinct pattern changes may not be discernible in ventilation characteristics.

If records of dust counts do not indicate any suspicious anomalies, dust counts at the time of inspection may differ appreciably from the most recent ones recorded. Samples must be collected and counted, of course, in the customary manner of the mine. Dust counts may be increased as a result of the explosion. They also may have returned to normal by the time the inspection team arrives, but if the counts are higher they are suspect.

Variation in dust counts in normal mining area may be more a hoped-for technique than a probability. Dust surveys in well-managed mines in this country sometimes do include counts in travelways and airways; more usually they include counts only in the working places. Dust counts in working places may be affected by ventilation pressure and velocity changes caused by a special mining project, but it is doubtful whether changes from this cause would exceed normal variations.

Mine dusts normally are analyzed for composition only infrequently. It is highly improbable that either recorded analyses or analyses of samples collected during the inspection will have any significance for the inspection team—with one exception. If the type of rock and/or ore excavated in the special project differs from that in the rest of the mine, some evidence of surreptitious mining activity may be found along the haulageways. It is practically impossible to transport muck by any system without some spillage. Material along haulageways, therefore, should be sampled systematically and analyzed, and the analyses should be compared to those of samples systematically collected in all working places and along haulageways immediately adjacent to working places.

This approach may be defeated if the material excavated from the special project is used to fill stopes underground, particularly if the filled stopes are made inaccessible by or after the nuclear test. It possibly may be defeated by thoroughly cleaning all haulageways, but it will be difficult to clean haulageways so thoroughly that no traces remain. In this instance, it might be necessary to analyze samples of dust collected from wherever it can be found. This will be tedious but perhaps justified because inordinately clean haulageways are most unusual and therefore automatically a cause for suspicion.

This approach is futile where the rock and ore in the special project section are the same as in the rest of the mine and where only one massive deposit—a salt dome—is mined.

TRANSPORTATION AND ACCESS

Although it will vary in method and complexity with the type of operation, some form of access and means of transportation will be required for mining. Access must be prepared and transportation provided to move men and materials to and from a site. Underground excavation requires access from the surface to the desired depth by drill hole, shaft, adit, or a combination of these. Removal of excavated rock requires some means of transport from underground to the surface and usually from the surface at the site to some other point of ultimate disposal or use. The physical evidence of access and transportation is difficult to conceal and may remain long after a mining operation has been abandoned.

Surface access and transportation may be by road, railroad, water, air, aerial tram, pipeline, or any combination of these. Underground access and transportation may be through drill holes, adits, vertical shafts, or inclined shafts. Although most countries have some preferred items or individual peculiarities of their own, the means of providing mine access and transportation, including the equipment used, are remarkably similar throughout the world.

Land clearing and maintenance of grade for construction of roads and railroads introduce anomalies into the natural configuration of the land surface that are not easily erased (fig. 7). These are often detectable on aerial photographs and are usually evident in a detailed surface inspection. The degree of evidence for land-based operations will range from nearly zero for a drilled well, where equipment, supplies, and labor are flown in by helicopter, to a complex maze of roads, railroads, and shaft entries equipped with the elaborate hoisting gear and transport terminal equipment of a large-scale underground mining operation.

In the first example, discovery of evidence of access and transportation could lead to a site of an underground opening suspected as being used for nuclear test purposes. The evidence of surface access and transport in the second example would be obvious but might have no direct relation to a concealed test site. A more detailed evaluation, both surface and underground, would be necessary to establish evidence of nuclear testing. Evidence found of rerouting the transport of waste material at the surface could be suspicious. Recorded evidence of unexplained changes in transport and hoisting schedules for men and material could be found. Changes or additions to the underground transport system could be significant, as would any new underground access opening. The amount of evidence exhibited by inspection of mine access and transport systems and its significance to possible underground nuclear detonations is a function of a specific site, but it is obvious that access and transportation must be a part of any test site preparation. The purpose of the inspection would be to establish that a noted condition might be an indication of access or transport to a nuclear test site. While need for secrecy and concealment may be of overriding importance and result in an arbitrary decision of site selection, nevertheless, commonsense and the limiting parameters of various access and transport systems must influence the decision. Some of the limiting parameters are indicated in figure 8.

The consistency of the access and transport system at a specific site with economics of its development, designed load, local practice and technology, and safety regulation may reveal circumstances open to suspicion. Many countries have special safety requirements applicable to underground access openings. A common requirement is for more than one exit.

Again, compatibility is a criterion for evaluating evidence. The compatibility of the access and transportation system to its intended use and local conditions should be investigated. This would include the design and layout of the system; travelways—roadbed, track, curves, and grade; control and traffic management; equipment; repair and maintenance; and transportation records.

ENGINEERING

The engineering department at a mine has a continuous function of surveying, mapping, sampling, and planning the mine openings. Because of their direct relation to the efficiency of the operation, these activities are carefully documented and preserved. Such data may provide important clues or evidence, indicative of an underground nuclear test at the mine.

The development of underground mines, particularly those that are deep and extensive, is normally controlled by careful surveys. Survey points underground are normally fixed in relatively stable sections in the back or hanging wall in untimbered zones and on firm timbers elsewhere. Practice varies widely, but generally such points are numbered or otherwise marked by some form of scribing, paint, or the attachment of noncorrosive tags. The calculations fixing the exact horizontal and vertical position of each point are normally recorded, and the

FIGURE 7.—Access Roads to the Oil-Shale Mine.

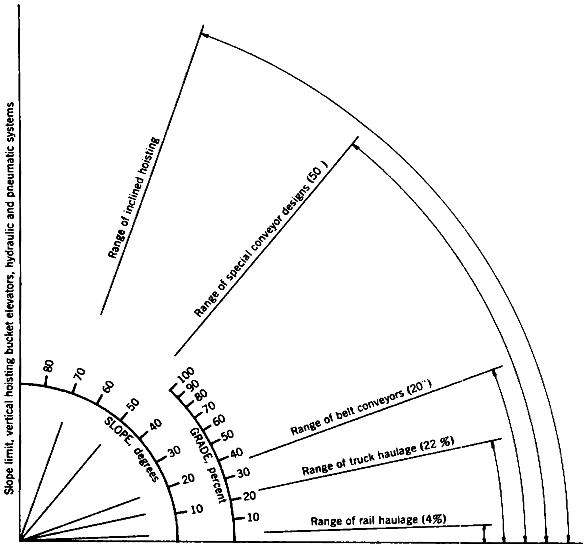


FIGURE 8.—Slope Limits and Range of Transport Systems.

points are usually identified on the mine maps. Because underground surveys present few opportunities to effect closures and base lines are normally very short, the points must be fixed with some precision. Where records of the point locations are available, relatively small displacements in latitude, departure, or elevation of any point should be disclosed by careful resurveying. A great deal of judgment and expert engineering would be necessary in interpreting such data, because the condition of the workings—the character of the formations and the elapsed time since the original establishment of the points—could, among other events, allow for some movement. Nevertheless, the subject would merit the careful attention of an investigation group because any of a number of anomalies might be disclosed through such effort. In large operations these would be difficult to conceal in a short period of time, because the task of resurveying, calculation, and remapping would be lengthy, regardless of the priority of effort given to it. A few of the inconsistencies that might be observed during an onsite investigation, aside from displacement of survey points, include: The absence or concealment of mine maps or point-location records; the absence of fixed survey points underground, particularly in new workings, tortuous workings, or at intersections; the establishment of new points in old workings, as evidenced by the condition of the point or its markings; inconsistencies in numbering sequence and similar departures from normal practice.

Detailed maps are maintained for an underground excavation of any consequence. Some countries require maps to be filed with the State. The mine maps are a very important element in any onsite mine inspection program. The maps can indicate what part of a mined area could be eliminated as a possible test site because of inadequate rock volume to contain a blast, or would transmit damaging shock waves to surrounding areas if the blast were contained. Conversely, the maps can indicate the more probable sections of the mine suitable for a nuclear test shot. Unexplainable openings shown on a map or evidence of openings not shown on the map would be suspicious conditions. The actual mapping is usually a standardized procedure so that any variation from standard practice may also be suspect.

General mine design data will be available either by documentation or observation of practice. The size of opening that can be maintained without artificial support could be determined. This would be very important in appraising a mine as a possible site for a decoupled shot. The general design criteria would indicate also the relative amount of effort in labor, materials, and so forth, that would be expended to prepare a test opening. Documentary evidence of special designs or plans may be related to test site excavation. Changes in pumping or ventilation installations, nonstandard designed openings, drill rounds, or blasting patterns may be significant.

Mining activity is related to the daily production, which in turn is often related to the ore-processing facilities. While a large mine could probably absorb a well-planned special project excavation, the chances are it would disrupt an orderly production schedule to some extent. Therefore, unscheduled or unusual mine activities would warrant questioning.

Mines are sampled by chipping a channel across the face of ore exposed in a drift or other opening. These channels are usually 2 or 3 inches wide and about an inch deep. They are spaced at intervals, often 5 feet, along the exposed ore. They may be either horizontal or vertical. The assay results of these samples are recorded on maps, and these serve as a guide to the mine foremen. The absence of any evidence of sampling could indicate a purpose other than mining.

Many mines have established standards, for drilling, blasting, size of openings, methods of support, and have standardized many equipment and supply items, such as drills, bits, and drill steel. A special opening for tests may require deviations from standard mine practice, evidenced by nonstandard practice or equipment in the mine.

WASTE DISPOSAL

Excavation of openings for atomic device emplacement is considered possible by drilling large-diameter holes, conventional underground mining, a combination of mining and drilling, or by solution mining. These operations will produce waste material that must be disposed of in some manner. "Waste material" is meant to imply that the material has no value so far as emplacement of the device is concerned. It may, in fact, be of economic value; for example, the salt or salt brine produced by conventional or solution mining.

The ideal condition would be one in which there was no waste; that is, the product of excavation for device emplacement would be a useful substance utilized in the local economy. While the ideal condition may be achieved, it is not considered likely, in view of the combination of conditions desirable for clandestine testing.

Since waste may provide a clue to the location of the clandestine event, disposal will be in a manner designed to attract little or no attention. To meet conditions of containment and concealment, large quantities of material may have to be excavated. Concealing or disposing of large amounts of rock in a manner that will not attract attention is difficult.

The use of large drilled holes (3-foot-diameter, or larger) has been considered a possible method of device emplacement. According to scaling laws, a 20-kt. device would need to be placed at a depth of 2,700 feet to provide complete containment. Drilling 3-foot-diameter holes, or larger, to such depths is feasible with drilling equipment now in use, including calyx (shot) drilling and modifications of oil-field-type, rotary-drilling equipment. However, shot drilling is a slower process, and the required depth is near the limit of holes attempted with present equipment; consequently, rotary drilling would be preferred. Large-diameter holes are normally drilled from the surface but could be drilled from an underground opening if sufficient headroom were provided for the purpose.

Waste produced by shot drilling would consist of rock cores the same diameter as the drill and fine rock cuttings. Waste from rotary drilling would be fine-to-coarse rock cuttings and barite or other material used to form a heavy liquid medium to remove drill cuttings from the hole. Both methods require large quantities of water unless oil-base mud or air is used as a drilling fluid. The quantity of waste from a 3-foot-diameter hole 2,700 feet deep would be 700 cubic yards in-place measurement.

The fine cuttings and sludge from a normal calyx drilling operation are allowed to flow into the natural surface drainage or, if required, are impounded to deposit the solid material and clear water overflowed to natural drainage. Drill core waste is taken to the nearest convenient dump site or consumed locally, such as for riprap.

The waste product from rotary drilling is usually a slurry or mud containing drill cuttings and the product used to create the drilling fluid. The drilling fluid is important because drilling to any depth without its use for cutting removal is difficult. One or more of the drilling fluid mixes such as Aqua Gel, clay, or barite may have been used, and some indication of its use may be found. The drilling fluid is circulated through the hole while drilling is in progress, and the return fluid containing the rock cuttings is passed over a screen or grizzly device that separates the rock cuttings from the fluid. In normal drilling operations rock cuttings are allowed to accumulate at or near the separation device and are left on the site after the hole is completed and the drill rig is removed. The quantity of cuttings produced by rotary drilling may be considerably less than the volume of the hole excavated. This is a factor of the type of material drilled and the extent to which it may be ground into very fine particles that go into, and are circulated with, the drilling fluid. In some cases a reduction of 50 percent from calculated hole volume might result.

Where extensive drilling operations have been, or are being carried on, evidence of drill waste by itself would have little or no value except as one means of spotting drill sites. Where drilling is not normal to a particular area, evidence of drill hole waste would be very important.

Past experience indicates that salt is easy to excavate and will stand unsupported around openings of large dimensions. For the purpose of concealment, the most practical method of excavation would be to produce a cavity in the salt by solution mining. Briefly, this system consists of drilling one or more holes to the desired depth in the salt, then pumping fresh water down the holes under controlled conditions to dissolve the salt. The brine thus formed is returned to the surface. The process is continuous and, in competent hands, can be made to produce cavities about as desired. In this system the brine would constitute the waste product for disposal.

A number of systems are known for disposing of brine from solution mining of salt. If the mine site is near a large body of salt water, the brine is carried by pipeline to this area and discharged. Where construction of pipelines to salt water areas is not practical, a system of injection wells may be used. In this system holes are drilled into an underground formation permeable enough to accept the salt water. The brine is then piped to these holes and injected under pressure. Use of this method depends upon the availability of underground formations with sufficient capacity to contain the volume of brine produced.

Evidence of disposal wells or pipelines and sampling of possible disposal areas may provide evidence indicating a test site. Samples could show increased salinity, stratification of the water due to change in salinity, or presence of salts foreign to a specific disposal area but indicative of an excavation site.

Preparation of a concealed detonation site by conventional mining would consist probably of crosscutting, shaft sinking, or a combination of shaft sinking and crosscutting. If the mine were deep enough below the surface to provide cover for containment, only crosscutting would be required. If the mine were shallow, then shaft sinking would be required to provide depth beneath the surface. Since an existing mine could provide some of the depth required, and since shaft sinking is more expensive and slower than crosscutting, it is probable that a combination of the two would be used.

Complete geologic information on the mine and area surrounding it will be necessary. Examination of underground openings will determine rock types and minerals mined. An examination will show also whether most of the underground openings were excavated in ore. This is an important factor in determining whether the size of the mine waste dump is about that expected from the number of underground openings shown. If a mill is present, then grade, recovery, and tonnage-milled figures will assist in evaluating the size of the mill tailings and waste dump. Rock types surrounding the underground opening are very important. If the rock types are different horizontally from or vertically below the mine openings from those exposed in the mine, the presence of this rock underground or on the surface may provide clues to a test area.

The quantity of waste for disposal will vary with the system used to provide emplacement. If crosscutting alone is required, a minimum tunnel section of 5 by 7 feet, 2,700 feet in length, can be assumed. This excavation would produce about 3,500 cubic yards, or about 7,000 tons. If shaft sinking or shaft sinking and crosscutting were used to provide emplacement, the volume of material excavated would be about the same. If more elaborate plans were followed or unusual conditions were encountered, the rock volume would be larger. In any case it would appear that the minimum volume of waste material to be concealed would be about 3,500 cubic yards. This is an in-place volume, and since broken rock occupies more space than dense in-place rock, we can assume the volume of material will be increased by about 50 percent to 5,200 cubic yards.

Waste disposal would be more critical for a small mine, or a mine excavated solely for the purpose of nuclear testing, than for a large operating mine. In each case the amount and type of material on the waste dump should correspond with the size of the underground areas excavated, and the rock types should be similar. If the mine appeared to be a recent excavation, an absence of mineralization in the mine or on the dump might be reason to suspect its use. It is logical to assume that waste from suspected additional excavation from a small mine will be disposed of in remote sites. A search for such areas would be made using aerial photography to note topographical changes and roads. All roads and surface irregularities noted would be examined in detail for possible dump areas, and for rock of the type suspected that might have fallen from a truck while it was in transit to the dumping area. All old mine shafts should be examined as possible disposal sites. A special search should be made for locations where a cut-and-cover method of disposal might be used. Recent planting of grass or shrubs may provide clues to such areas. A possibility of waste disposal in rivers, lakes, or seas must be considered where such are available.

In large mines and large waste dumps it may be necessary to excavate cuts through the dumps to determine if the suspected waste material had been placed there and covered with normal mine waste. If there is a large operating mill, the mill tailings dump might have to be examined in the same way to determine whether the suspected waste had been ground and run through the mill.

If the mine is large with extensive underground workings, these would have to be examined for hidden waste. For complete inspection all loose or broken rock should be removed from every face or heading in the mine to insure that the broken rock is not for the purpose of concealing additional excavation. All mine floors should be cleaned and examined for possible shafts or winzes.

Where the rock waste is foreign to the normal rock type found in a mine, scattered evidence may also be found in drainage ditches, sumps, rock dust on walls, along haulageways, caught in shaft timbers, or at the bottom of a shaft from spill in hoisting.

ROCK SUPPORT

Any opening in rock introduces pressures and stress around the opening. The chief causes of rock pressures are the residual stress in the rock itself and the weight of the overlying rock.

The stresses are rendered more complex in any given area underground by defects in the rock, such as fractures, joints, bedding, and chemical action due to alteration and decomposition. In strong homogeneous rock, such as some limestones and granites, even a large excavated chamber may stand indefinitely unsupported. Soft rock or rock where weakness is induced by structural defects such as joints, falls or caves quickly if not supported. Figure 9 shows surface subsidence resulting from block caving.

In a general way, layered (bedded) formations tend to resist pressures in a manner analogous to a beam action. Homogeneous massive formations tend to form an arch to redistribute the stress. To maintain the desired size and shape of an underground opening and provide safe working conditions some method of rock support is often required.

In most parts of the world, timber is the most economical natural material used to support rock. Its advantage is that before breaking timber splits and cracks with audible noise, thus warning the miner of increasing load before an actual fall of rocks occurs. These splits and cracks are visible after they occur and form a record of movement (fig. 10).

Timber may be a simple length of tree trunk used to support the back in stopes in a flat-lying ore body or the walls in a more-or-less vertical ore body. Such timbers are called stulls. Usually a headboard of sawn timber such as a short, thick plank is wedged in place on the top of a vertical stull. A headboard is placed on the end of a stull that is against the overhanging (hanging wall) face of a stope that is mined along a nearly vertical vein or ore body. The headboard gives a large bearing surface for support of the overhead rock. If the rock had a tendency to break or separate into small-size blocks, then the stulls would be placed closer together. Some interlacing of headboards is often used on particularly bad rock.

In many mines round timber is cut to specific lengths for upright posts and framed on one end in a special manner so that additional pieces of shorter timber fit horizontally into the framing, thus providing a bearing surface on top of the post. The special framing will make a four-way fit horizontally and key into a post above and below the four-way key. This permits one set of timber to fit vertically above the other and to fit on either side or ahead of a single starting set (fig. 11). This is known as square-set timbering, and it can be carried as support for large open-stope mining in wide veins. Most of the many versions and different methods of timber support grew out of necessity to reduce costs, special mine problems, and scarcity of timber.

Short pieces of timber—scrap is often used—can be arranged into a form of cribbing to support the stope back. Mines using square-set timbering often use solid scrap timber bulkheads or cribbing along the sides of drift timber to assist in holding heavy overhead pressures.

Waste rock is backfilled around the timber to aid in supporting the stope walls. Usually this waste is just dumped into the old stopes without any effort to compact or place the rock to advantage for better fill or tightness.

In exceedingly heavy ground, or where timber is not available, steel supports are often used. The cost of transportation may preclude its use at mines in remote areas. Steel generally is more expensive than timber. Although it will support greater loads, it tends to bend or, if tempered too hard, to break. It is much more difficult to repair or relieve than timber and the steel does not give the audible warning before failure. A new type of steel support designed to yield under increased load is now being used for mine supports.

In the last few years the design of reinforced concrete support has improved and the use of this material for ground support is increasing. The cost is high and although the strength is high, repair is difficult and expensive.

Roof bolts are an effective method of supporting some types of ground. They are used for general support purposes and minor support for holding key rock on the surface tightly to the supporting rock arch or beam.

Brick and stone are rarely used in American mines. They are used in foreign mines and in some ground form adequate support for holding key rocks in place in the natural arch.

Slimes from mill tailings are often utilized to fill and seal stopes for wall support. These slimes or tailings are mixed with water and are delivered to the mine stopes by pipeline either by pumping or by gravity flow. The water filters out with a resulting filter-packing action that gives good compaction support. This filling also is helpful in sealing off air to old workings that are subject to heating and fire (oxidation of sulfide ores generates heat).

Some rocks tend to air-slake after exposure in openings. One means of supporting this rock is with Gunite, a half-inch layer of cement (stucco) over the rock surface. This also is often done in drifts or passageways used as

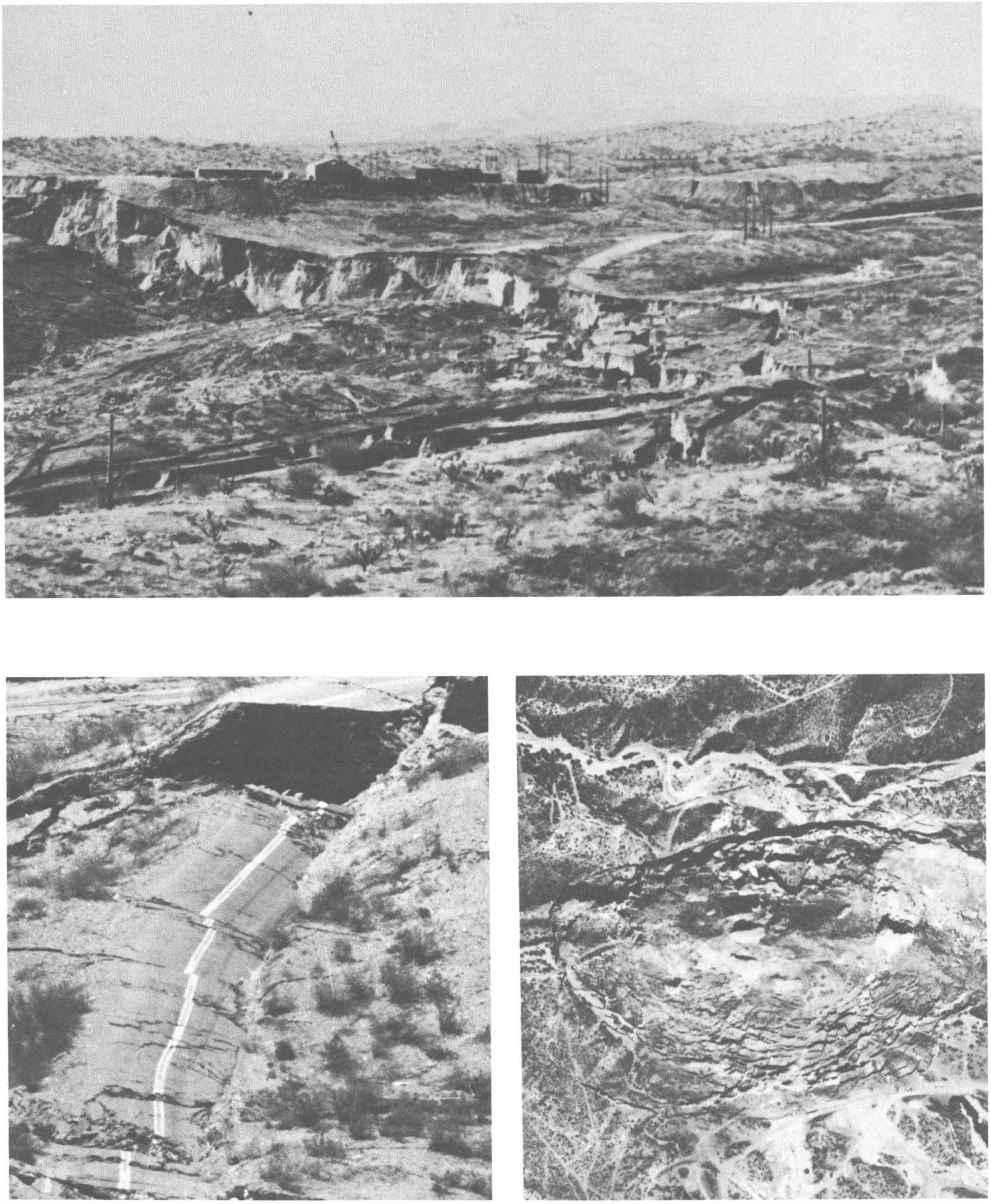


FIGURE 9.—Surface Subsidence From Block Caving.

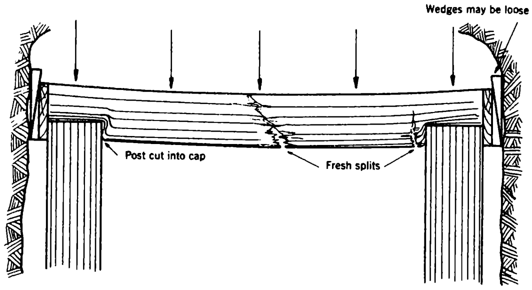


FIGURE 10.—Points Where Cracks and Splits Show in Timber Supports After a Surge of Weight.

part of the main ventilation systems for mines to help reduce resistance to air flow.

All types of ground support react to a sudden surge of weight; indications of such are as follows:

Timber:
1. Wedges are loose.
2. Fibers flatten in cap over post.
3. Splits develop along cap in areas not supported.
4. Thickness of cap over post is reduced.
5. Fibers in post tend to tear apart.
6. Cap and/or posts bend.
7. Back lagging is bowed between sets.
8. Side lagging is bowed between sets.
9. Post is pushed inward.
10. Track or floor of drift bulges upward.

Steel:
1. Rust scales snap off to expose iron.
2. Member is distorted or broken.
3. Member is out of line.
4. Slide or back lagging is bowed inward or broken.
5. Slippage occurs at joints.

Reinforced concrete:
1. Cracks occur in face of drift.
2. Massive movement of wall occurs.
3. Chips of concrete fall from face.

Roof bolts:
1. Bolt is broken or loose.
2. Head of bolt is pulled through wooden shell.
3. Spalling shows around head of bolt.
4. Significant change in torque occurs.

Hard ground requires little or no support; medium ground requires a fair amount of support and is the most common type. Soft or heavy ground requires a great deal of support. The first timbering is in the mine shaft, adit, or drifts and crosscuts. In adits the simplest form of roof support is a one-piece set; the most common type is the three-piece set. In very heavy ground a four-piece set is used. The one-piece set consists of a single cap notched and wedged into the top of the drift (fig. 12). The three-piece set consists of a cap above supported by two posts; placing this set on a floorsill results in a four-piece set.

The main causes of the destruction of mine timber are decay, insect attack, breakage, wear or abrasion, or fire. In a mine that operates for any considerable length of time, decay causes more damage than any other one factor. Decay is caused by the growth within the wood of fungi or molds. Molds require favorable temperature and a small amount of air and moisture. Almost all mines have a favorable atmosphere for the development of mold. The life of untreated timber in mines is usually quite short, averaging 3 to 5 years. This life can be increased by treating the timber with some preservative to prevent the formation of molds and attack by insects.

Timber is not attacked uniformly by molds and therefore the life of a number of sets in a drift may vary considerably. After the timber has been weakened by mold, it will fall when the ground is active and moving. However, in many mines once the initial set has taken place in the rock, there is no stress on the timber. This timber will stand sometimes for years even though rotten. The failure of a single set in a drift thus would not be suspicious. However, failure or indicated strain on all timber in a long drift, possibly starting with minimum indications and increasing through the length of the drift to a maximum, then decreasing, would indicate the possibility of a major seismic disturbance (fig. 13).

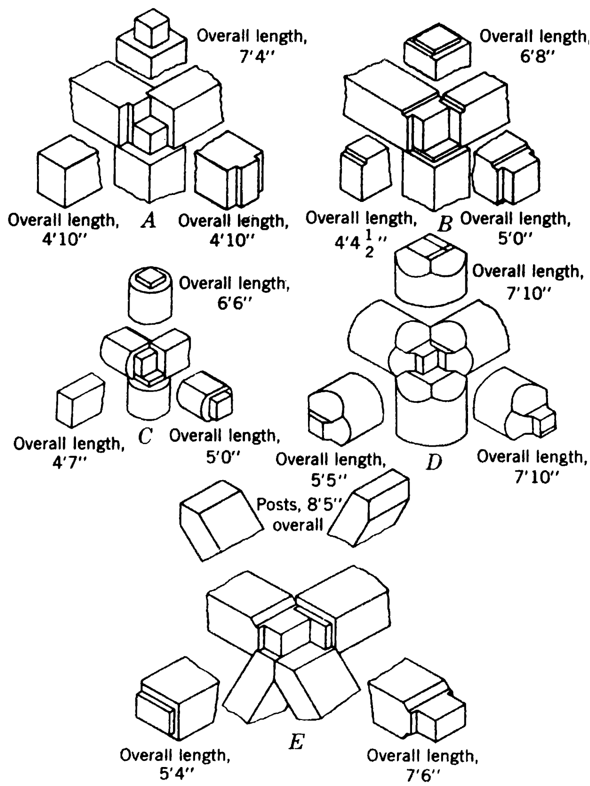


FIGURE 11.—Typical Methods of Framing Square-Set Timbers. *A*, Cananea (Mexico) Post-Butting Joint. *B*, Bingham (Utah) Cap-Butting Joint, Round Timbers. *D*, Beveled Joint on Round Timbers. *E*, Moore Diagonal Set.

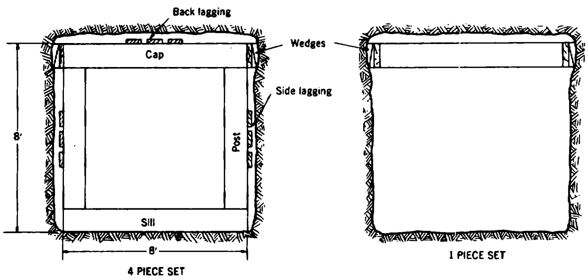


FIGURE 12.—Typical Timber Supports.

Replaced supports or new supports, particularly in areas where the need is not apparent, could indicate a hidden or caved entry to a detonation site. Ground support is usually done in a systematic manner, and local crews may even have their own peculiarities of assembly and placement. Noted variations could indicate foreign crews or an abnormal condition worth investigating. An entry driven off an existing drift to reach a detonation site would require a turnout from the drift to accommodate transport units. This might be reflected in the support required to hide the entry.

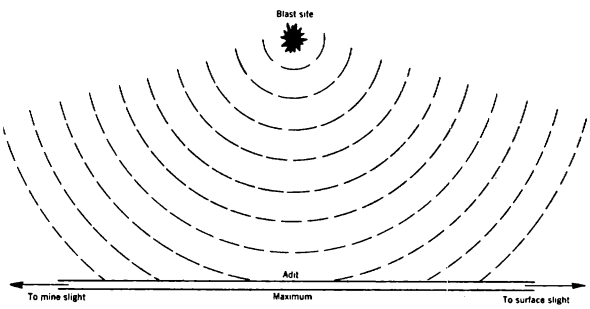


FIGURE 13.—Hypothetical Arrangement of Disturbance and Damage Zones.

ACCOUNTING AND RECORDS

Accounting is for two purposes: Financial or cost control, and production or performance control. The general officers in the home office are interested in the costs so that they may be sure the mine is operating profitably. The manager of the property is interested in performance so that he may be sure that production of ore is as efficiently as possible. The income of mining properties is usually limited to a few products sold in large quantities to a few outlets. Mine accounting records, then, are mainly concerned with distributing the expenditures. Usually, these are divided into three sections: Labor, warehouse material, and other expenses.

Production control comprises planning, routing, scheduling, dispatching, and sampling functions so organized that movement of ores, performance of machines, and operations of labor, however subdivided, are controlled and coordinated as to quantity, grade, time, and place. In mining, production is generally expedited by the engineering department, but decisions are based on records kept by the accounting department.

Production of metal can be varied by changing the tonnage rate or by changing the metal content of the ore. Thus, production can be increased by sending a larger number of tons of ore of the same grade or the same number of tons of ore with a higher grade for a given period. To be in a position to decide at a moment's notice how to make various changes in production rates, all accessible working places are sampled, a reserve of ore is estimated, and the grade of ore is recorded. This requires a certain amount of development or preparation expense. The efficiency of this development or preparation work is determined by the number of tons of ore or pounds of metal available as a result. Accounting records are generally consolidated and totaled for a period of time, usually a month, and then presented in reports. A typical period report should show the quantity of ore produced, the amount of development work and equipment required to produce this ore, and the labor, supplies, and materials, consumed to accomplish this work. From these figures general management can learn the cost.

The basic information for mine accounting is recorded on operating reports, time cards, supply issue slips, or similar type forms. Often each man and each operating machine is covered by a report of this type. Sometimes the report is prepared by the foreman, sometimes by the worker. Damaged forms or copies of these forms are often thrown away and can be found lying around in corners and drifts (fig. 14). In the mine office they are filed on hooks and kept for periods of a month or year. This practice of reporting generally is not followed in so much detail by contractors on construction jobs. The absence of a well-defined system of ore and production control should be viewed with suspicion.

Personnel records, and especially the checkout system used at a mine, may be a source of information. The possibilities of production records are obvious and may show inconsistencies between tons mined, tons hauled or hoisted, tons milled or shipped, and metal recovery. A mill will record weight and grade of ore received and processed. The amount of reagents being used at any time is recorded for reference in recovery studies. Mine and mill will have records of power consumption which may be anomalous with recorded production.

Left half

OPERATING

Date: October 4, 1955

Smith DAY SHIFT — Green NIGHT SHIFT — Ass't Foreman

Bosses' Best: Zone 1-1300

Checked: White

Form 1-4-4-54-5M.

Circle "O" All Used Material. Rd = Round, Sq = Square, Seg = Segment.

Contract No. and Place	Shift	Account	Labor C't.	Labor D.P.	Cars Ore Reg.	Cars Ore	Cars Waste H	Cars Waste F	Posts	Caps	Girts	Sills	Lagging 5'4" 2"	Lagging 5'4" 3"	Lagging 7'9" 2"	Lagging 7'9" 3"	Blocking	Braces 1"	Braces 6"	[illegible]	Stringer	Special	Crib	Explosives Pow	Explosives Reg. Prim.	Explosives Elec. Prim.	Drill Type	Drill Nos.
606	D	01-03	2									2	1			4												
1-13-21CWGD2	N	13-10C	2		5								3					1										
607	D	01-05	1		15																			135	12		JL	3
1-13-21CWUCDR	N	13-01	2		12							4			7													
607	D	01-04	1																				8	62	9		P	
1-13-21 CW FR	N	13-01																										
616	D	01-01	2		2				2	1	2		6	5										160	17		JT	3
1-13-X 18	N	13-01	2		7			3-3/4"x6' Rock Bolts																127	13		JT	3
622	D	01-14	2					6-3/4"x6' Rock Bolts 4																35	6		JL	2
A1345XSW	N	13-01																										
636	D	01-03	2		4			4-1"x6' Rock Bolts					11											47	5		JL	2
1-13-24CWGD4	N	13-01																										
640	D	01-07	2		2																			117	14		JL	3
1-13-24CWSLDr	N	13-01	2		9			7-3/4"x6' Rock Bolts																			JL	3
812	D	01-14	2																					210	23		P	6
1-13-21AW VR	N	13-01	2		11				6	3	4		7	13														
X-12	D				246																							
CaveRock	N				258																							

Right half

OPERATING

DAYS PAY LABOR

Remarks	Place		01-01 Haulage & Cuts	01-02 Grizzly Raises	01-03 Grizzly Levels	01-04 Finger Raises	01-05 Undercut	01-06 Bound. Work	01-07 Slusher Drifts	01-08 Repairs	01-09 Undercutting	01-10 Chute Tapping		01-14 Vent.	01-16 Drain	01-18 Tram Rock	01-18 Zone Re. Inc.	01-20 Hoist	01-22 S.S.P.L.	01-24 Drills	01-26 Tools	01-36 Misc.	01-38 Fire	85-1 Explos.	85-2 Timber		Day	Night
	1300									2		6		1		3	1			1	1				1	Cont. Shifts	14	10
	Level									2		6				3	1						1		1			
																										Days Pay Shift	16	14
																(Ore drawing X-12)										Cars Ore	246	258
																(Development 1300 level)											23	44
																					(Total)					Cars Ore	269	302
																										Cars H. Waste		
																										Cars F. Waste		
																										Holes Blasted		
																										Holes Missed		

EXPLANATION:–
- GD 2 = Grizzly Drift 2
- 1-13-21 CW = Zone 1, 1300 level, Block 21 Panel C West
- UC DR = Undercut drift
- FR = Finger raise
- X 18 = Crosscut 18
- SL Dr2 = Slusher drift 2
- VR = Ventilation raise

FIGURE 14.—Sample Mine Reports.

Records of the receipt, checkout, and distribution of equipment, materials, and supplies, together with labor charges for service, repair, and maintenance, could supply clues. The mine electrician, maintenance crew, or mechanic could be called upon for service. They might record job, parts used, and location of work that would be significant.

Explosives used at a mine must be delivered from some outside source; special transportation, handling, and storage are necessary. Explosive supplies are carefully controlled and allotted to the miners, usually on written order. Additional care would be necessary in any country with political unrest. A producing mine has a fairly uniform consumption of explosives related to tons of rock blasted. Increased orders or recorded use without commensurate production in headings or stopes would be suspect.

Safety activities, accident records and statistics, and records of the local first-aid room, infirmary, or hospital may provide clues to concealed mining activity.

Inconsistencies in records and accounts may have a natural explanation but timed with a recorded seismic disturbance should be cause for suspicion.

FACILITIES

The facilities serving a mine vary with the type and size of the mine, but usually include a primary source of power, mine plant, and auxiliary plant such as housing, recreation, and commissary. Drilled holes, which we class as mine openings, would not have any permanent facilities. A large mine operation, such as Anaconda's at Butte, would include an entire complex of permanent facilities.

Power

Electricity, generated by diesel, steam, or hydro plants, is the usual source of power for mining. Electricity may be generated at the mine or transmitted to the mine from an outside powerplant. Gasoline- or diesel-driven air compressors may supply compressed air directly as a power source for small mine operations or as a small auxiliary supply, and a few special mining techniques may use waterpower directly. Mine equipment is ordinarily powered by electricity, compressed air, and diesel fuel. Records of power consumption may indicate an extra or unusual activity at a mine. It is of interest to note that mines are frequently underpowered. This has been particularly true since the rapid increase in mechanization that has taken place in many of the operations. An extra powerload of any consequence may require addition or revision of the normal power source and transmission system.

Electric power cables and compressed-air pipes are normally hung from the walls or roof of a mine on pins fastened in holes in the rock. Such holes and pins could reveal a recent addition or removal of such transmission lines.

Mine Plant

The normal surface plant for an underground mine consists of office, changehouse and cap lamphouse, compressor plant, fans, warehouse, magazine, repair shops and, if hoisting is required, a hoisthouse and headframe. Additional plant facilities may be underground, such as pumps, office space, magazine, crusher plant, storage, and repair shops. Although it would be difficult to pinpoint definite evidence displayed by the mine plant in relation to an underground nuclear test, any part, or all, of the plant could be affected. A general check of the plant and comparison of records made during a suspect period with those of a more or less normal period could be revealing; so could a new underground magazine or radical changes in quantity and distribution of explosives.

Mill Plant

In general, the mill plant should have little relation to, or be little affected by, a nuclear test. The most obvious anomaly would be a sizable mining operation with no provision for milling the ore, or a mismatched mill with regard to the ore produced.

Auxiliary Plant

This is the plant necessary to provide for the needs of the mine personnel. It may be very crude or, with all its appendages may assume the sophistication of a city. Essentially, some provision must be made at or near an underground test site to provide for the people involved. Evidence supplied by the auxiliary plant will be revealing at a new excavation, or where preparations are being made for a test at an inactive or abandoned mine. Such evidence would be least observable at a large, active mining operation. To quote an example, the need to provide for 20 visitors at a remote mining operation in Canada overtaxed available facilities and completely disrupted the normal pattern of activity at this mine.

SUPPLEMENTAL TECHNIQUES

In searching for evidence of a clandestine underground nuclear explosion, certain supplementary information should be evaluated that in its nature is peculiar to the country or district being investigated. The culture of a country, and its human activity, tradition, and local customs, may furnish important evidence. The economic and national status of the mining industry can be important.

The onsite investigators will be searching for anomalies indicating a clandestine nuclear explosion.

The normal pattern must be understood to recognize a significant variation from the norm. Motor transportation of employees from home to working place is common in some countries but not customary in others. In the United States and Canada, house trailers may virtually form a town at a new mine site, while in other countries house trailers are never used by mine workers. Miners' dress, tools, entertainment, living accommodations, and even superstitions are fixed by tradition in many areas of the world. Significant deviations may be meaningful evidence in an onsite investigation. Even the lowly shovel, which is almost a symbol of mining, is not indigenous to mines in some countries.

Refuse and waste found scattered or in dumps at supposed inactive or abandoned mines could be important evidence of recent activity. Even at active mines such material might indicate the presence of personnel or an activity anomalous to the locale. Old mine areas are frequently littered with refuse and waste that provide an astute observer with information about previous visitors and activities. Discarded tobacco containers, cigarettes, matches, clothing, broken tools and machine parts, liquor bottles, spent carbide from lamps, newspapers, magazines, and food containers are all common refuse. What items are found, where they are found, and what condition they are in may furnish leads to past occupants and their activity.

Underground debris may also indicate recent activity or openings caved by blasting. Muck piles often contain unconsumed or partially consumed dynamite, pieces of detonators, leg wires, and connecting wire. Scrap from explosives packaging and the stemming material used for blasting are frequently scattered about a working area. This type of evidence could indicate recent mining activity and possibly variations from normal or standard mine practices.

Individual mines and even entire mining districts frequently employ standard mining practices and equipment. Although it is not uncommon to introduce new practices and equipment into a mine, these should be viewed with suspicion when coupled with the timing of a suspected nuclear detonation. Standard practices and equipment may include: Size of drill hole; pattern and length of drilled round; quantity and type of explosives used; scaling practice; type of support and method of installing; equipment and methods for installing utilities (air, water, power); drills; drill bits and steel; the equipment, practices, and scheduling for loading and transport; and the cycling of the work and working force. Evidence of some of these is usually exposed on the rock walls of the mine opening, for instance, the length of drill round and size of drill hole.

Underground openings sometimes accommodate a large population of small animal life. Deep mines that have produced without long interruptions, and have only recently been fully mechanized, will invariably be inhabited by mice, and sometimes by other rodents.

It is not known how a sharp environmental change would affect such a population. However, an observer should be alert to: (1) The absence of rodents in any workings employing animal haulage; (2) the absence of rodents in deep shaft mines that have been operated without long interruptions, including flooding, for 20 years or more; (3) the presence of dead rodents.

Because of time factors, the knowledge to be gained from laboratory tests exploring the direct or side effects of radiation on this animal life is questionable. Yet it appears desirable that such tests be made on a routine basis in view of the potential information which, under certain conditions, could be most important.

The phenomenon of animal sensitivity to impending major natural earth movements, should such have any substance, would, at least from the standpoint of the local uninformed observer, provide some measure for differentiating between major natural and manmade seismic events—no one yet has attributed extrasensory perceptiveness to animals preliminary to the latter. In the absence of scientific substance no significance is attached to this subject, except that it could be included as a minor item in discussion with local persons, anticipating that the fiction might be employed locally to support claims that the event under investigation was occasioned by natural events.

The various instrumental surveys and logging techniques have been investigated and reported in some detail by SRI and others. However, certain techniques that appear to have value as tools for mine-examination techniques deserve further emphasis.

Radioactivity surveys, using portable, battery-powered, sensitive survey meters, should be made of any surface or subsurface area investigated. The radioactivity of air or other gases may be determined by drawing the gas through an ionization chamber, using portable instruments. This especially is recommended within mine openings and at the surface openings of any visible drill holes, shafts, or other vents. The radioactivity of solid surfaces may be determined by surface measurements of radioactivity using an external-probe type of survey meter. The radioactivity of liquids may be measured by monitoring above their surfaces or by using a waterproof, dipping-type detector. In addition to the detection of gamma radioactivity by such types of measurement, the radioactivity caused by alpha and soft beta radiations might be measured in any suspect areas by making swab tests and counting the radioactivity of the swabs in a suitable radiation-detection instrument.

Whenever any significant anomalous radioactivity is detected, it is recommended that local samples of solids, liquids, or gases be obtained for determining, through spectral analysis and observation of decay rates, the nature of the substances responsible for the anomalous radioactivity. The analytical equipment required for doing this might easily be transported to and used in the field, especially if transistorized, battery-powered circuitry, and mechanically actuated instruments were assembled or designed specifically for this purpose.

Existing drill holes, shafts, or other vents should be logged to determine radioactivity if possible. If the area under investigation is covered by water, logging on a grid basis may be advisable. In such logging operations, particular attention should be paid to radioactivity measurements of the solid bottom of the water body. Compact logging equipment capable of logging to depths of several thousand feet is available and easily transportable, and may be used conveniently and with comparative rapidity.

Dependent upon circumstances, different types of radioactivity-logging methods should be used; the simplest type of logging is to determine gamma radiation. This may be done by the use of Geigertube, ionization-chamber, or scintillation logging devices. For small holes or vents, Geigertube logging probes of good stability and reasonable sensitivity have developed.[60] Scintillation probes of greater sensitivity also are available, although normally they have somewhat greater diameters. Ionization-chamber probes are still larger in diameter.

Inasmuch as some of the radioisotopes that might be distributed over comparatively wide areas are principally or entirely beta emitters (for example, krypton 85, strontium 89, and strontium 90, respectively), the availability and use of a beta-logging probe is suggested. Although such devices are not used commonly, there are no serious technical difficulties precluding the design of a beta-logging probe of good sensitivity.

Spectral logging, using a scintillation probe and surface analytical equipment, is a common practice in petroleum and mineral-exploration operations. Equipment is available that may be transported easily and used reliably in the field. If either gamma or beta logging detects appreciable anomalous radioactivity, the gamma spectra of the hole should be determined to learn whether any fission products are responsible for zones of high radioactivity.

It is doubtful that neutron logging will be useful to an onsite inspection team. Although some fissile material might be ejected from the point of a nuclear detonation, its distribution would not be expected to be as widespread as that of some of the radioactive gases, and all of the free neutrons should long since have been absorbed by the time an inspection team arrived. Alpha particles emitted by fissile isotopes would probably not be detectable by logging. Laboratory analyses of samples of solids and liquids might be used to identify uranium or plutonium, although it is logical to assume that, if fissionable material is identifiable, fission products should be even more so.

Neutron-gamma logging commonly is used in combination with gamma logging in petroleum operations for stratigraphic correlations, in the identification of hydrogen-bearing liquids (hydrocarbons or water) in porous zones, and in estimating porosity. This technique might be useful in detecting unusual stratigraphy or anomalous porosity, caused by intersection of a crushed or fractured zone formed by a subsurface nuclear detonation. However, it is likely that anomalous radioactivity in such zones would be more indicative evidence than stratigraphy or porosity determined by neutron-gamma logging.

A completely new tool in the petroleum industry is the downhole particle accelerator used for the production and acceleration of charged particles. By the use of a suitable incorporated target, the tool may be used to produce fast, monoenergetic neutrons. Fast neutrons are useful in logging because of the

[60] Armstrong, F. E., Gamma-Ray Detector Aids Oilfield Surveys: Electronics, vol. 31, May 23, 1958, pp. 61–63.

ability to activate elements that normally are not made radioactive by bombardment with thermal neutrons. By the simultaneous analysis of prompt gamma rays emitted by short half-lived isotopes of such elements as oxygen, nitrogen, silicon, aluminum, and magnesium, the determination of trace elements and consequent analysis of rock conditions is made possible. A downhole particle accelerator is a possibility for detecting the presence in boreholes or shafts of solid, liquid, or gaseous substances that would not normally be expected to be present.

Moxham and Bunker have suggested that surveys to determine the concentration of radon in soil, gas, and boreholes might be desirable in investigating a possible nuclear explosion and that alpha-counting equipment might be used for that purpose. The decay products of radon contribute significantly to the gamma radioactivity of water produced in many wells and to the surface-radioactivity method of determining the limits of oil-productive formations through detection of the halo phenomenon. Either radon distributed as a result of a nuclear detonation, or anomalies in the normal radon-decay radioactivity of a borehole or shaft, caused by rock disturbance, might be a useful technique to an inspection team.

The short-wavelength ultraviolet lamp, such as the types employed in prospecting for certain minerals that are fluorescent under such light, may be effectively employed to detect oil and grease stains not otherwise visible. Exhausts from air-powered drilling equipment deposit oil films in the immediate vicinity of their operation. Even after equipment has been removed and the site cannot be otherwise recognized, the oil stains would permit a fairly effective means for localizing such activity. The effect deteriorates slowly. The stains are difficult to erase.

EVALUATION

The potential effectiveness of some combination of mine-examination techniques applied to the locating and ultimately identifying clandestine underground nuclear detonations is based primarily upon a proper application of logic. Accumulated evidence is essentially acquired from observation of interrelated physical conditions and events which may or may not be logically related to a particular circumstance or intended purpose. Conclusions must be evaluated repeatedly against each piece of evidence and weighed carefully as to their significance and implications. Unless a serious miscalculation, oversight, or accident occurs during a test, the probability is slight that any single technique or piece of evidence will lead directly and conclusively to the identification of a clandestine test site. Thus, the investigative process includes the exercise of good judgment in selecting techniques best applicable to a particular situation and sound logic in weighing the findings.

The approach, reasoning, and logic must further be tempered by the knowledge that an illogical site or arrangement of evidence may have been deliberately established for aiding concealment.

Thus talent for reasoning is essential to a successful investigator, and the need for special competence in this area will not decrease, even with vast improvements in instrumentation or detection devices. The possible evidence that could be involved cannot readily be determined in advance but can require mastery of varied disciplines, techniques, cultures, and industrial experiences. The possibility of any small group of persons having all the necessary or desirable background is remote. This suggests that the permanent inspection unit might consist of a small cadre of personnel with broad background in the major disciplines, techniques, and cultures. The ultimate composition of an inspection group can then be composed of the cadre complemented by consultants with expert knowledge of the investigation techniques required at any specific site.

Several broad conclusions resulted from the study. For example, while recognizing circumstances that would dictate otherwise, it would appear that if an 18-inch drilled hole could be used for the test, such an opening would be the most logical "mine" for a clandestine detonation. Placed in this fashion the test would be easier to conceal and more difficult to discover (especially if drilled under a body of water), would allow a wider choice of location and rock conditions, and would be less expensive to conduct. However, it would be difficult to undercut a chamber in such a hole for purposes of decoupling. Increasing the diameter of the hole to allow bottom chambering for a decoupled shot, or to accommodate a larger device, would decrease the advantages of a drilled hole.

An opening designed specifically as a detonation site and driven from an underground opening of an active mine would offer some opportunities for concealment and under certain circumstances would be difficult to discover. At least two factors would deter the selection of this type of site: First, operating mines are regarded as economic assets by all countries and, as such, the potential hazard of serious damage or possible destruction from an underground nuclear detonation would place a high premium on the need to use such sites. A second factor, bearing somewhat on the first, is that geologic conditions in and around most deep mines are not conducive to clandestine test purposes. Structural breaks and waterflow in the rock will complicate containment and in many cases eliminate the possibility of employing large openings for decoupling.

New openings excavated expressly for accommodating a clandestine detonation (other than drilled holes), abandoned or inactive mines, and natural caverns, if intended for test purposes, will produce a variety of physical evidence of the activity that will be difficult to erase. In addition, abandoned or inactive mines and natural caverns will not normally be in a favorable geologic setting.

It is obvious that the successful application of many of the stated mine-examination techniques depends on the amount and quality of information available to the inspectors. Access to records and opportunity to talk with local citizenry are important adjuncts to learned observation and physical testing, whether the purpose be a conventional investigation of mineral property or the investigation of a site of a suspected seismic disturbance. Records and questions may not only furnish significant evidence to the investigators but may in fact be the essential elements in delineating logical areas for investigation. For example, while it is doubtful that a mine map would show an underground excavation designed for the purpose of a clandestine test, it would indicate the more logical areas suitable for that purpose. When

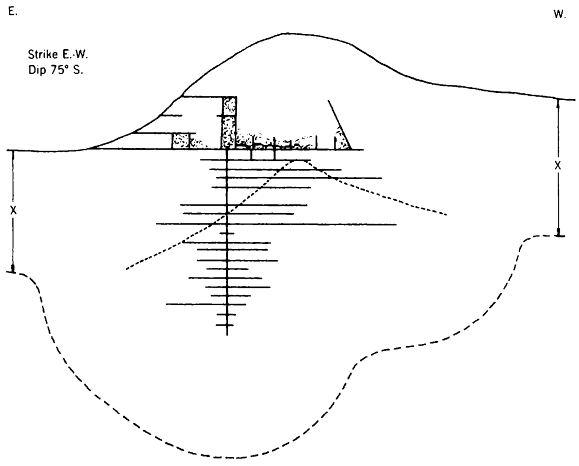


FIGURE 15.—Example of the Use of Mine Maps, an Idealized Sketch.

related to corresponding geologic maps, the logical areas for such testing could be further delimited.

A simplified illustration of a use of mine maps is shown by figures 15, 16, 17*A* and 17*B*. In the plane of the drawing on figure 15 a detonation site must be located below the dashed line to obtain adequate burial with reference to the surface and mine workings.

In a plane normal to the drawing, a crosscut driven from the workings below the dotted line and a distance *X* from the northern or southern extremities of the mine workings would be required, where *X* is the required depth of burial. In figure 15 the west section of level 8 would be a logical location for driving an opening for test purposes.

Figure 16 is a sketch of an actual mine layout similar to the idealized sketch 15. It is apparent from this sketch that no area within the mining limits would provide an adequate depth of burial. It is also apparent that the southeast area of the mine is the most logical section to drive test workings.

Figures 17*A* and 17*B* show the plan and section of an actual mine. The plan illustrates complication to site selection presented by adjoining mine workings and fault systems. From the sketches it would appear that an underground opening driven to the northeast from

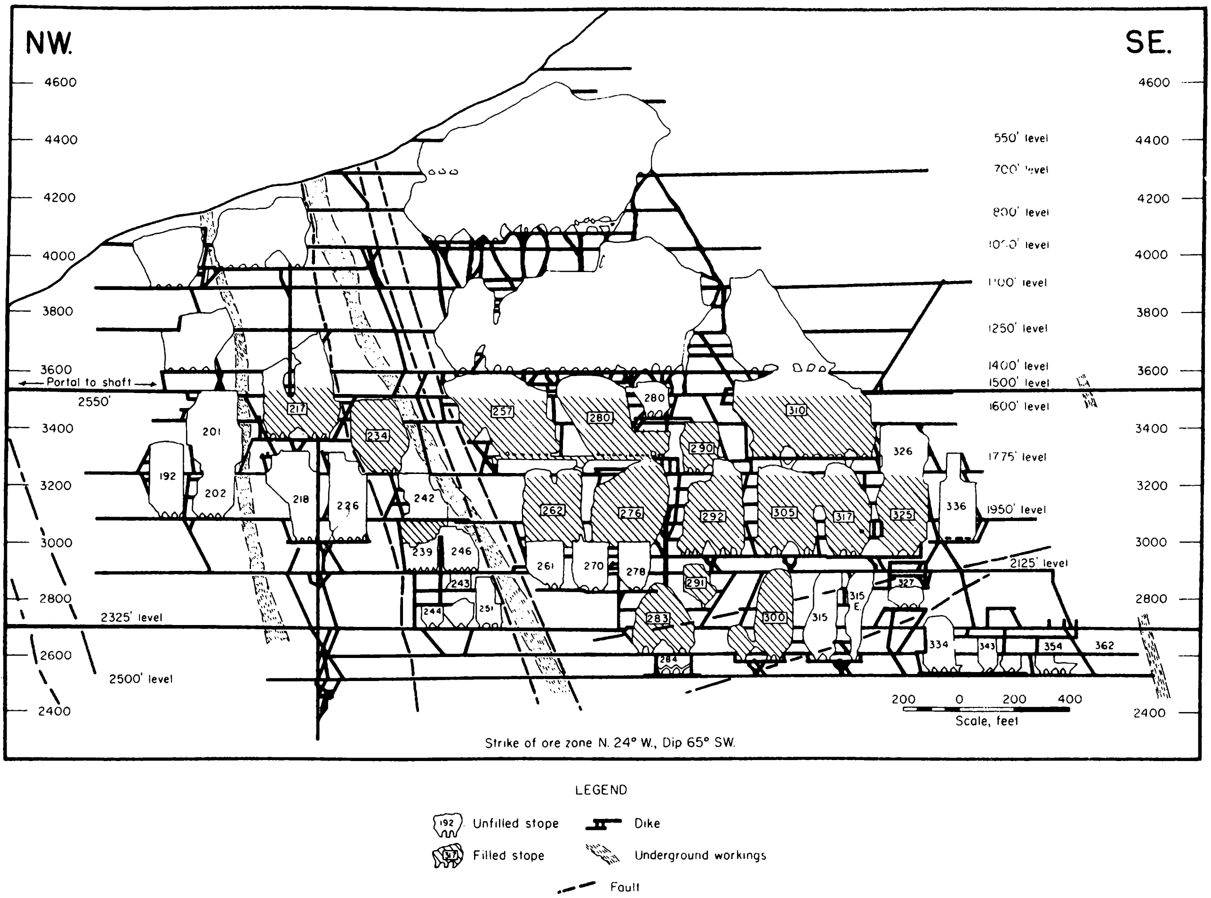


FIGURE 16.—Section Map of an Actual Mine.

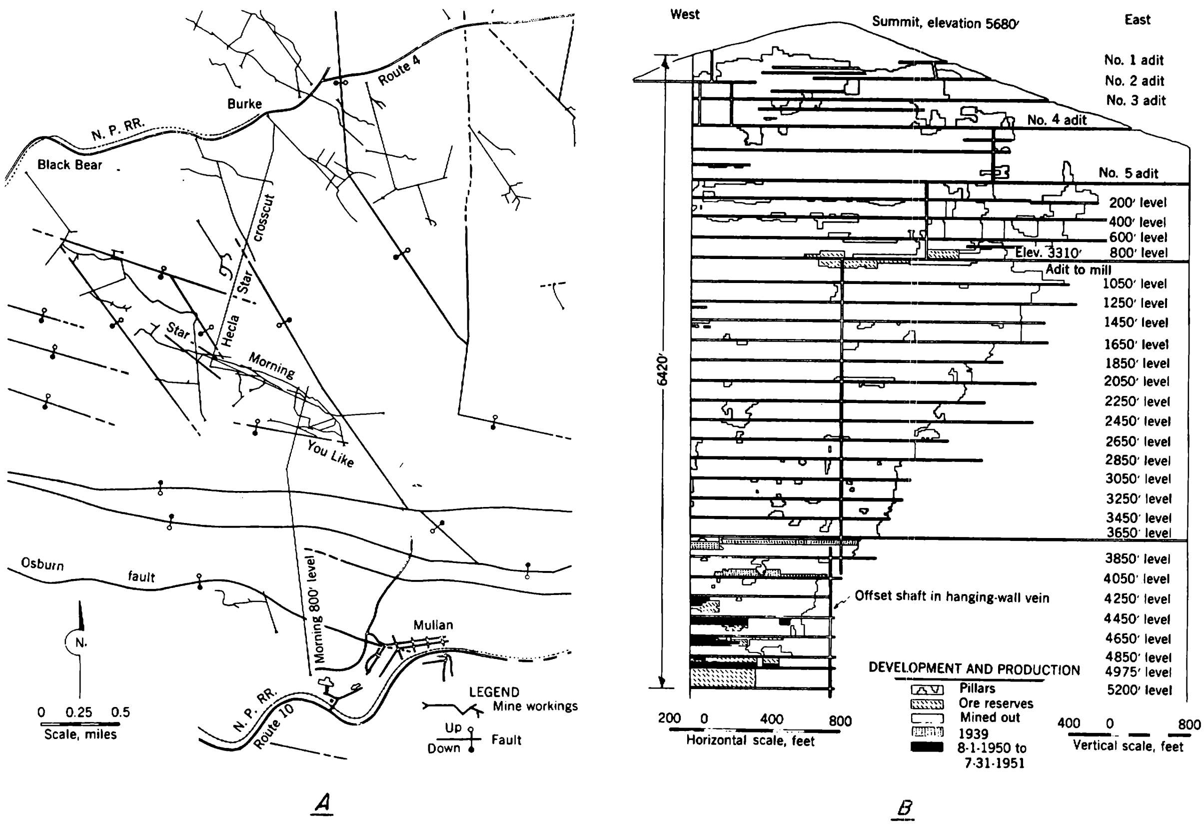


FIGURE 17.—Plan, *A*, and Section, *B*, of an Actual Mine.

the boundaries of the mine workings below the 2450 level would be the most logical choice.

The sketches are intended only to illustrate the use of mine maps and data as a source of information for deductive logic in evaluating a site.

The scaling laws and factors related to underground nuclear detonations are important criteria to an onsite inspection. They will indicate not only logical locations for a detonation site but, with the application of the instrumentation techniques and knowledge of rock mechanics, can furnish evidence important to the physical location and possible identification of a detonation.

Geology and rock properties are directly related to selection of a detonation site, to the physical and chemical effects of a detonation, and to most of the mine-examination techniques that can be applied to onsite inspection. Geology can be equated with scaling laws so far as importance to onsite mine-examination techniques is concerned.

The importance of the remaining examination techniques (surface and underground water, ventilation, mine technology, and waste disposal) is dependent to a large extent on the conditions of an individual site and the possibility of miscalculation, oversight, or carelessness on the part of those conducting a test. Their effectiveness is enhanced because of limited knowledge of the effects of underground nuclear detonations, particularly in different rock types, and the normal human tendency toward carelessness coupled with a requirement or need for documentation of efforts.

Table 5 is a summary of the mine-examination techniques considered by the panel with an evaluation of probable applicability to various types of mine sites.

Thought must be given to the unavoidable confusion in terminology introduced in this table by the word "mine." The table, under the general heading "Type of 'Mine'," refers to a mine in the broad sense taken in this report as any natural or manmade excavation in the earth. However, the subheadings for columns A, B, and C have to be given the conventional designation of a mine for identification. The word "mine" in the subheadings means mine in the conventional sense. Open-pit mines are not listed separately because a test site for emplacement of a device would involve drilling or underground excavation from the pit. In that sense, an open pit can be considered a special type of surface area. Drilled holes and shaft excavation can, of course, be started from within a conventional underground mine or natural cavern. The various inspection techniques listed frequently are interrelated and interdependent; for example, "Underground Transport System" and "Standard Equipment."

TABLE 5.—*Summary and evaluation of inspection techniques* [1 2]

Onsite inspection technique	Type of "Mine": Drilled holes 20 inches or less in diameter			Large-diameter drilled holes or shafts			New-mined excavation for a nuclear test site			Active underground mine			Abandoned or inactive underground mine			Natural cavern			Final test drilling to prove site
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	C
Preliminary high-level aerial photoreconnaissance	2	2	---	2	2	---	2	2	---	2	2	---	2	2	---	2	2	---	------
Preliminary low-level aerial photoreconnaissance	1	1	---	1	1	2	1	1	---	1	2	---	1	1	---	1	2	---	------
Preliminary low-level aerial geophysical surveys	2	2	---	2	2	---	2	2	---	---	---	---	2	---	---	---	---	---	------
Preliminary low-level aerial radioactive monitoring survey	1	1	1	1	1	1	1	1	1	2	1	1	2	1	1	1	1	1	------
Preliminary low-level aerial observation	1	1	---	1	1	---	1	1	---	1	2	---	1	1	--	1	1	---	------
Onsite ground radioactive monitoring survey	1	1	1	1	1	1	1	1	1	---	1	1	2	1	1	2	1	1	1
Ground observation and interrogation	1	1	2	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	------
Area geological study	2	1	2	2	1	2	2	1	2	2	2	---	2	2	---	2	2	---	------
Detailed geological study of specific sites and mines	1	1	2	1	1	2	1	1	1	2	1	1	2	1	1	2	1	1	1
Relating local geology to observed conditions	1	1	1	1	1	1	2	1	1	---	1	1	2	1	1	2	1	1	1
Application of geophysical techniques to a specific mine site	1	1	1	1	1	1	2	1	1	---	1	1	2	1	1	1	1	1	1
Hole logging techniques	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	1
Examining available logs and samples of existing drill holes	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Examination for surface evidence of drilling	1	1	2	1	1	2	2	1	---	2	1	2	2	1	2	---	1	1	------
Examination for underground evidence of drilling	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	------
Instrument surveys to locate drill sites	1	1	1	1	1	1	---	1	1	---	1	1	---	1	1	---	1	1	------
Scaling laws for nuclear phenomena	1	1	1	1	1	1	2	1	1	---	1	1	---	1	1	---	1	1	1
Physical property tests of rock	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	1
Chemical tests of rock	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	1
Analysis of the structural stability of mine opening	---	2	2	--	1	2	--	1	2	---	1	1	---	1	1	---	1	1	------
Microseismic noise monitoring	1	1	1	1	1	1	2	1	1	---	1	1	---	1	1	2	1	1	1
In-situ stress measurements	2	2	2	2	2	2	---	1	1	---	1	1	---	1	1	---	---	---	------
Radioactive and chemical analyses of surface water	1	1	1	1	1	1	---	2	1	---	2	1	---	1	1	---	1	1	------
Radioactive and chemical analyses of underground water	2	1	1	2	1	1	---	1	1	---	1	1	---	1	1	---	1	1	1
Underground water level measurement	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	------
Examination of mine drainage system	---	---	---	---	---	---	---	2	2	---	1	1	---	1	1	---	1	1	------
Condition and adequacy of pumping plant	---	---	---	---	---	---	---	2	2	---	1	---	---	1	---	---	---	---	------
Operating source water	1	2	---	1	2	---	---	---	---	---	2	---	---	2	---	---	2	---	------
Available ventilation system	---	---	---	---	---	---	---	2	---	---	2	---	---	1	---	---	---	---	------
Ventilation survey and comparison with ventilation records	---	---	---	---	---	---	---	1	2	---	1	1	---	1	1	---	---	---	------
Dust analyses	---	---	---	---	---	---	---	---	2	---	1	2	---	1	1	---	1	1	------
Gas analysis	---	---	---	---	---	---	---	1	1	---	1	1	---	1	1	---	1	1	------
Evidence of access on the surface	1	1	2	1	1	2	1	2	2	1	2	---	1	2	---	1	2	---	------
Evidence of access underground	---	---	---	---	---	---	---	1	1	---	1	2	---	1	1	---	1	1	------

See footnotes at end of table.

TABLE 5.—*Summary and evaluation of inspection techniques* [1] [2]—Continued

Onsite inspection technique	Type of "Mine"																		Final test drilling to prove site
	Drilled holes 20 inches or less in diameter			Large-diameter drilled holes or shafts			New-mined excavation for a nuclear test site			Active underground mine			Abandoned or inactive underground mine			Natural cavern			
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	C
Surface transport system	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	1	1	---	---
Underground transport system	---	---	---	---	---	---	---	1	---	---	1	2	---	1	1	---	1	1	---
Haulage and hoisting records	---	---	---	---	---	---	---	1	1	---	1	2	---	---	---	---	---	---	---
Mine maps	---	---	---	---	---	---	---	1	1	---	1	1	---	1	1	---	---	---	---
Mine design	---	---	---	---	---	---	---	1	1	---	1	1	---	1	1	---	---	---	---
Mine surveying	---	---	---	---	---	---	---	1	1	---	1	1	---	1	1	---	---	---	---
Mine sampling	---	---	---	---	---	---	---	1	---	---	1	---	---	1	---	---	---	---	---
Standard practices, equipment, and supplies	---	---	---	---	---	---	---	1	---	---	1	---	---	---	---	---	---	---	---
Waste disposal	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	---	1	1	---
Rock support	---	---	---	---	---	---	---	1	1	---	1	2	---	1	1	---	1	1	---
Damage to rock support	---	---	---	---	---	---	---	1	1	---	1	1	---	1	1	---	1	1	---
Mine accounts and records	---	---	---	---	---	---	---	1	---	---	1	2	---	---	---	---	---	---	---
Mill accounts and records	---	---	---	---	---	---	---	1	---	---	1	---	---	---	---	---	---	---	---
Safety activities and records	---	---	---	---	---	---	---	1	---	---	1	---	---	---	---	---	---	---	---
Power facilities	1	1	2	1	1	2	---	1	---	---	1	2	---	1	1	---	1	1	---
Mine plant facilities	1	1	2	1	1	2	---	1	---	---	1	---	---	1	---	---	1	---	---
Supporting plant facilities	1	1	2	1	1	2	---	1	---	---	1	---	---	1	---	---	1	---	---
Supplementary techniques	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	---

[1] "A" equals relative usefulness to initially locate a "mine" site. "B" equals relative usefulness to indicate a possible test site. "C" equals relative usefulness to indicate source and/or identify a seismic disturbance.

[2] "1" equals major importance; "2" equals secondary or limited importance; leaders indicate no application.

RECOMMENDED RESEARCH

Much research can be performed that would enhance ability to detect clandestine, subsurface nuclear explosions. Many of these are beyond the immediate scope of this study but difficult to separate from it because of the obvious interrelationship between detection and investigation techniques; for example, the primary and most obvious field in which research is needed is seismology. Judging from published information, much can be done to improve the sensitivity of detecting shock waves through the design and use of more sensitive detectors, study of the optimum numbers and arrangement of detectors in a seismic array, experimentation with detectors at both higher and lower frequencies, and deep-hole detection. Perhaps even more important is research on the interpretation of seismic data, both theoretical and actual. It is possible that intensive research on seismic-noise surveying will reveal pertinent information on earth noises caused by residual stresses and strains for some time following a subsurface nuclear or chemical explosion.

Much research could be done in the field of radioactivity detection and analysis, particularly in logging methods. Beta logging should be a valuable technique in investigating subsurface nuclear phenomena. There are difficulties inherent to the design of a practical beta-logging tool; however, they are not insurmountable.

Considering the present refinement of logging tools and services within the petroleum industry, it is reasonable to expect that applied research on subsurface instrumentation would result in the development of a single logging unit capable of making gamma, neutron-gamma, beta, spectral, electrical, thermal, sonic density, and other desirable types of logs through the exchange of logging probes and surface integrating and recording instruments.

Research should be performed on the utility of aerial, surface, and subsurface instruments adapted to analyzing phenomena associated with underground openings and explosions and, particularly, nuclear explosions. In addition to seismic and radioactivity instruments described above, gravimetric, magnetic, electromagnetic, electrical, radiofrequency, thermal, and acoustic instrumentation all justify further research and study to determine the limits of applicability to the problem.

Listed are specific recommendations for onsite techniques:

1. The total absence of any practical experience in conducting onsite investigations for clandestine nuclear tests precludes realistic evaluation of present capabilities. Learned opinion ranges present capability and future potential anywhere from 0 to 100 percent effective. Accordingly, testing this capability with presently available tools and techniques is suggested as the most effective means of giving direction and purpose to future research on instrumentation, techniques, tools, or concepts. It is specifically recommended that realistic exercises involving both the conduct of clandestine tests (simulated) and their investigation be given a first priority of attention.

2. Knowing that various agencies, institutions, and individuals have sought and accumulated various data on mining, petroleum and gas production, geology, major construction, and equipment development throughout the world, the panel was concerned with its inability to find and assess the value of such information on short notice. It is recommended that single responsibility be fixed for physically assembling data that might be significant for classification of areas adaptable to clandestine testing and for production of analyses that would expedite and facilitate onsite inspection. The panel considers this recommendation valid, even in the absence of any international agreement. The recommendation recognizes that similar data are being collected by other agencies for other purposes, and it is not proposed that this operation would substitute for or interfere with the continuance of such activities.

3. Similarly, responsibility should be fixed for analysis and appraisal of the mineral industry of the world with onsite inspection in mind. Special attention should be given to studies of mining practices little known in the United States and to theoretical and laboratory research being conducted by other nations. Regular dissemination of such information in the form of quarterly publications among professional engineers and mining companies would lead to better utilization of both private and government funds available for research.

4. Seismic-noise monitoring presents interesting possibilities for detecting underground nuclear detonation sites by the noise of caving rock. Various ranges of frequencies should be tested for their capability in different rock formations. Frequency ranges of 1,000 to 1,500 c.p.s. appear very promising.

5. More work is necessary on the elastic properties of rocks. This is needed for predicting the competency of rocks to support large cavities that may be used for decoupled detonations.

6. Information is needed on the slabbing or rock burst problem and how it relates to similar damage caused by explosion force on free face of mine openings.

7. It is necessary to know more about absolute stress in rocks and how they will react if subjected to added stress of an underground nuclear detonation.

8. More information is needed on the close-in seismic effects of nuclear detonations underground.

9. More needs to be known on the potential solubility of fission and other radioactive products in rocks other than tuff. This may increase the target area when drilling to discover a clandestine detonation.

APPENDIX—GENERAL BACKGROUND ON MINING

A conventional mine may be an open excavation on the surface or it may be underground, in which case it is entered either through a shaft (vertical or inclined opening downward), or an adit or tunnel (horizontal opening into the side of a mountain). The use of drilled holes or wells to extract petroleum, brines, and sulfur, and for solution mining of various salts is a type of mining and although it is not common practice, the hole or well could be termed a mine.

It is important to recognize here that the ultimate purpose of an excavation has a most significant influence on the development method employed, the design, and the location. In this sense there is a vast difference in design criteria between excavations planned primarily for the purpose of exploiting a mineralized substance and excavations incidental to some construction projects such as railroad tunnels, aqueducts, and security sites. While economic considerations are important to both, they are critical in the first instance. Here the excavation has a value only in that it accomodates an effective extraction process to exhaustion of the substance sought. Collapse thereafter may be of minor consequence and in fact encouraged, provided that unrelated surface works are not affected. Essentially the economics of mining for mineral substance are inevitably related to an effective system of getting in and getting out in a planned period of time. Thereafter the remaining excavation is normally a liability rather than an asset. Ideally, the economics of mineral mining are improved with a reduction in the investment of materials and devices employed to support the subsurface openings to the point where these are effective only to the exhaustion of the substance sought. Accordingly, the design of the excavation as well as the methods of support enter into such planning. Where the purpose of an excavation is for some purpose other than mineral exploitation, the economic and design criteria are entirely different and should be immediately obvious.

Mineral deposits, in the broad sense, are found virtually everywhere in the land masses of the earth and to some extent in and under the oceans and seas. Mining sites are determined by geologic conditions that favor concentration of mineral; by local demand, such as that occasioned by population centers that require large quantities of common mineral commodities like crushed rock, clay, and other construction or chemical materials; or by economic factors, such as commodities like coal or salt being favorably located with respect to the surface.

In general, deep, large-diameter drilling is practiced principally in oil-productive (including natural gas) areas or for petroleum exploration in areas in which geologic, structural, geophysical (including seismic), and other information suggest that petroleum might be found. Exceptions to this are areas in which minerals are extracted by solution mining, or brine is produced for minerals extraction, and areas in which liquefied petroleum gas or other products are stored underground. Drilling activity may be expected in some localities for water supplies and waste disposal.

Minerals are concentrated in deposits by geological processes. Conditions differ according to the type of mineral and mode of occurrence. Thus, coal, salt, and limestone are deposited in beds, and metallic minerals are disseminated in relatively massive rocks, or are deposited in seams in many types of rocks. Liquids such as water and oil are contained by porous rocks.

The geological and physical conditions of the mineral deposit have a major influence on the layout and design of a conventional mine. Table 6 lists many of the characteristics of the earth formations that may have to be con-

TABLE 6.—*Physical characteristics of earth formations*

- I. Quality:
  - A. Grade,
  - B. Rank, and
  - C. Mineral association.
- II. Extent:[1]
  - A. Size:
    - 1. Specific dimensions:
      - a. Length,
      - b. Height, and
      - c. Width.
    - 2. Comparative dimensions:
      - a. Small,
      - b. Medium, and
      - c. Large.
  - B. Shape—descriptive:
    - 1. Ellipsoidal,
    - 2. Lenticular,
    - 3. Tabular,
    - 4. Irregular.
    - 5. Horsetail, and
    - 6. Pipelike.
  - C. Continuity:
    - 1. Continuous:
      - a. Uniformly, and
      - b. Pinching and swelling.
    - 2. Discontinuous:
      - a. Offset, and
      - b. Eroded.
    - 3. Massive:
      - a. Uniformly, and
      - b. Irregular.

TABLE 6.—*Physical characteristics of earth formations*—Continued

III. Position:[1]
- A. Geographical.
- B. Relative to topography.
- C. Attitude:
  1. Strike,
  2. Dip, and
  3. Pitch.
- D. Overburden—overlying unconsolidated rock.
- E. Capping—overlying solid rock.
- F. Boundary limits:
  1. Hanging wall and footwall,
  2. Roof and floor, and
  3. Limitation by grade and quality.
- G. Included bodies of waste.

IV. Structure:
- A. Structures imposed by a dynamic earth stress:
  1. Fractures (common to all rock types):
     - a. Joints,
     - b. Fracture cleavage (including shear and bedding cleavage), and
     - c. Faults and contemporary associated features.
  2. Flextures (common to sedimentary and metamorphic rocks):
     - a. Domes, noses, basins, and
     - b. Linear folds.
  3. Intrusive structures (occur in all rock types):
     - a. Dikes and sills (igneous), and
     - b. Other intrusives (igneous).
  4. Petrofabric—foliation (secondary)—the ability of rocks to break along approximately parallel surfaces:
     - a. Flow cleavage—parallel orientation of platy minerals such as micas and chlorites, or of elongate minerals, such as hornblende:
       - (1) Slaty,
       - (2) Schistose, and
       - (3) Gneissose.
     - b. Lineation (secondary)—parallelism of minerals constituting the rock. Usually lies in same plane as foliation. Does not show cleavage break.
- B. Inherent formation structures:
  1. Rock alteration (affects all rocks)—by hot or cold solutions or weathering or by heat and pressure.
  2. Stratification (common to sedimentary rocks).
  3. Extrusive structures (igneous):
     - a. Vesicular, and
     - b. Amygdaloidal.
  4. Petrofabric—foliation (primary):
     - a. Lamination (sedimentary rocks)—bedding plane fissility.
     - b. Extrusives (flow structure).
     - c. Intrusives:
       - (1) Platy flow structure, and
       - (2) Primary lineation (parallelism through prismatic mineral orientation. No cleavage break visible).
  5. Vugs (common to all rocks).

V. Associated natural phenomena:
- A. Surface water:
  1. Location and flow,
  2. Quantity, and
  3. Quality.
- B. Ground waters:
  1. Classification:
     - a. Pore water,
     - b. Fissure water, and
     - c. Cavern water.
  2. Hydrologic properties:
     - a. Porosity,
     - b. Specific yield,
     - c. Specific retention,
     - d. Specific absorption, and
     - e. Permeability.
- C. Natural gases—types:
  1. Methane,
  2. Carbon dioxide,
  3. Hydrogen sulfide, and
  4. Nitrogen.

VI. Mechanical properties:
- A. Apparent specific gravity.
- B. Apparent porosity.
- C. Compressive strength.
- D. Tensile strength.
- E. Flexural strength (modulus of rupture).
- F. Impact toughness.
- G. Abrasive hardness.
- H. Scleroscope hardness.
- I. Elastic constants:
  1. Modulus of elasticity (Young's modulus),
  2. Modulus of rigidity,
  3. Apparent Poisson's ratio,
  4. Specific damping capacity, and
  5. Longitudinal bar velocity.

[1] Extent and position are more often established by actual measurement and mapping.

sidered. The size, extent, attitude, and depth below the surface are obvious influencing factors. The physical condition of the rock itself is a major factor in determining the method of mining.

Other factors that affect the type and kind of mining in a specific locality are the culture and industrial background. Mineral development and exploration are at various stages of maturity in different countries. The technology and administration of mines generally reflect the national character of their development, either provincial, by outside nationals, or more frequently a mixture of both. This background factor is reflected in such items as type and grade of mineral exploited, method of mining, labor, equipment, supervision, management practices, and marketing.

The necessary structures, supply areas, shop, storage, office buildings, and transportation facilities are generally part of the mine plant. Where the ore is crushed, ground, and a concentrate of the valuable mineral removed from the bulk of the rock, which is rejected as tailing, there will be a second group of structures comprising the mill or concentrating plant. Sometimes the mine plant and the concentrating plant are separated, and some form of transportation from mine to mill is provided. For some minerals, such as copper or lead, a smelting plant is built, and the concentrate is further reduced to metal, which is sent to a refining plant located near a population center and source of cheap power.

A mining operation must be located where the deposit of mineral is found. This location is often in an isolated place where other activities are limited. As a result, employee housing, stores, supply centers, schools, churches, social centers, powerplants, and utilities systems are built around the mine plant. Until an ore body is exhausted, the activity at a mine plant is relatively uniform, and a well-developed transportation network evolves from population center to mine entrance, dumps, shops, and other points of activity.

Evidence of oil-drilling activity in the United States might not be the same as in other countries, especially if efforts were made to conceal activities. In this country a drilling area, particularly one under current extensive exploration or development, is characterized by pipe yards, oilfield equipment, stores, well-servicing companies, oil-company vehicles and large trucks, and many personnel easily identified with their occupations by appearance, actions, and habits.

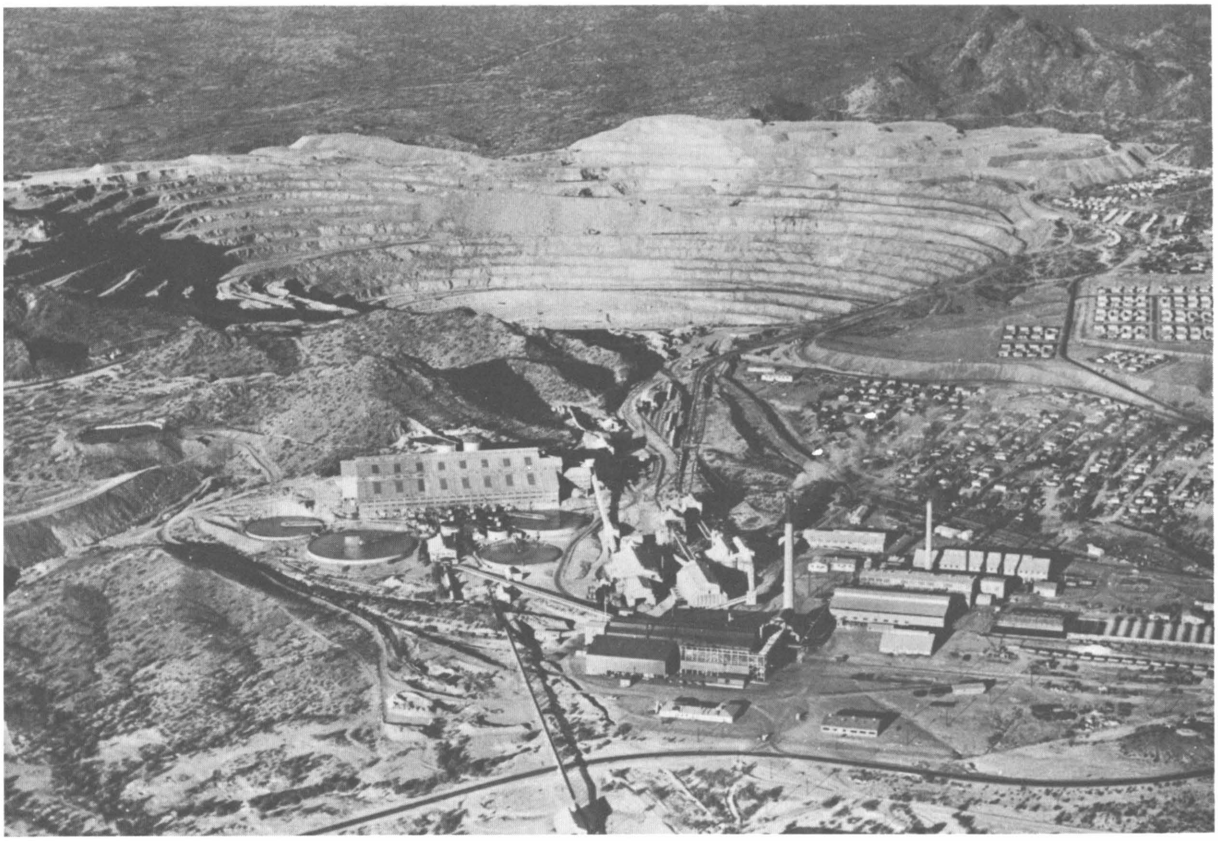


Figure 18.—Opencut Mine.

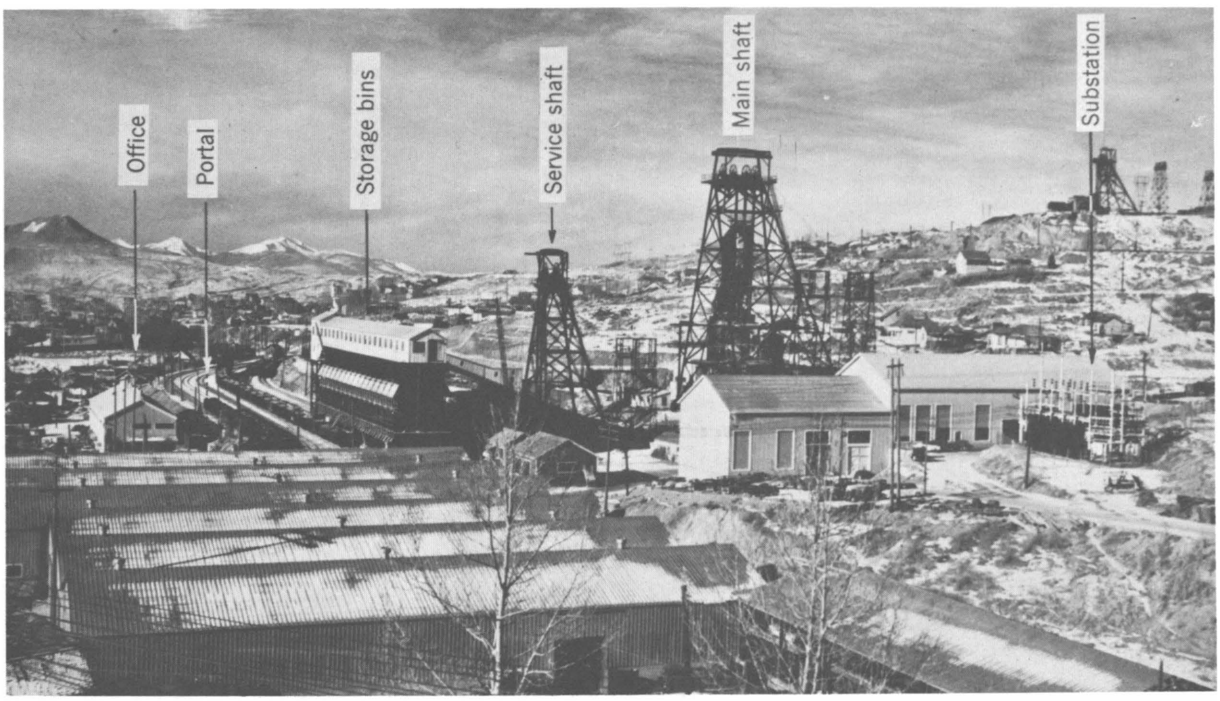


Figure 19.—Surface Plant for Large Underground Mine.

Exploitation of a mineral deposit follows a general pattern of: (1) Exploration, (2) development, and (3) mining or production. The two major classifications of mining are (1) surface (fig. 18) and (2) underground (fig. 19). These are commonly further subdivided into the classifications shown in table 7.

TABLE 7.—*Classification of mining methods*

- I. Surface mining methods:
  - A. Placer mining:
    - 1. Hydraulicking, and
    - 2. Dredging.
  - B. Open pit and quarry:
    - 1. Single bench, and
    - 2. Multiple bench.
  - C. Glory hole.
- II. Underground mining methods:
  - A. Stopes naturally supported:
    - 1. Open stopes without pillar support:
      - a. Open stopes in small ore bodies, and
      - b. Sublevel stopes.
    - 2. Open stopes with pillar supports:
      - a. Irregular pillars, and
      - b. Regular pillar arrangement.
  - B. Stopes artificially supported:
    - 1. Open stopes:
      - a. Rock bolted, and
      - b. Stulled.
    - 2. Shrinkage:
      - a. With pillars,
      - b. Without pillars, and
      - c. With subsequent waste filling.
    - 3. Cut and fill.
    - 4. Square-set (and fill).
  - C. Caved stopes:
    - 1. Caving:
      - a. Block,
      - b. Sublevel, and
      - c. Longwall.
    - 2. Top slice.
  - D. Combined methods.
  - E. Solution methods.

Excavation in a mine is done by repeated cycles of (1) breaking the material from its in-place position (usually accomplished by drilling and blasting), (2) loading the material for transport (mucking), and (3) transporting the material from the mine (hauling and hoisting). The major items of mine technology and their general relationship are shown in figure 20.

The most important factor determining choice between surface and underground mining is the position of the deposit relative to the surface. The choice is basically one of economics, which is demonstrated by an old but reasonably reliable rule of thumb that the border between open-pit and underground metal mining is a waste-ore ratio of 3 to 1. Because the principles of surface mining are relatively simple and visible to inspection, they are more widely understood than underground mining.

Underground mining is usually more complex than surface mining, less visible to an observer, and, therefore, not as easy to comprehend.

The exploration stage uses similar technology for any type of mining, and a single project may utilize one technique or any combination of several. Field parties may conduct location, geological, geochemical, or some type of geophysical survey. Work may include sampling, trenching, test pitting, and exploration drilling. When surface testing and drilling prove the existence of an ore body, further exploration may be done by driving tunnels or shafts to confirm ore grade and provide large volume samples for testing. Figure 21 shows a typical exploration core drill setup.

Success in the exploration project will result in development and exploitation of the deposit. Open-pit development consists of stripping the overburden and establishing access and pit benches necessary for removal of the ore. Underground development consists of providing access entries to the ore body and driving underground openings required for the planned mining method and removal of the ore. Figure 22 illustrates a section and plan of development for a block-caving operation.

The entrance to an underground mine may be either a vertical or an inclined shaft, horizontal adit or tunnel, or a combination of these. The shaft may be round, square, or rectangular in cross section. The exact size and arrangement of compartments depend on designed purpose of the opening. Method of arranging compartments in a shaft is shown in figure 23.

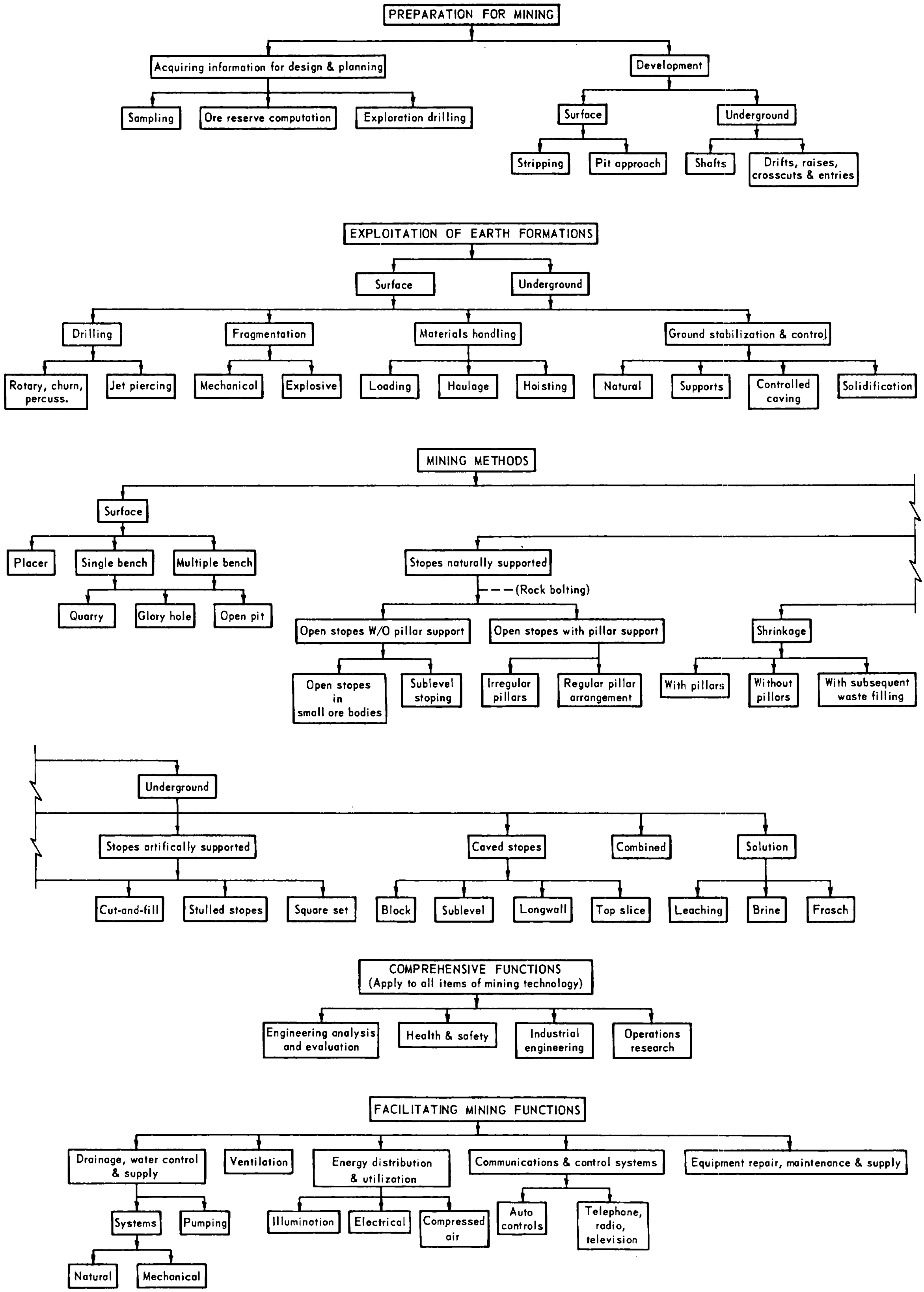


FIGURE 20.—Mining Technology Flowsheet.

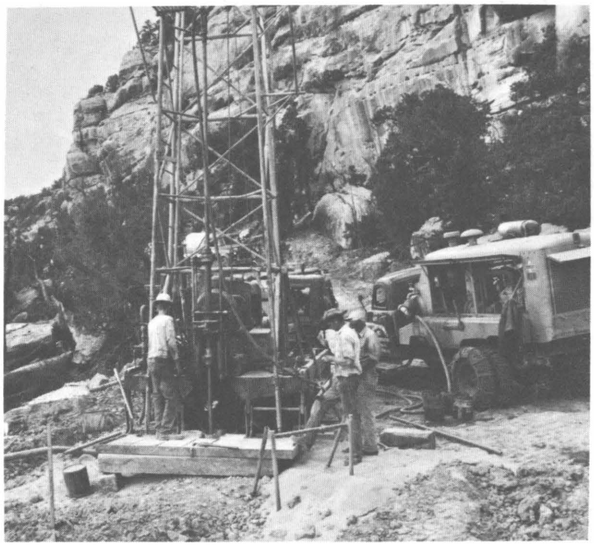


FIGURE 21.—Mineral Exploration by Core Drilling.

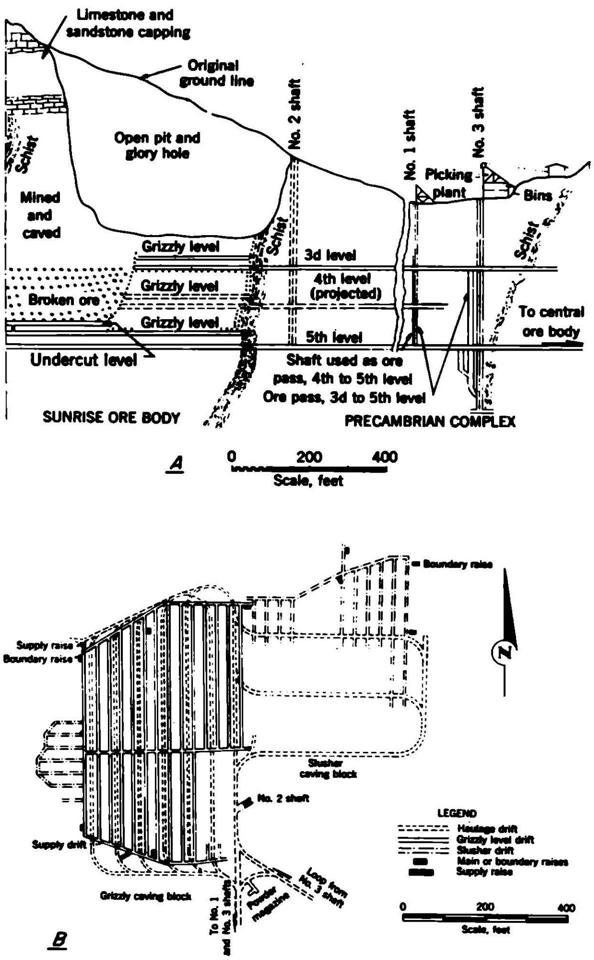


FIGURE 22.—Section, *A*, and Plan, *B*, of Development for Block Caving.

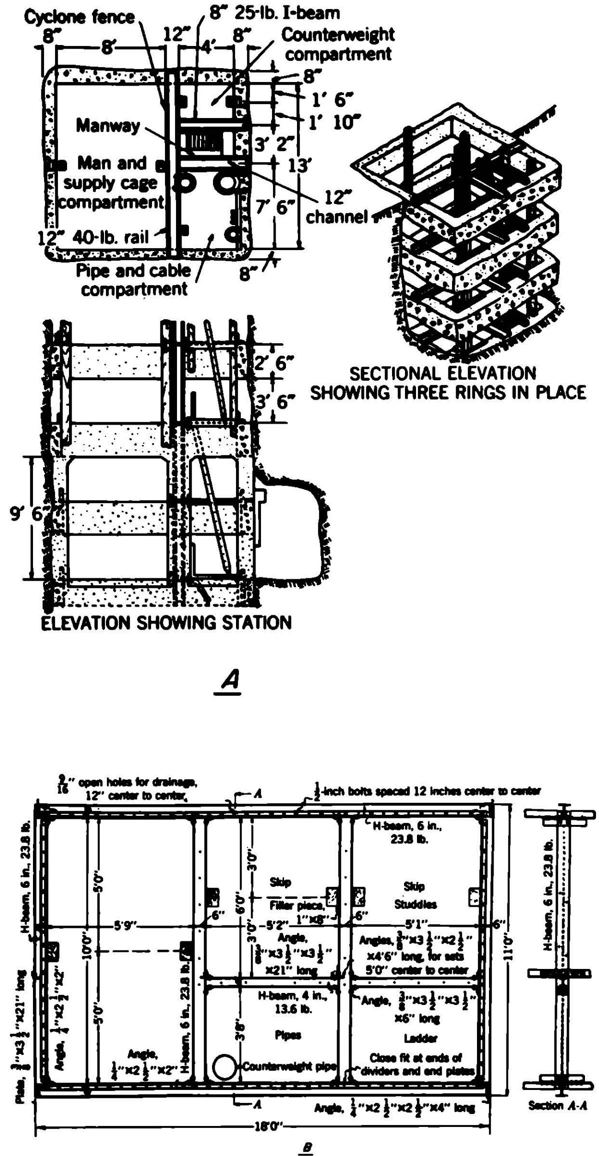


FIGURE 23.—Arrangement of Compartments in a Shaft: *A*, Service Shaft With Concrete Sets; *B*, Hoisting Shaft With Steel Sets.

Two types of openings are usually required for underground mining: (1) Development openings (shafts, tunnels, drifts, raises, cross-cuts); and (2) extraction openings (stopes). Extraction openings designate the classification of underground mining methods. (See table 7.) Stopes may vary widely in size, attitude, and specific detail of design and practice, even within a single classification, but the general characteristics have universal application throughout the world. The principal classification is based on type of ground support required, which in turn is dependent on condition of the ground. The three major divisions are: (1) Naturally supported stopes, (2) artificially supported stopes, and (3) caved stopes. Figures 24 to 30 illustrate some of the more common stoping methods for each of the three major divisions.

It is impossible to classify or state definite limits on the type, size, attitude, and extent of mine workings related to a specified commodity, geologic condition, or surface expression of mineral deposits. There are exceptions to any stated condition; however, certain general statements can be made to specify a normal pattern.

1. The more economical open-pit method of mining is used to extract mineral deposits near the surface. The ratio of waste to ore is the determining factor. The depth of surface mining operations ranges from a few feet to 2,000 feet. Quarries and single-bench workings will rarely extend beyond a depth of 150 feet. Multiple-bench open pits, common in metal mining, usually have a depth range of 200 to 600 feet.

The depth of underground mines ranges from less than 200 feet below the surface to more than 10,000 feet. Underground workings extend laterally for tens of miles in some areas where individual mines interconnect, and a single large mine may have several hundred miles of underground passageways. Figure 31 is a section of several large mines with interconnected underground workings.

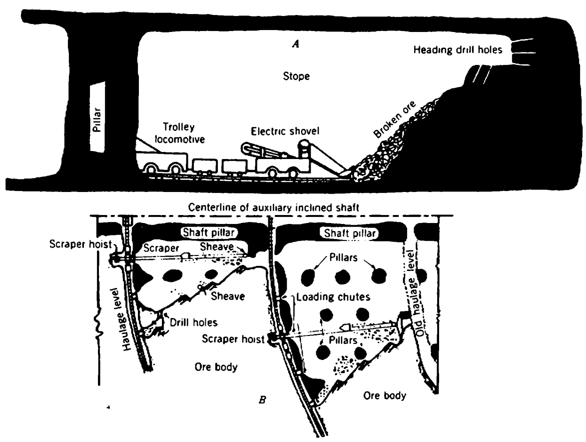


FIGURE 24.—Naturally Supported Stopes, Room and Pillar.

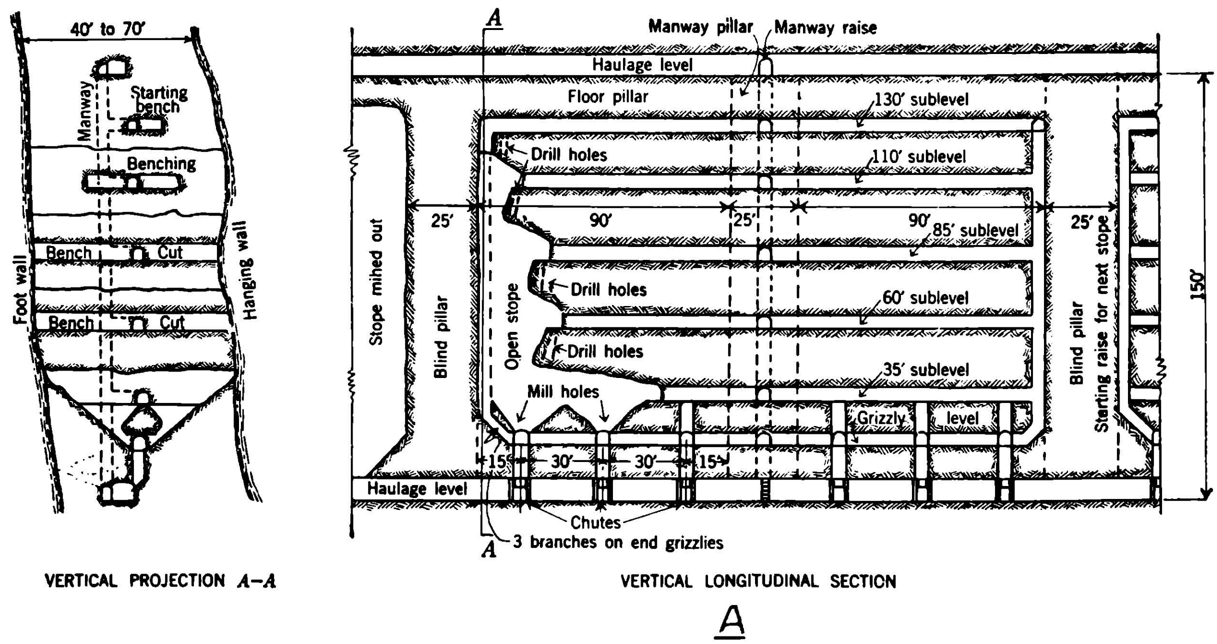
2. Other generalizations can be made on the relationships of type of deposit, depth, and method of mining. Flat-lying tabular or bedded deposits are usually mined at relatively shallow depth (less than 1,000 feet) by some type of room-and-pillar method. Examples are limestone, coal, salt, gypsum, potash, and some lead-zinc and iron deposits. The mine workings are of limited vertical extent but often are very extensive laterally.

Steeply dipping tabular or bedded deposits and vein deposits are often deep and of limited lateral extent. Many variations of mining methods may apply but usually some type of open stoping or artificially supported stoping is used. Sublevel open stopes, cut-and-fill, and shrinkage stoping are commonly applied. The deepest mines fall in this group, and depths of 5,000 feet or more are not uncommon. The gold mines in South Africa and India are more than 10,000 feet deep.

3. A final grouping includes large, massive deposits (usually low grade) that are amenable to caving. The usual method of mining is by block caving or sublevel caving. Mines of this type usually range from a depth of 1,000 to 3,000 feet.

Although there are variations depending on local conditions, the mining cycle follows a general pattern. Blastholes are drilled in the rock, usually in a predetermined pattern. The holes are loaded with explosives and blasted. The new rock surface is scaled (barred down) to remove loose rock. The blasted material is loaded into a transport unit and moved out of the mine to the surface. As the underground openings are advanced, the necessary artificial support is installed, and provisions are made to advance utilities such as ventilation, rail, and power, up to the working face.

Drilling and loading holes for blasting in a development heading are shown in figures 32*A* and 32*B*, and stope drilling is shown in figure 33. Figure 34 shows rock blasted in a development heading (muck pile) and a miner barring down loose rock. Other methods of scaling are shown in figures 35*A* and 35*B*. Artificial ground support may be provided by timber, steel, concrete, or roof bolts. Figures 36 and 37 show principal methods of ground support. Two principal methods of loading rock into cars—machine and chute—are illustrated by figures 38*A* and 38*B*. Rail, truck, and conveyor haulage are shown in figures 39 *A*, *B*, and *C*, and a typical hoisting arrangement is shown in figure 39*D*.



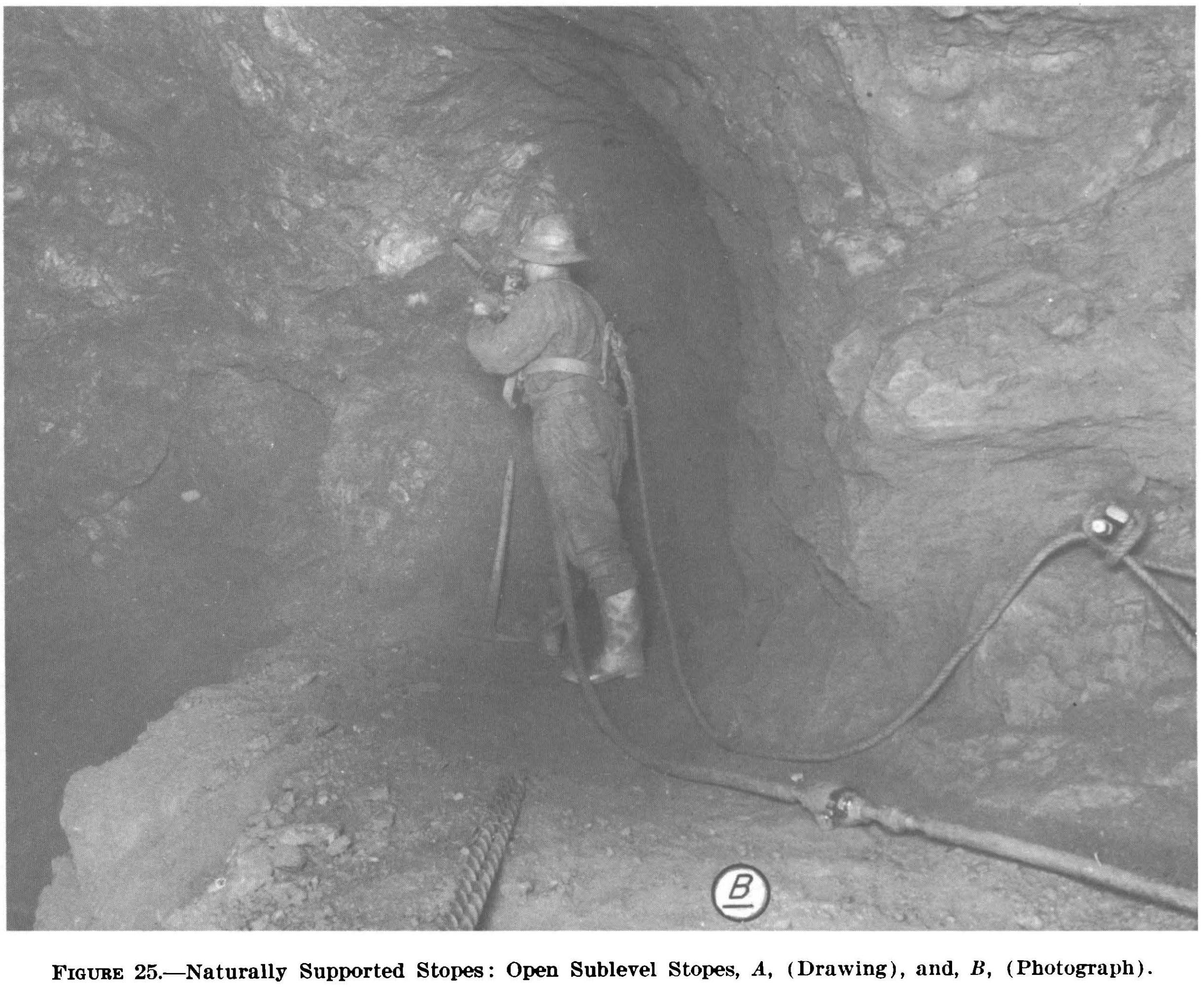
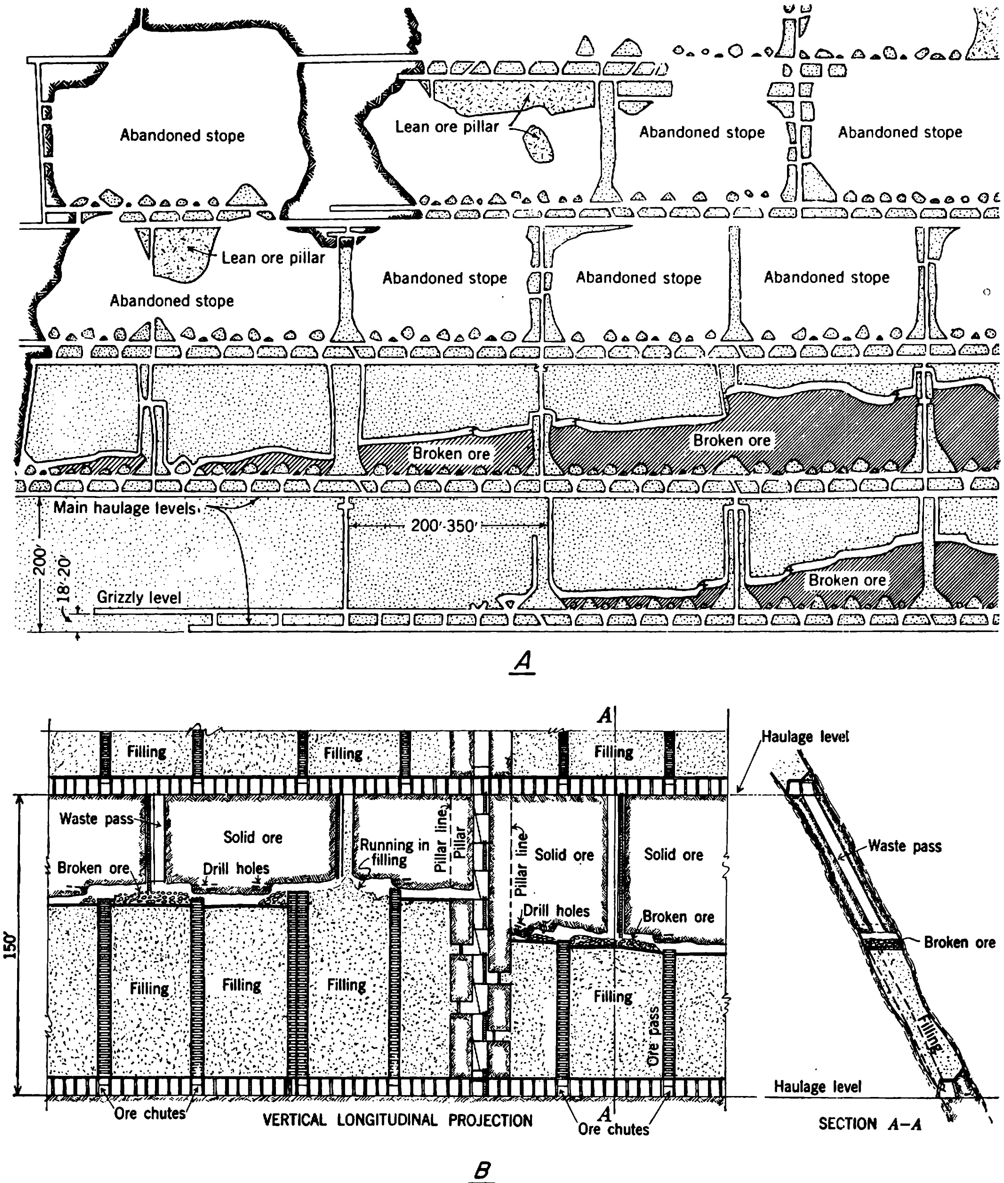


FIGURE 25.—Naturally Supported Stopes: Open Sublevel Stopes, *A*, (Drawing), and, *B*, (Photograph).



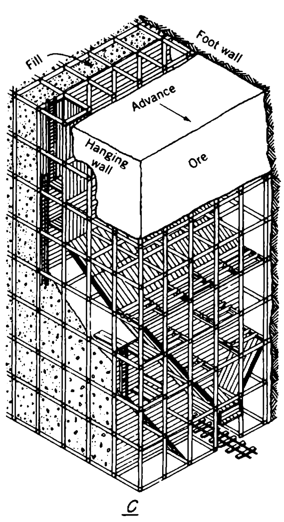


FIGURE 26.—Artificially Supported Stopes: *A*, Shrinkage; *B*, Cut and Fill; *C*, Square Set.

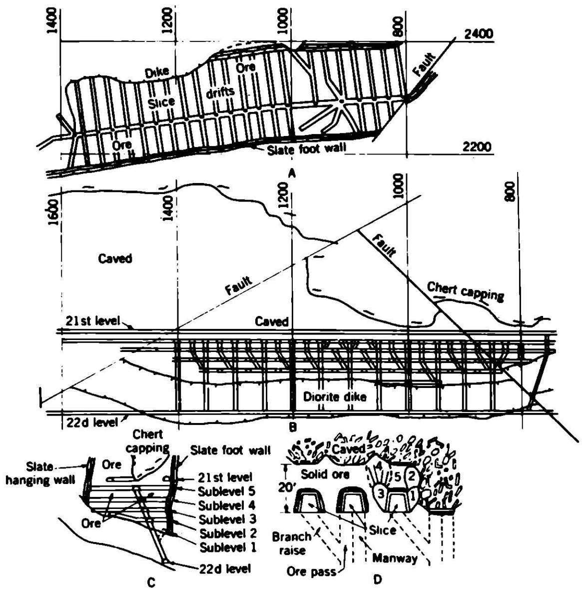


FIGURE 27.—Caved Stopes—Sublevel Caving: *A*, *B*, and *C*, Development of Ore Body for Caving; *D*, Cross Section Showing Details of Caving Back—Cuts Blasted in Order Shown.

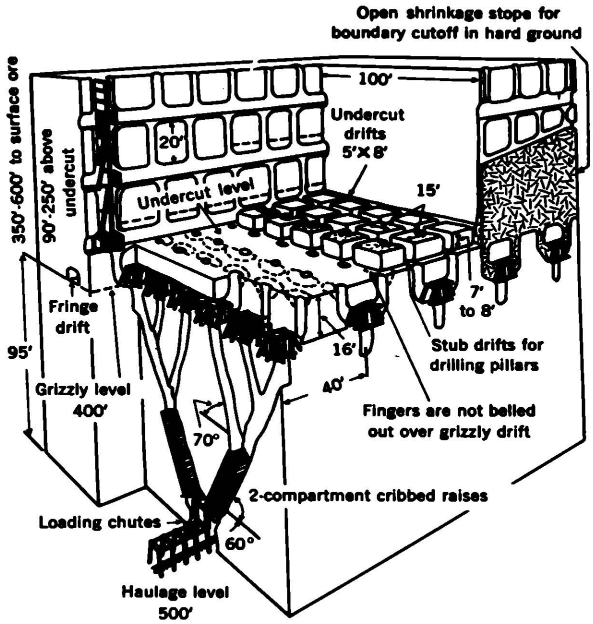


FIGURE 29.—Caved Stopes, Block Caving.

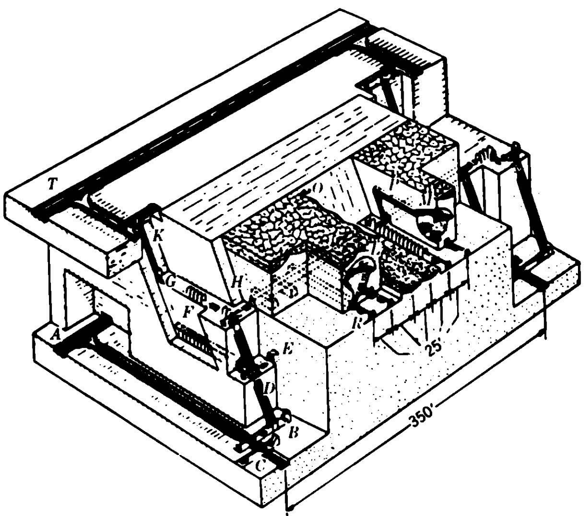


FIGURE 28.—Caved Stopes—Sublevel Caving and Tramcar Loading, Using Slushers: *A*, Main Haulage Level; *B*, Tramcar Loading Drifts From West Raise; *C*, Tramcar Loading Drifts From East Raise; *D*, Ore Raise and Manway; *E*, Transfer Drift—50-Foot Substarting Development; *F*, Ventilation and Supply Crosscuts, 50-Foot Sub; *G*, Ventilation and Supply Crosscuts, 1,000-Foot Sub; *H*, Transfer Drift, 100-Foot Sub; *K*, Ventilation and Supply Raise; *L*, Cross Section of Stope; M, Longitudinal Section of Stope and Manway; *O*, Caved Gob; *P*, Manway to Stope; *R*, Stoping Crosscuts 20 to 120 Feet Long; *T*, Former Haulage Level—Now Used for Ventilation, Manway, and Supplies.

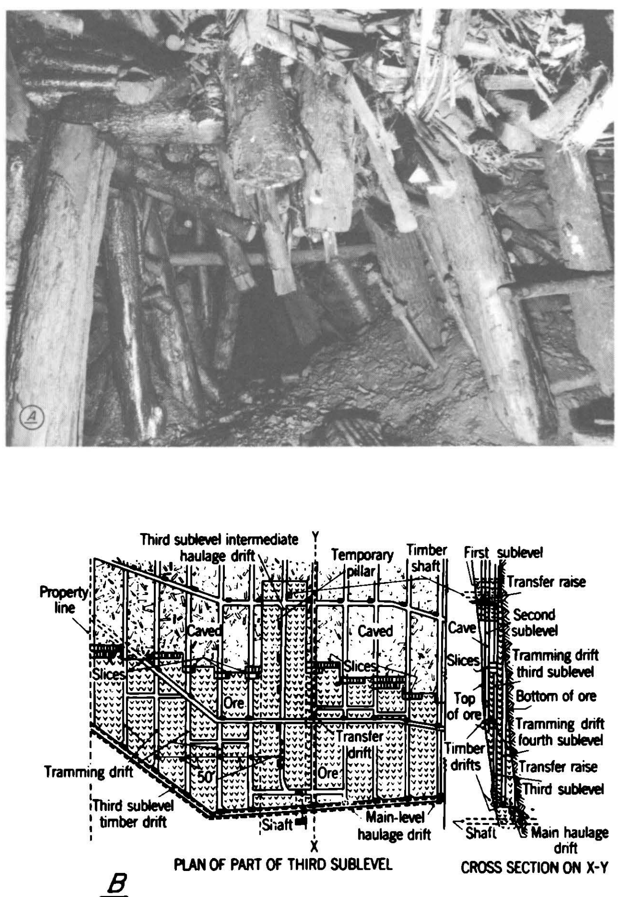


FIGURE 30.—Caved Stopes, Top Slicing: *A*, Photograph; *B*, Drawing.

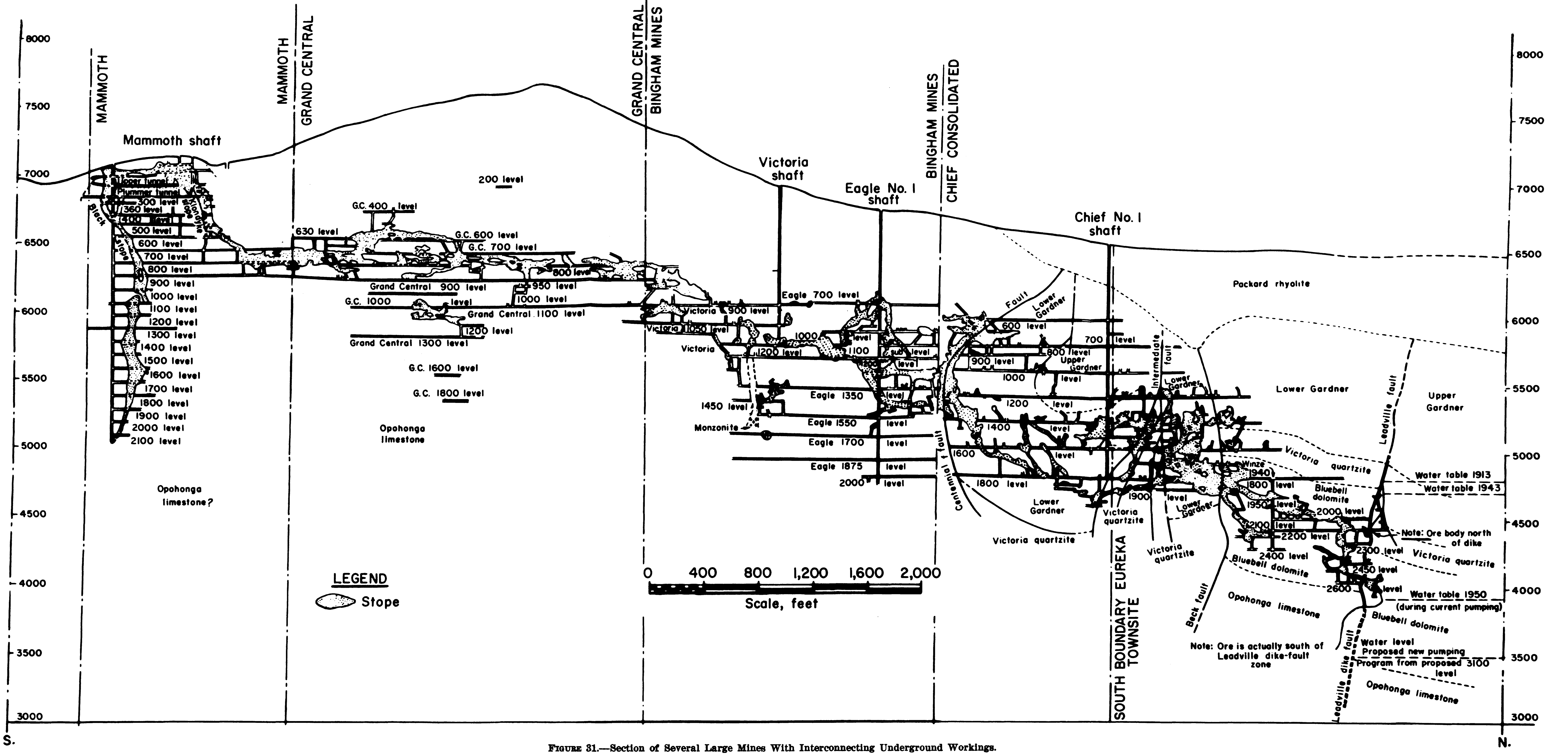


FIGURE 31.—Section of Several Large Mines With Interconnecting Underground Workings.

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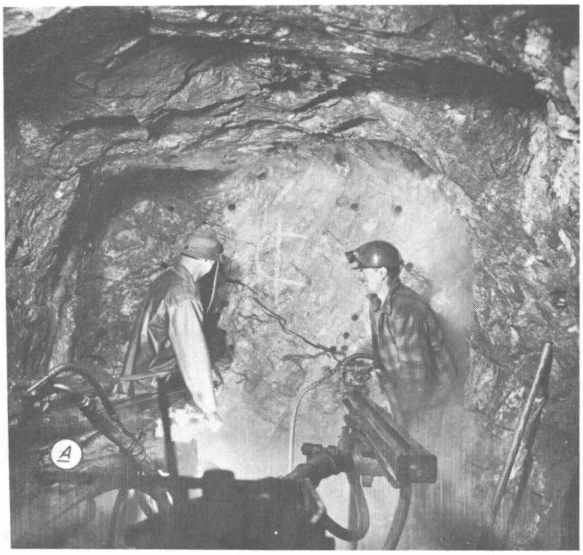

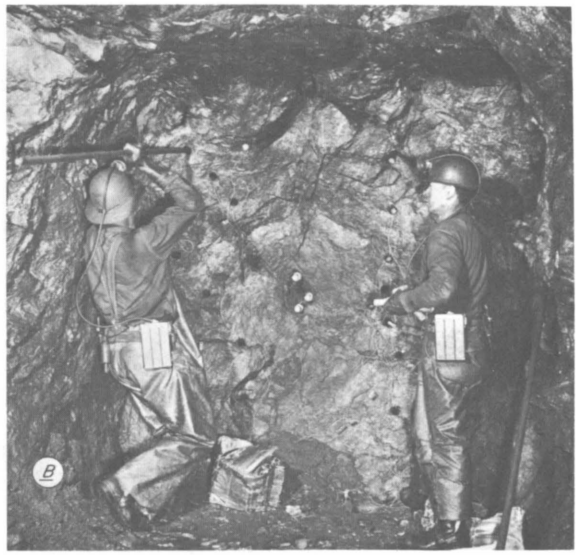

FIGURE 32.—Drilling and Loading Explosives in a Development Heading: *A*, Drilling a Round; *B*, Loading Explosives.

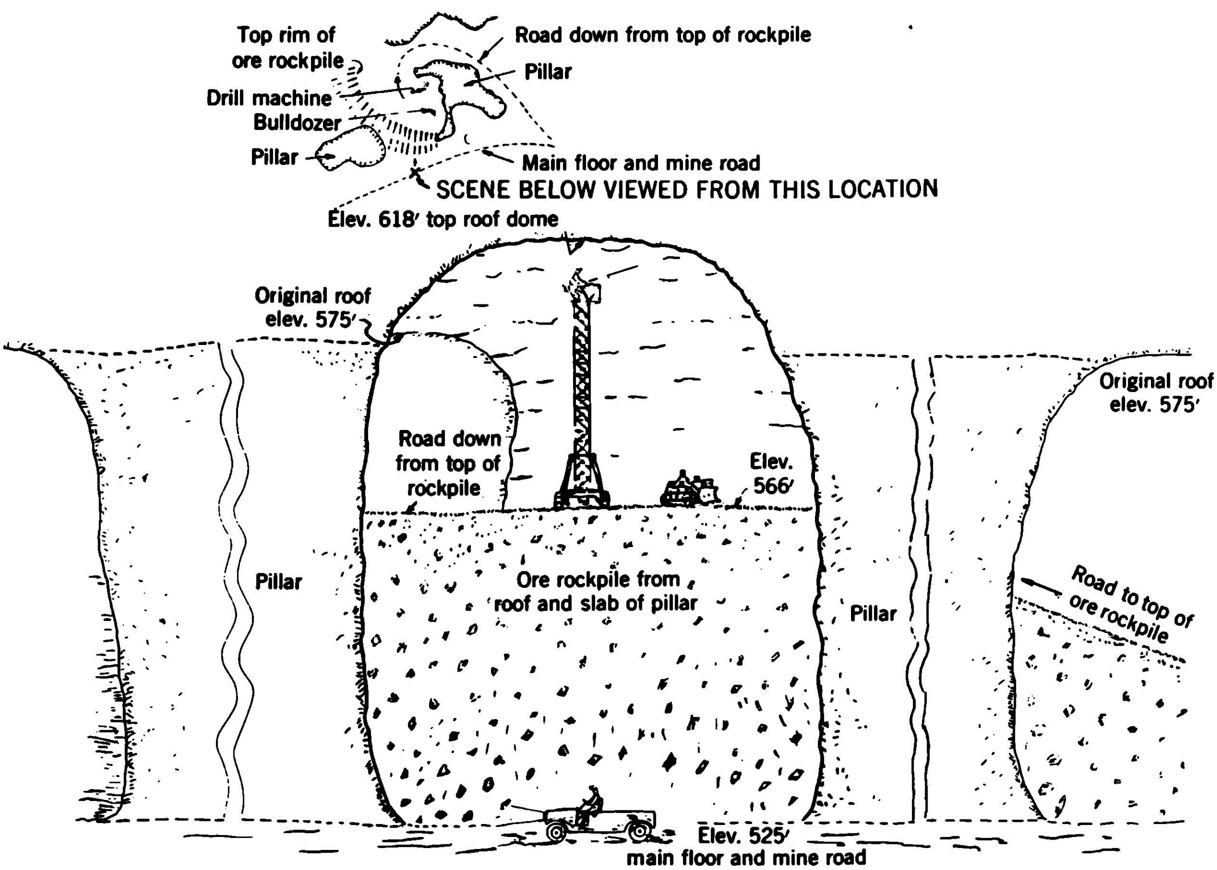

FIGURE 33.—Drilling in Stopes, Room and Pillar.

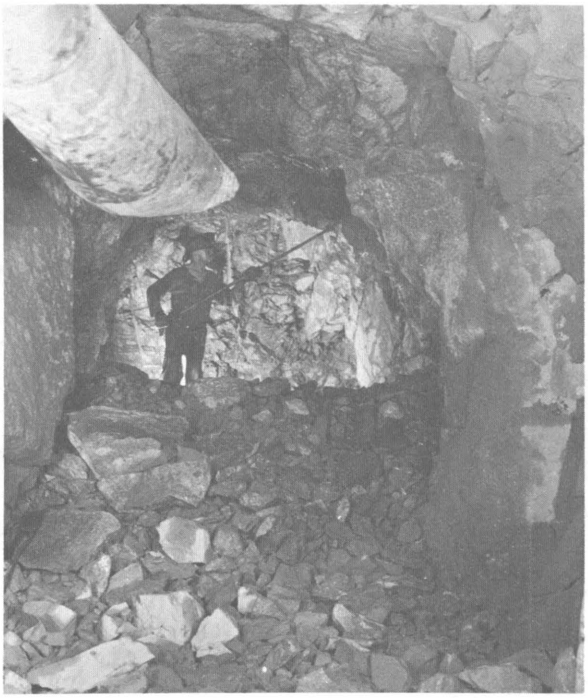

FIGURE 34.—Blasted Rock (Muck Pile) in a Development Heading. (Man at the Face Is Barring Down or Scaling.)

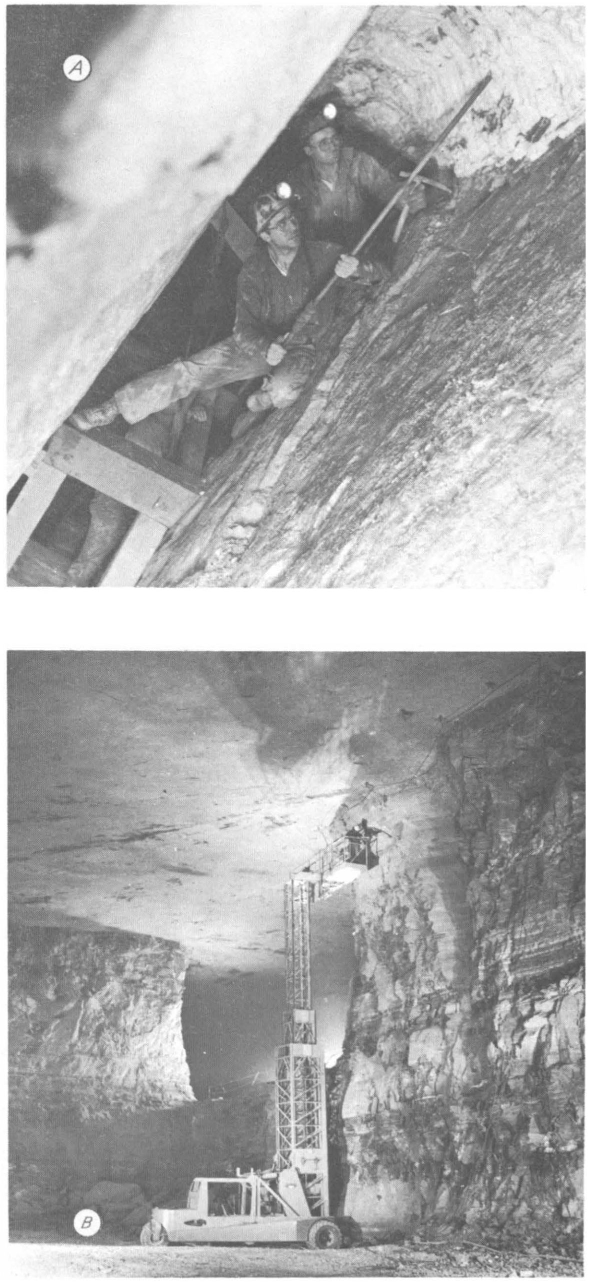

FIGURE 35.—Scaling: *A*, Steep Narrow Stope; *B*, High Room.

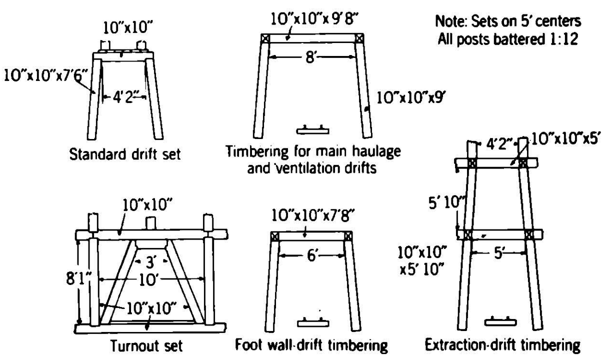

FIGURE 36.—Ground Support, Types of Timber Sets

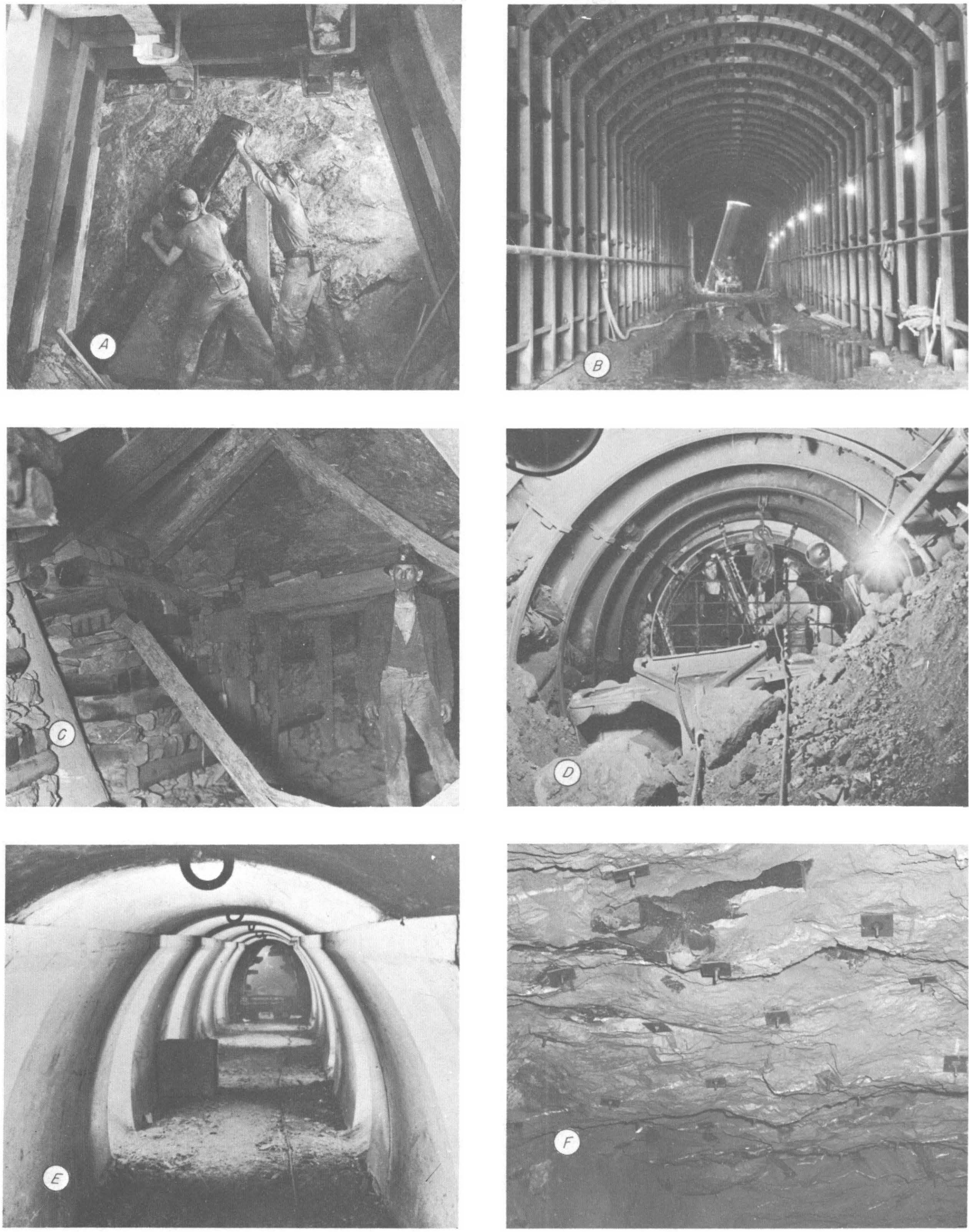

FIGURE 37.—Ground Support; *A*, Timber Crew Placing Supports; *B*, Steel Sets in Tunnel; *C*, Rock-Filled Crib in Deep Mine; *D*, Circular Steel Sets in Scraper Drift; *E*, Concrete Support; *F*, Rock Bolting.

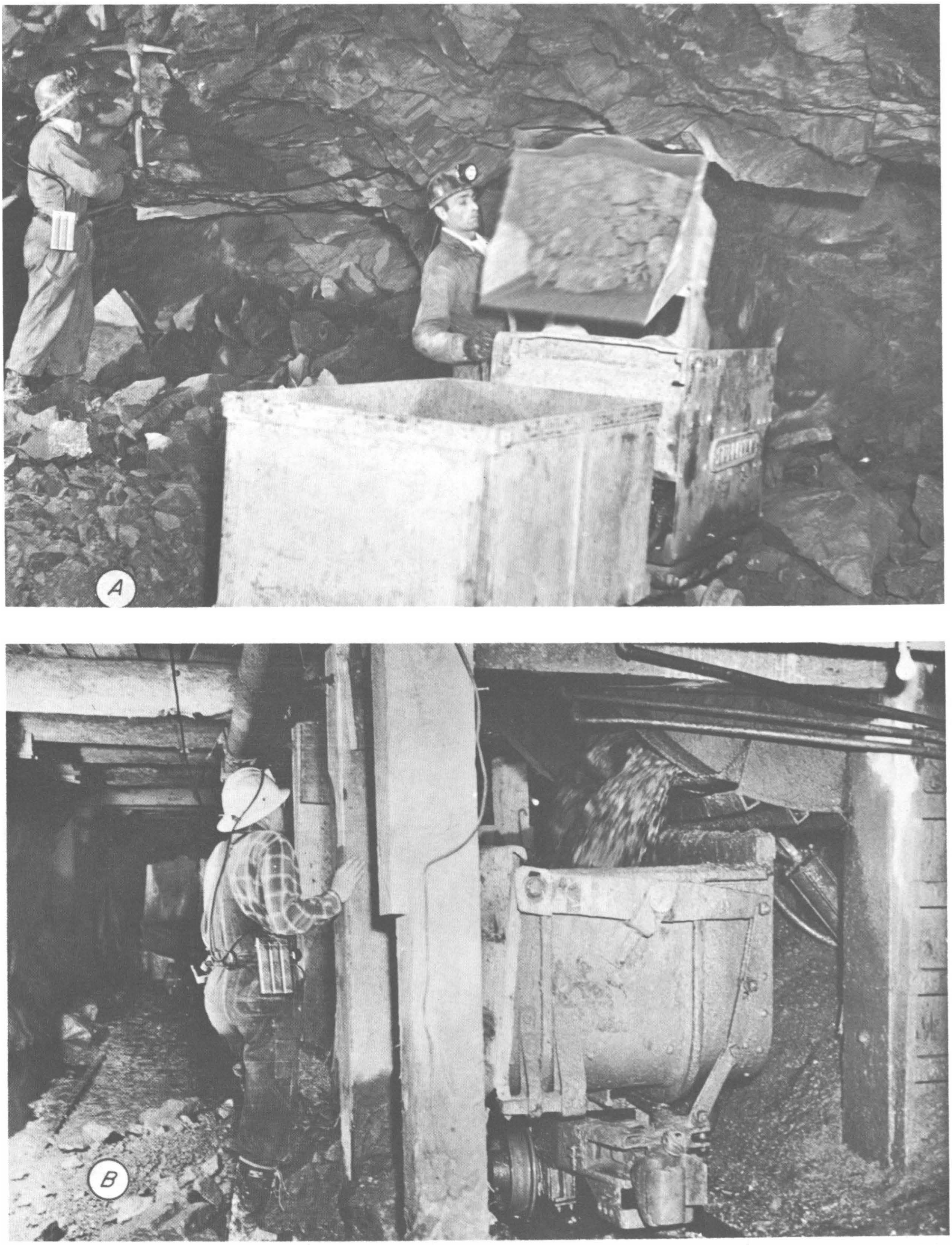

FIGURE 38. Underground Loading: *A*, Mine Car Loader; *B*, Chutes.

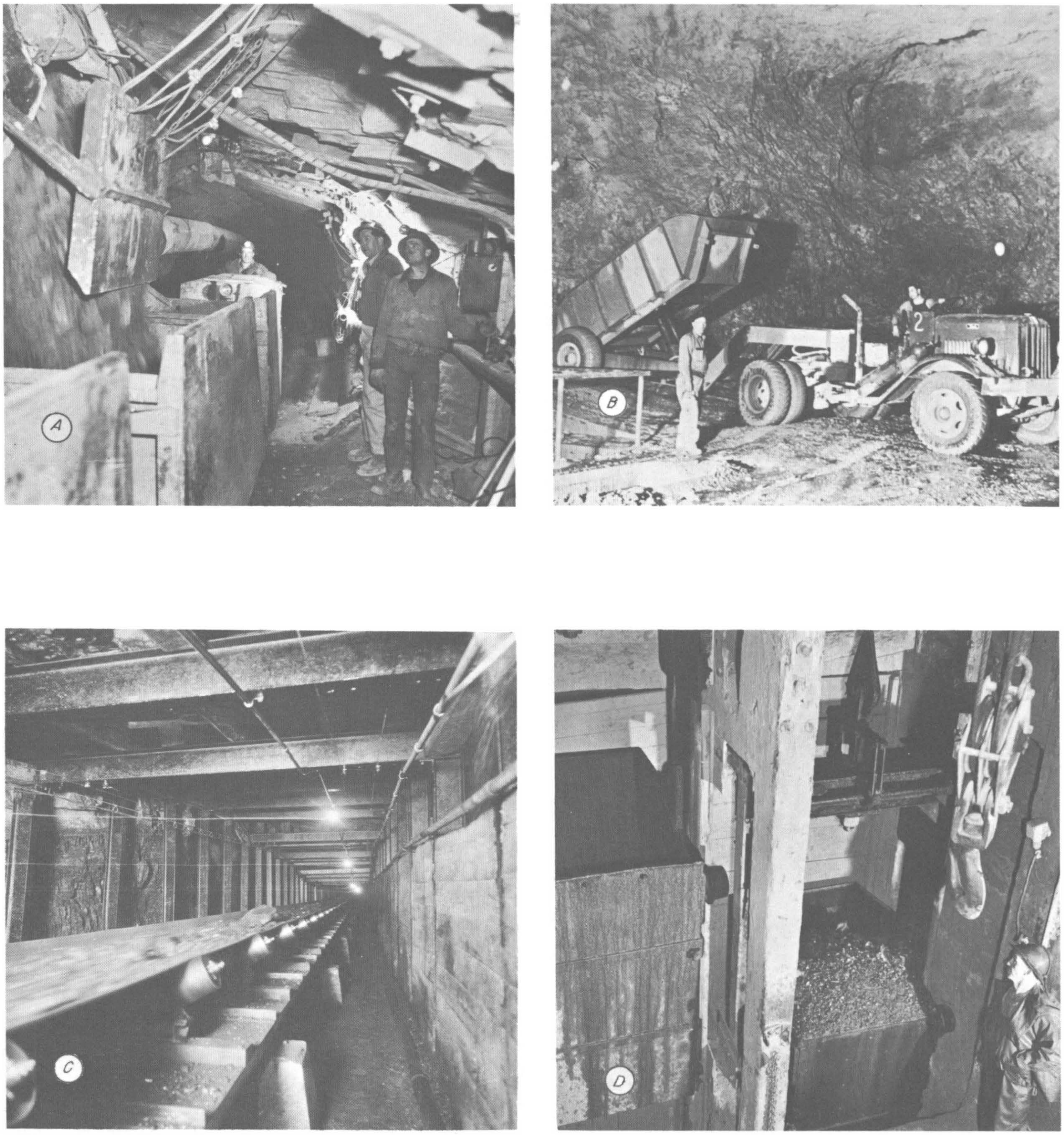

FIGURE 39.—Underground Transportation: *A*, Mine Train Loading at Chute; *B*, Truck; *C*, Conveyor; *D*, Ore Skips for Hoisting.

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