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MINERAL TECHNOLOGY AND
OUTPUT PER MAN STUDIES

ROCK DRILLING

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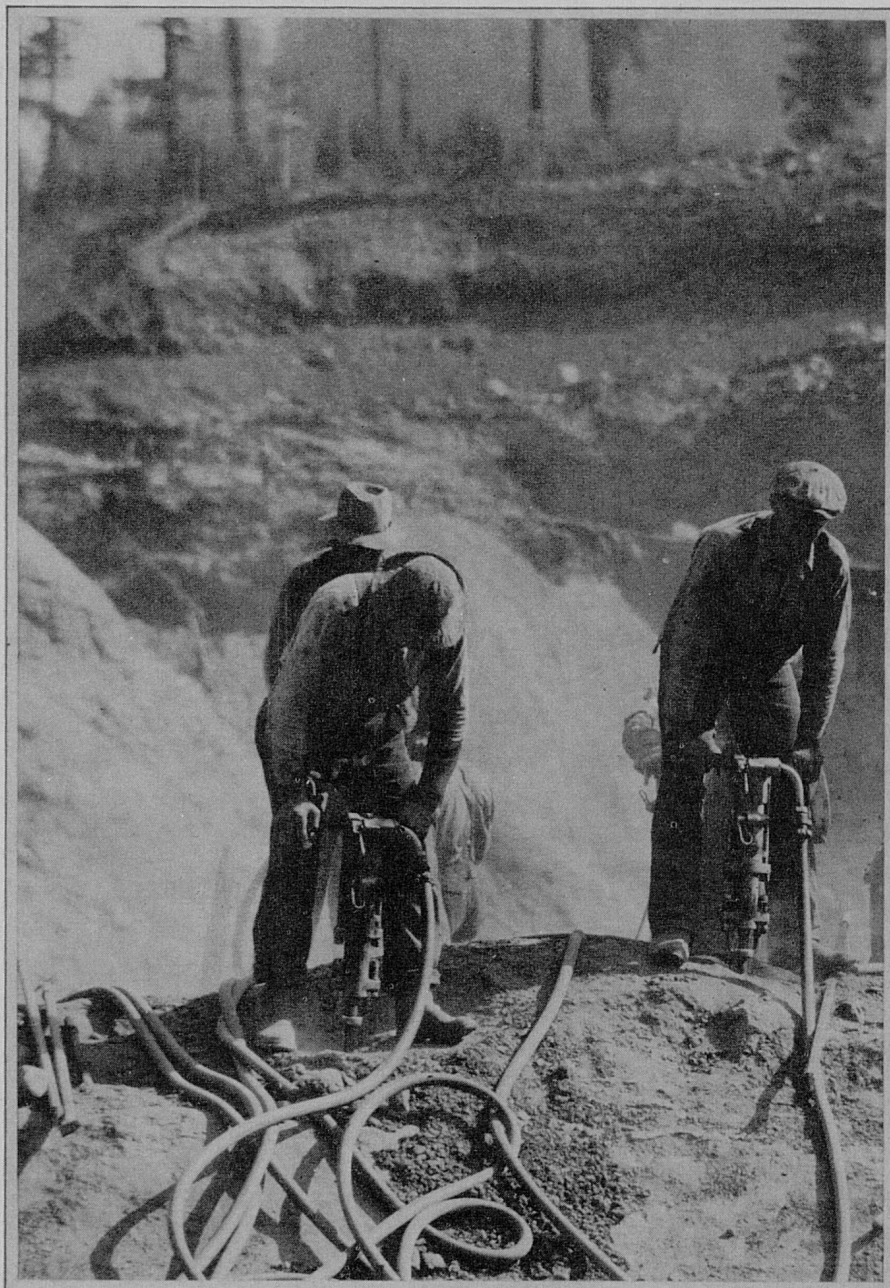
DAVID WEINTRAUB
Director

In cooperation with
UNITED STATES DEPARTMENT OF THE INTERIOR
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JOHN W. FINCH, Director

Mineral Technology and Output Per Man Studies

— O. E. Kiessling, Economist in Charge



MODERN JACKHAMMER DRILLS AT A SURFACE OPERATION

This hand-held machine weighs about 50 pounds and is actuated by compressed air. The hammer strikes the drill steel, which is automatically rotated, about 2,000 blows per minute. The jackhammer is used principally to drill holes in a downward direction.

The development of the jackhammer represented one of the greatest advances in drilling technology. It not only is widely used in mining and quarrying but is employed extensively for many other types of work. With this tool a man can drill at least 20 times as rapidly as he could by hand.

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MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES

ROCK DRILLING

by

C. E. Nighman

and

O. E. Kiessling

WORK PROJECTS ADMINISTRATION, NATIONAL RESEARCH PROJECT

In cooperation with

DEPARTMENT OF THE INTERIOR, BUREAU OF MINES

Report No. E-11

Philadelphia, Pennsylvania

February 1940

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THE WPA NATIONAL RESEARCH PROJECT
ON REEMPLOYMENT OPPORTUNITIES AND RECENT CHANGES
IN INDUSTRIAL TECHNIQUES

Under the authority granted by the President in the Executive Order which created the Works Progress Administration, Administrator *Harry L. Hopkins* authorized the establishment of a research program for the purpose of collecting and analyzing data bearing on problems of employment, unemployment, and relief. Accordingly, the National Research Program was established in October 1935 under the supervision of *Corrington Gill*, Assistant Administrator of the WPA, who appointed the directors of the individual studies or projects.

The Project on Reemployment Opportunities and Recent Changes in Industrial Techniques was organized in December 1935 to inquire, with the cooperation of industry, labor, and governmental and private agencies, into the extent of recent changes in industrial techniques and to evaluate the effects of these changes on the volume of employment and unemployment. *David Weintraub* and *Irving Kaplan*, members of the research staff of the Division of Research, Statistics, and Finance were appointed, respectively, Director and Associate Director of the Project. The task set for them was to assemble and organize the existing data which bear on the problem and to augment these data by field surveys and analyses.

To this end, many governmental agencies which are the collectors and repositories of pertinent information were invited to cooperate. The cooperating agencies of the United States Government include the Department of Agriculture, the Bureau of Mines of the Department of the Interior, the Bureau of Labor Statistics of the Department of Labor, the Railroad Retirement Board, the Social Security Board, the Bureau of Internal Revenue of the Department of the Treasury, the Department of Commerce, the Federal Trade Commission, and the Tariff Commission.

The following private agencies joined with the National Research Project in conducting special studies: the Industrial Research Department of the University of Pennsylvania, the National Bureau of Economic Research, Inc., the Employment Stabilization Research Institute of the University of Minnesota, and the Agricultural Economics Departments in the Agricultural Experiment Stations of California, Illinois, Iowa, and New York.

Since September 1, 1939, the Project has been sponsored by the National Resources Planning Board, Executive Office of the President, Washington, D. C.

**FEDERAL WORKS AGENCY
WORK PROJECTS ADMINISTRATION**

1734 NEW YORK AVENUE NW.

WASHINGTON, D. C.

F. C. HARRINGTON
COMMISSIONER OF WORK PROJECTS

February 8, 1940

Colonel F. C. Harrington
Commissioner of Work Projects

Sir:

One of the most time-consuming operations in the extraction of minerals is that devoted to the drilling of holes preparatory to blasting. A great deal of effort has therefore been concentrated on the improvement of drilling techniques. Since the introduction of the first practical mechanical rock drill, about 1865, the progress of drilling technology has been rapid and has increased labor productivity in all fields of mining. The report herewith transmitted is concerned with the types of advance that have been made in drilling technology, with the rate at which drilling has been mechanized, and with the effects of its mechanization on production, employment, and output per man.

Since about 1917, total employment in mining has been decreasing and the increased productivity of labor in drilling has doubtless contributed to this decline. For example, the rate of drilling underground with hand methods was about 4 feet per driller-shift. About 1910 the piston drill was putting down holes at the rate of roughly 20 feet per man-shift. The hammer drill which replaced the piston drill accomplished at least 80 feet per man-shift.

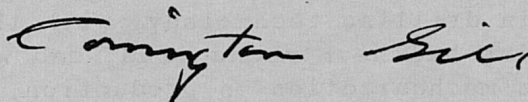
Changes in drilling methods have also reduced the proportion of the mine labor force engaged in drilling and brought about changes in the nature of the drilling job itself and in the aptitudes and skills required of the driller. Strength and endurance are no longer so important as quick reaction time and training in the use of mechanical devices. Individual experience and skill are not so necessary as they once were. To an increasing extent the drill operator

drills in accordance with specifications prepared by mine technicians.

It may be assumed that the demand for minerals will maintain a moderate increase with the growth of population and the continued expansion of industry. The outlook for the near future, however, indicates a minor reduction in the labor force employed in mineral drilling unless the production increase is greater than anticipated. That is, it is likely that the tendency of greater production to increase employment will be more than offset by technical advances continuing along lines followed in the recent past.

Over a longer period forces of depletion will necessitate the working of lower-grade deposits and the drilling and breaking of much greater tonnages of ore and rock in order to obtain a given amount of commercially useful product. In spite of the expected continuance of advance in drilling techniques, and assuming that the United States will continue to provide its own mineral supplies, it appears that long-time forces will make for an increase in the number of men employed in drilling at mines.

Respectfully yours,

A handwritten signature in cursive script, reading "Corrington Gill". The signature is written in dark ink and is positioned above the typed name.

Corrington Gill
Assistant Commissioner

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PREFACE

This Project's reports have repeatedly pointed out that the kinds of technical changes introduced and the rates at which they have been incorporated into industrial practice have had important effects on the volume of production as well as of employment. In the extractive industries advances in the methods used in drilling operations have been an important feature of these changes. Progress in this aspect of mineral technology has affected all the mineral industries and has been closely related to technological developments in such other phases of mine operation as loading and transportation of ore and rock. The development of drilling technology in the bituminous-coal industry and in petroleum and natural-gas production has been covered in other National Research Project reports.¹ This report deals with rock drilling in other important mineral industries.

The first rock-drilling machines, though heavy and cumbersome, brought about enormous increases in the output per driller. As the machines were improved, as new types were developed, and as management and labor became familiar with them, their use became general in the mineral industries. By 1909 all the basic types now used had become available. Further technical progress centered on improvements of motive power, materials, and parts and the adaptation of machines to the requirements set by the widely different conditions encountered in the various types of mining. These later types of change are believed to have had, in the aggregate, as large an effect in increasing the productivity of drilling labor as did the initial shift from hand to machine work.

Advances in rock-drilling technology and gains in drilling productivity have been closely related to technological progress in such other mining operations as blasting, loading, transportation, and methods of extraction. The direct relation between rock-drilling mechanization and mining employment is therefore difficult to trace. The immediate result of the increased output per man in drilling tended to be a contraction of total employment, but this has been largely offset by other factors. In the first place, the lower drilling costs which have resulted from mechanization and the improvement of equipment have been an important factor in the vastly increased mineral production. This production increase, vital

¹Willard E. Hotchkiss, F. G. Tryon, and Others, *Mechanization, Employment, and Output per Man in Bituminous-Coal Mining* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-9, Aug. 1939); O. E. Kiessling, H. O. Rogers, and Others, *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-10, July 1939).

in supplying the needs of an expanding industrial economy, increased the total amount of drilling to be done. Another offsetting factor has been the long-time tendency for grade of ore to decline. After the richest ores are exploited, a proportionally greater amount of drilling is required to obtain a given quantity of commercially useful product from progressively lower-grade deposits. Similarly, as the most accessible deposits are mined, a greater volume of drilling is necessary to remove overburden or to develop underground workings. These tendencies have operated in the past and may be expected to influence the volume of drilling labor in the future.

This report was prepared by C. E. Nighman, of the National Research Project, and O. E. Kiessling, of the United States Bureau of Mines, as one of a series of studies conducted by the National Research Project in cooperation with the Bureau of Mines under the direction of Dr. Kiessling. The manuscript was edited and prepared for publication under the direction of Edmund J. Stone.

DAVID WEINTRAUB

PHILADELPHIA

February 6, 1940

ACKNOWLEDGMENTS

Acknowledgment is made of important assistance given by officials of the U. S. Bureau of Mines. Helpful suggestions and criticisms were supplied by Charles F. Jackson, Chief Engineer, and McHenry Mosier, Senior Mining Engineer, Mining Division; and by E. D. Gardner, Supervising Engineer, Southwest Experiment Station, Tucson, Arizona. Information regarding technical aspects of nonmetallic operations was kindly furnished by Oliver Bowles, Assistant Chief Engineer, Nonmetals Division. Data regarding the effect of drilling practices on the health and safety of workers were supplied by Daniel Harrington, Chief, Health and Safety Branch. W. W. Adams, Supervising Statistician, and M. E. Kolhos and Virginia Wrenn, Employment Statistics Section, gave major assistance in assembling material on employment and accidents in mines and quarries. Mabel E. Winslow, Information Division, read the manuscript and suggested numerous improvements.

The following members of the staff of the WPA National Research Project made contributions that are not otherwise noted. P. J. Wester, Marguerite Lane, and L. D. Nierenberg carried out special assignments connected with the preparation of the manuscript. Cooke Settle prepared the graphic material.

Thanks are also extended to Dr. R. R. Sayers, Chief, Industrial Health Division, U. S. Public Health Service, who gave many suggestions regarding the health and safety aspects of rock drilling that were helpful in the preparation of the study. Indebtedness is also expressed to F. G. Tryon, Chief, Research Section, Bituminous Coal Division, U. S. Department of the Interior, who served in a consulting capacity during the initial stages of the study.

Manufacturers of rock-drilling and quarrying equipment generously supplied test and operating data and many of the photographs that have been incorporated in the text. The cooperation of the following concerns is cordially acknowledged: Bucyrus-Erie Co., South Milwaukee, Wis.; Chicago Pneumatic Tool Co., New York, N. Y.; The Cleveland Rock Drill Co., Cleveland, Ohio; Gardner-Denver Co., Quincy, Ill.; Howells Mining Drill Co., Plymouth, Pa.; Independent Pneumatic Tool Co., Chicago, Ill.; Ingersoll-Rand Co., New York, N. Y.; Jeffrey Manufacturing Co., Columbus, Ohio; Keystone Driller Co., Beaver Falls, Pa.; and Sullivan Machinery Co., Chicago, Ill.

CHAPTER I

INTRODUCTION

The transition from manual to mechanized drilling and the subsequent improvement of rock drills¹ have been among the most important technical advances in mining and are closely related to the changing character of the mineral industry in the United States and to the development of other aspects of its technology. Progress made in the art of drilling is one of the most important reasons why it has been possible to meet the demand for minerals at constantly lower relative prices.² The success of applied technology in reducing unit drilling costs, which are chiefly labor costs, followed from the greater volume of output resulting from each unit of labor spent. Other reports of this series of Mineral Technology and Output per Man Studies discuss the relationships between the changing demand for minerals, technological progress, and employment opportunity in the various branches of mining. Insofar as drilling improvement decreased the unit labor requirements it is of special interest in interpreting the record of rising output per man and of changes in total labor requirements that accompanied technological progress in the mineral industries.

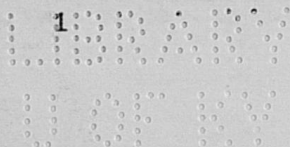
THE STIMULUS FOR DRILL MECHANIZATION

With the great expansion of the railway network in the latter third of the nineteenth century, engineers found it advantageous to bore rock tunnels in overcoming obstacles of terrain. Such work, however, was time-consuming and costly with the hand methods then in vogue, and railway-tunnel construction provided a great incentive for the development of a mechanical drill. About the same time the development of the western bonanza metal deposits provided a proving ground for underground drilling machines in mining. However, as the bonanzas were soon depleted and few new rich deposits were found, attention turned to the possible exploitation of the lower-grade ore deposits. These deposits represented the large-tonnage resources required by an expanding industrialism and

Note.- The authors are grateful to H. P. Sweeny, R. L. Kiessling, and E. Weinberg, respectively mining engineer and research associates of the WPA National Research Project, who conducted extensive background studies utilized in the preparation of this report.

¹Although the early manual drills were rock drills in a strict sense, the terms "rock drill" and "rock drilling" are employed in this discussion as commonly used to connote power rock drills and the act of drilling with them.

²F. G. Tryon, T. T. Read, and Others, *Technology and the Mineral Industries* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-1, Apr. 1937), chart 2, facing p. 4.



they could be successfully exploited provided the costs of mining were reduced. Since, under the hand methods prevailing in the seventies, drilling constituted the major fraction of total mining costs, mechanization of the drilling operation provided a very great opportunity for cost reduction.

A few examples will help to illustrate the importance of hand drilling, with respect to both mining cost and labor required, in mining as it was practiced more than a half century ago. In 1874 Professor Spilsbury pointed out the "crying want of the Western miners for some cheap and effective machine, capable of economizing on the heavy item of hand-drilling" Reasoning from European experience, Spilsbury said "fully two-thirds . . . of the entire cost of mining is consumed by the expense of drilling holes for blasting purposes" and, allowing for the much higher American wage, he concluded that in this country "drilling will probably represent 75 per cent of the entire expense of mining." In considering these broad estimates, it should be noted that Spilsbury apparently used the term "mining" in a somewhat restricted sense to cover operations immediately essential to breaking ground.³ Nevertheless his estimates were closely in line with actual costs prevailing in the seventies at Michigan copper mines that were operating in moderately hard rock. For example, at the Allouez mine in July 1876 nearly half the underground men were engaged in stoping; if the men so engaged are included with those employed on development work nearly 70 percent of the labor crew was primarily occupied in drilling and blasting.⁴

The availability of a type of mechanical power that could be transmitted to individual machines and used underground was another important force aiding the development of the rock drill. Although pumping and hoisting were early tasks of the steam engine, the mining process remained essentially a hand operation throughout the greater part of the nineteenth century. Neither the ordinary steam engine itself nor the conventional method of transmitting power by means of belting and shafting was adaptable to the task of ore production. The technique of air compression was already available, however, when the first practicable rock drill appeared. It was utilized almost immediately to supply the flexible type of mechanical power needed by such machines as drills which were essentially powered hand tools and were operated under the widely varying physical conditions encountered in mines and quarries.

³For the data referred to in connection with this early estimate, see E. Gybbon Spilsbury, "Rock-Drilling Machinery," *Transactions of the American Institute of Mining Engineers*, Vol. III, pp. 144-6.

⁴T. Egleston, "Copper Mining on Lake Superior," *Transactions, A.I.M.E.*, Vol. VI (1879), p. 291.

As the incentive for mechanization was strong and the mechanical means available, technical advance of rock-drilling equipment was initiated. The history of mechanical drilling now covers three-quarters of a century of steady progress from the early crude, heavy machines, uncertain in performance, to the lightweight, highly efficient rock drills that are the most commonly used mechanical devices in mines and quarries today. Throughout the period the technical improvement of drilling equipment and practice has been a focal point of the technologists' attempt to lower mining costs.

THE FUNCTION OF DRILLING

The role of drilling in the process of ore extraction explains why the engineers' initial efforts to increase production and reduce mining costs centered largely upon improving the technique of breaking ground. The actual process of mining may be divided into three closely interrelated steps: breaking the rock at the working face, loading it into cars or other conveyances, and transporting it to the surface or plant. The task of breaking the rock - usually accomplished by drilling and blasting - is the initial step in the extraction of ore and, as already noted, engages a substantial part of the labor force.

Drilling in mines and quarries serves two⁵ principal purposes: to make a cavity into which some form of explosive can be inserted and detonated to break or shatter the rock, and to discover what lies beneath the surface or beyond the working face by examining the cores or cuttings from the drill holes.

In underground mines the immediate object of almost all drilling is to break rock, either in the work of development or in the stopes.⁶ Frequently the deposit is prospected from the surface before actual mining is begun and if the ore body is continuous and regular its position and extent may have been well delineated. When the ore deposit is irregular additional prospecting from within the mine may be done by driving exploratory drifts, crosscuts, raises, or winzes,⁷ or by taking cores or cuttings from deep or shallow drill holes.⁸

⁵Holes are sometimes drilled for other purposes; for example, to carry electric feeder lines underground, to provide entrance for water to quench mine fires, for ventilation, etc. Such drilling, however, is comparatively unimportant in volume.

⁶A stope is a relatively large underground excavation from which the greater part of the ore is obtained by means of a series of horizontal, vertical, or inclined workings in veins or large, irregular bodies of ore, or by rooms in flat deposits.

⁷The term "raise" theoretically applies to any opening of limited cross section driven up from below at an angle above the horizontal and the term "winze" applies to any similar opening driven down from above. In practice both terms generally refer to openings more than about 20° from the horizontal.

⁸C. F. Jackson and J. B. Knaebel, *Sampling and Estimation of Ore Deposits* (U. S. Dept. Com., Bur. Mines, Bull. No. 356, 1932), pp. 32-4, 43-73.

In surface mines or quarries practically all prospecting - both for locating and delineating a deposit - is done by drilling. The same type of drills employed for prospecting are also used to do most of the blast-hole drilling.

Advances in drilling techniques have been closely related to the mechanization in other departments of mining. The incentive to develop speedier and less costly methods of loading and transporting ore and waste grew as improved methods of breaking the ore from the face increased the tonnage broken per driller-shift and existing systems of loading and transportation proved inadequate for efficient handling of the larger production. As early as 1874 it was noted that the use of dynamite and mechanical rock-drilling equipment was "doubling and trebling the old rates of progress attained by hand drilling and black powder."⁹ On the other hand not all of the increased output per driller-shift can be attributed to mechanical rock drills alone. Part of the greater efficiency can be credited to the early use of dynamite in place of black powder, to improved methods of mining, better mine ventilation, and other changes in mining practice that were either largely independent of or influenced only indirectly by the use of rock drills.

SCOPE OF THE STUDY

This report describes the principal advances in the development of the rock drill and the broad gains in drilling productivity resulting from these improvements. In a large sense, progress in drilling cut across all mining activity and to understand more clearly how improvements in drilling practice affected the output per man and employment in the several branches of the industry it is necessary to examine separately this technical development. The material assembled for study was limited mainly, however, to that concerning changes in the United States in the following mineral industries for which special analyses were being conducted by the WPA National Research Project in cooperation with the United States Bureau of Mines; namely, the mining of iron, copper, lead, zinc, and gypsum and the production of crushed and dimension stone. Drilling progress in oil and gas and bituminous-coal production has been discussed in other reports of the Mineral Technology and Output per Man series.¹⁰

⁹Henry S. Drinker, "The Musconetcong Tunnel," *Transactions, A.I.M.E.*, Vol. III, p. 248.

¹⁰O. E. Kiessling and Others, *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-10, July 1939), pp. 75-119, 173-6; Willard E. Hotchkiss and Others, *Mechanization, Employment, and Output per man in Bituminous-Coal Mining* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-9, Aug. 1939), I, 20-3. For a discussion of machine cutting see Hotchkiss and Others, *op. cit.*, pp. 13-9.

Blasting, although essential to the ore-breaking process, is not covered by this report. The efficiency of drilling frequently is measured in terms of the tonnage broken which results from the methods and equipment used in both drilling and blasting. The development of explosives, moreover, was closely parallel to that of the rock drill.¹¹ However, the labor time consumed in blasting has always been small compared with drilling operations, which usually require 80 to 90 percent of the labor directly engaged in breaking ground, and therefore this survey, although limited to rock-drilling progress, covers the outstanding technical changes in rock breaking which affected employment in mines and quarries.¹²

The following chapters discuss drilling technology and its relation to mining employment and productivity. Chapter II contains a brief description of hand-drilling methods and of the shift to mechanized drilling. Chapters III and IV present detailed descriptions of the various types of drills used for underground and surface mining, respectively. The purpose, development, construction, operation, and limitations of each kind of drill are described, together with changes in motive power, materials, and parts. Readers whose interest does not extend to the details of mine technology may find it convenient to skip over these two chapters. Chapter V outlines the factors influencing the productivity of drilling labor and presents the available data on drilling productivity with different types of drills and at different stages in their development. In the concluding chapter the influence of changing drilling technology on the volume of employment, on occupations and skills, and on the health and safety of miners is considered, and the outlook for employment and further technological change in drilling is discussed.

¹¹Just before the first practical power rock drill was developed, Nobel patented nitroglycerin in 1863 and in 1866 it was used in the Hoosac Tunnel, which also served as the proving ground for the drill. A few years later the first successful brisant explosive - straight dynamite - was manufactured and at once began to be used by the miner.

¹²Discussion on a broader economic basis would require more attention to the development of explosives. Explosives are available today, for example, in a large variety of strengths, sizes, densities, and types suitable for widely different purposes. According to the circumstances, the use of improved explosives may entail an increase or a decrease in the amount of drilling work done in breaking a given volume of rock. Notable progress has been made, moreover, in the safe transport and handling of explosives, in increasing the certainty of detonation, and in reducing the volume of noxious gases produced by explosion.

The reader interested in the use of explosives in mining and tunneling will find an account of the early types utilized in Henry S. Drinker's *A Treatise on Explosive Compounds, Machine Rock Drills and Blasting* (New York: John Wiley & Sons, 1883). A description of modern types and their applications is given in such manuals and journals as the *Blasters' Handbook* and *The Explosives Engineer*, published respectively by E. I. Du Pont de Nemours & Co. and the Hercules Powder Co., both of Wilmington, Del. A detailed story of their production is contained in Arthur P. Gelder and Hugo Schlatter, *History of the Explosives Industry in America* (New York: Columbia University Press, 1927), and the U. S. Department of the Interior, Bureau of Mines, has issued numerous publications related to explosives production and use.

CHAPTER II

THE TRANSITION FROM HAND TO MECHANIZED DRILLING

Before the Drake oil well was drilled at Titusville, Pa. in 1859 and the construction of the Hoosac Tunnel was begun in Massachusetts in 1865, underground and surface drilling ordinarily was done by manual methods. For some time after the first power rock drills were introduced, moreover, hand drilling continued to be widely used, both in competition with the machines and under conditions where the early mechanical drills could not perform satisfactorily. Rock drills, like many other machines, were gradually developed from hand tools in the effort to replace human energy with mechanical. A description of the principal hand-drilling appliances and techniques is helpful in understanding the more complicated mechanical drills that have been developed. In addition, the effectiveness of the hand methods provides a benchmark for comparison with the work done by the first mechanical drills.

HAND-DRILLING METHODS

The manual tools employed most widely were of three general types, the auger drill, the hammer-and-drill, and the churn drill. In addition there was a crude forerunner of the hydraulic rotary drill utilizing both men and horses or mules, but it was not widely used.

The Auger Drill

For prospecting¹ and boring blastholes in relatively soft materials such as earth, slate, gypsum, coal, and soft iron ores, the most commonly used hand-drilling tool was the auger drill. In its simplest form the auger drill was similar to the carpenter's auger; however the auger drill generally had a diamond (inverted, flat, V-shaped) or "fishtail" bit or cutting edge. Its penetration was due largely to pressure and was assisted materially by the scraping action that accompanied the rotary motion of the bit.

The earliest models and those generally used for earth and some soft ores were hand-held. For light work they were operated by one man. This type was ineffective in harder ground because the driller could not exert enough pressure to cut the rock. Under such conditions the auger was supported and was fed forward by a screw attachment, while other simple

¹For a description of the use of the auger drill in prospecting cf. Charles Catlett, "The Hand Auger and Drill in Prospecting Work," *Engineering and Mining Journal*, Vol. LXIV, No. 4 (July 24, 1897), p. 94.



FIGURE 1.— DRILLING WITH A HAND AUGER

The auger drill was one of the commonly used manual drills but was limited to relatively soft ground both for prospecting and blasthole boring. In its simplest form it was held in the hands like a carpenter's brace. In the above illustration the auger is supported by a column to which is attached a feed nut that feeds the drill forward as the crank is turned. In more complex forms of mountings power was sometimes applied through gearing.

accessories such as universal joints permitted the miner to bore holes close to a wall or roof. Thus, although hand power was still used, the application of the simple mechanical principles of the lever and screw marked a step toward mechanization.

The effectiveness of the drill was further increased by making heavier machines mounted on columns or tripods, and by the use of gears with two or more men frequently required to turn the crank. The auger drill could be employed for boring in any direction but it was generally used for "flat" or "down" holes.

The Churn Drill

The simplest form of the churn drill, or "jumper", consisted of an iron or steel bar, usually 6 to 8 feet long, shaped into a pointed or chisel bit at one end. The operator raised the bar and plunged² it against the bottom of the hole, turning it slightly as he raised it for the next stroke. Turning the drill in the hole presented a fresh rock face to the bit, helped to keep the hole round, and prevented wedging or sticking of the drill.

²Drills longer than the "ball drill" described below are allowed to fall freely and not hurled against the rock.

The effectiveness of this method of drilling depended on the force with which the bar struck the bottom of the hole. This force varied with the weight of the tool and the power applied to the stroke. Efforts to increase the efficiency of hand churn drilling resulted in some changes in the form of the bar. It was often made 8 to 10 feet in length and 1 to 2 inches in diameter, with a bit at both ends. To provide more weight and a better grip for the operators the bar was enlarged near the midsection to an egg-shaped mass or ball. For greater depths the churn drill often was made of pipe to which a solid steel bit was attached. With such drills, holes have been put down 25 to 30 feet in soft ground. These heavy churn drills generally were worked by two and sometimes by three or more men.³

As pointed out, the hand churn drill was suited only to the boring of relatively shallow holes. For greater depths the spring-pole drill - a crude device but one in which the elements of the modern churn drill can be seen - was used extensively. This more complex form of the hand churn drill consisted of an iron or steel bar with a chisel bit at one end attached to a string of solid wooden rods (later replaced by iron) $\frac{7}{8}$ to $1\frac{1}{2}$ inches in diameter. The string of tools was suspended with a rope and swivel from the free end of a spring pole. This consisted of a small tree or pole inclined at about 15° to 30° to the horizontal across a support or fulcrum with its butt end anchored or counterweighted to balance the weight of the tools.

Like its simpler form this drill operated by percussive cutting. Power for the downward or cutting stroke was manually applied by workmen to the rope from which the rods were suspended. The downward motion of the string of tools quickly depressed the pole and allowed the drill to fall and strike a blow at the bottom of the hole. When the blow was struck the men relaxed their grasp and the elasticity of the pole lifted the string of rods and the bit into starting position for the next blow. During the upstroke the tool string was turned.⁴

Since gravity was the most important factor in the operation of churn drills they were used almost exclusively for boring vertical "down" holes. This type of drill could be employed where the auger could not cut but the work was extremely tiring and progress correspondingly slow.

³Some "drop drills", essentially very heavy churn drills, made use of animal power to raise the drill but very few of this type were ever employed.

⁴For a detailed discussion of variations in spring-pole drilling techniques employed about half a century ago, see Edgar G. Tuttle, "Spring-Pole Drilling," *The School of Mines Quarterly, a Journal of Applied Science*, Vol. XVI, No. 1 (New York: Columbia College, Nov. 1894), pp. 1-25.

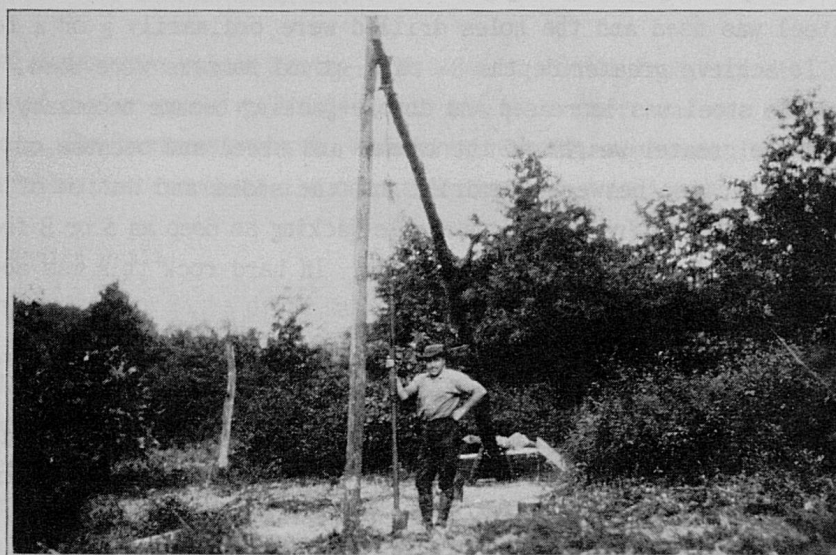
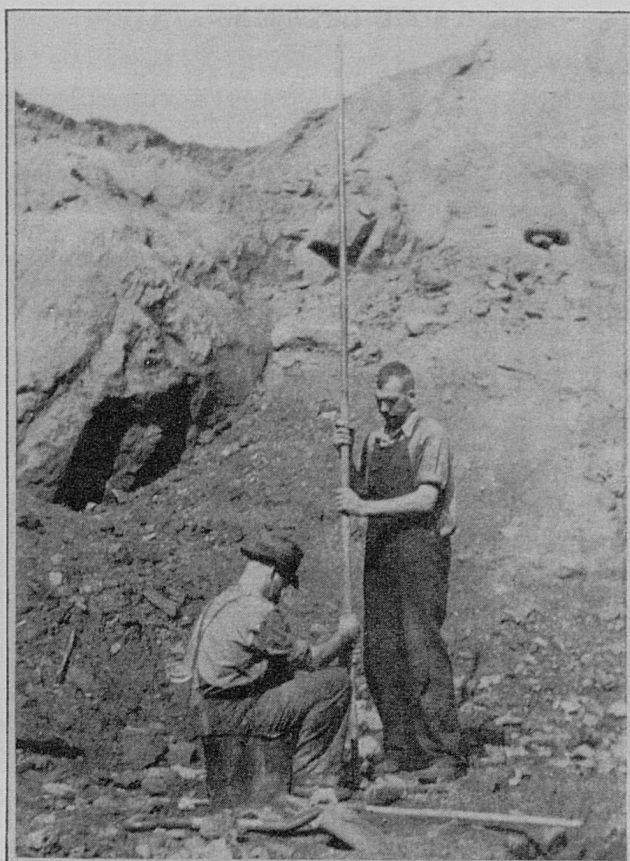


FIGURE 2.- HAND CHURN DRILLS

The upper illustration shows two men drilling a vertical "down" hole with a simple hand churn drill. The operators alternately plunged the drill against the bottom of the hole and raised it for the next blow. Between blows the drill was revolved slightly to keep the hole round.

The more complex hand churn drill, equipped with a spring pole, is shown in the lower photograph. The drill bit is at the end of a string of wooden or iron rods suspended from the spring pole. In relatively soft strata this type of hand drill succeeded in boring holes 250 feet or more in depth.

Nevertheless the churn drill was widely used; spring-pole types commonly drilled holes 2 to 4 inches in diameter 250 feet or more in depth.

The Hammer-and-Drill

The hand-drilling method employed most widely in quarrying and mining - and particularly in metal mining where hard rock usually was encountered - was the hammer-and-drill. Two tools were used, a hammer and an iron or steel bar. The bar was usually $\frac{3}{4}$ to $1\frac{1}{4}$ inches in diameter and somewhat pointed or flattened at one end like a chisel.

Like the churn this drill worked by percussion; the hammer delivered a succession of blows on the head of the drill which was turned slightly after each blow. Unlike the churn drill, however, the cutting edge was held against the bottom of the hole and the energy of the hammer blow was transmitted through the steel to the bit end.

When one operator handled both the hammer and drill, the operation was called "single-jacking." When one man held and turned the drill and one or two additional men struck it, the operation was called "double-jacking." Occasionally, in drilling deep holes, two men were needed to lift and turn the heavy steel and there were three hammermen.

In single-jacking a 4- or $4\frac{1}{2}$ -pound double-faced hammer with $\frac{3}{4}$ - or $\frac{7}{8}$ -inch steel was used and the holes drilled were ordinarily 3 or 4 feet deep. To achieve greater depths 8- to 10-pound hammers were used, the size of the steel was increased and double-jacking became necessary because of the greater weight of the hammer and steel and because of the increased friction between the drill and the sides and bottom of the deeper hole. Holes were drilled by double-jacking as deep as 6 or 8 feet⁵ depending on the character of the ground. In hard rock this was about the economic limit for double-jacking.

The hammer-and-steel could be used satisfactorily in all but the very soft types of rock. Highly skilled operators could drill holes at all angles but with widely varying efficiency. In general, holes could be drilled most effectively when they pointed below the horizontal (in down-holes the weight of the drill steel increased the force of the blow) and less effectively when they pointed above the horizontal (uppers).

It is of interest to note that there was technical improvement even in such simple manual equipment as the hammer-and-drill. The early tools were made of wrought iron; later cast steel was used for the drill and

⁵Occasionally holes as deep as 30 feet have thus been drilled. Cf. George C. McFarlane, "Methods and Costs of Excavating Granite in Open Cuts on the Grand Trunk Pacific R. R.," *Engineering - Contracting*, Vol. XXVIII, No. 22 (Nov. 27, 1907), p. 301.



FIGURE 3.— DOUBLE-JACKING UNDERGROUND

By this method, and using 8- or 10-pound hammers, holes could be drilled to a depth of 6 or 8 feet in hard rock. A high degree of skill was necessary to drill holes at all inclinations because considerable force and great accuracy were essential to effective performance. Note the wrist and arm positions of the hammermen.

steel faces were welded to the iron hammers. Still later the drills were made of higher-grade rolled sections and the hammer head was entirely of steel. The hardness, temper, and durability of steel made it a superior instrument and increased the output of the worker employing it.

The Empire Drill

The Empire or Banka drill was utilized in America to drill water wells and in the Dutch East Indies to prospect for tin. About 1906 it was first applied in alluvial-gold prospecting operations in the United States.⁶ It was a combined churn and rotary drill, worked by manual or animal power and could bore to depths of 100 to 125 feet but was generally used to drill much shallower holes.⁷ This machine was a forerunner of the modern power rotary drill.

The drilling equipment consisted of a pipe, a round platform, rotating and driving devices, and drilling, pumping, and pulling tools. The pipe was fitted with a toothed cutting shoe at the lower end and the platform

⁶J. P. Hutchins and N. C. Stines, "A B C of Empire Drilling - I," *Mining and Scientific Press*, Vol. 102, No. 1 (Jan. 7, 1911), p. 39.

⁷Robert S. Lewis, *Elements of Mining* (New York: John Wiley & Sons, 1833), p. 106.

was clamped to the upper end. With the help of a driving ram the pipe was driven into the ground until it could stand without support. A sweep, operated by animal or man power, was attached to the platform to rotate the pipe or casing. A combination drill and pump, screwed to rods and worked by hand, was used as a churn drill while the pipe was being rotated. The drill was driven into the ground by a combination of the weight of the pipe and the platform, the weight of the drillmen who stood on the platform, and the weight and jarring effect of the rods and tools. As the rotated pipe sank into the ground a core was cut by the toothed shoe and crushed and forced into the pump by the churning process. To remove the core the pump was raised and emptied and then reinserted into the pipe. As the platform approached the surface of the ground it was unclamped and raised 3 or 4 feet along the pipe; drilling then proceeded as before. Lengths of pipe and drill rod were added as required.

The unique feature of this drill - the constant rotation of the pipe - enabled it to make fair progress into soft rock or unconsolidated strata but it was quite ineffective in hard rock. Although depths exceeding 100 feet sometimes were reached, drilling became increasingly difficult below 30 feet. Because of its lightness and portability the machine found some use, especially where transportation was difficult and where labor was very cheap, but in the United States it was rapidly supplanted by more powerful and speedier powered types.

TRANSITION TO MECHANICAL DRILLS

Manual-drilling equipment gave way only gradually to power-drilling devices. Although W. L. Saunders noted in 1913 that "the history of modern mining engineering is closely related to the history of progress in the art of building a rock drill [without the rock drill] the wealth of the world, especially in its gold, silver, copper, zinc, lead, and tin, would have been enormously curtailed, limited by an inability to increase the output in proportion to the demand, and further limited by the fact that low-grade propositions could not have been worked at all",⁸ this statement was made at a meeting of mining men about 50 years after the first mechanical drills appeared.⁹ Within this half century - and especially in the early period - the transition to the rock drill

⁸W. L. Saunders, "Rock-Drilling Economics," *Transactions of the American Institute of Mining Engineers*, Vol. XLVII (1914), p. 149.

⁹However, the rock drill was not unappreciated during the early years of its existence. As early as 1877 George G. Andre wrote that "the most remarkable advance which, in recent, or perhaps in any, times, has been made in the practice of mining, consists in the substitution of machines for hand labour in rock boring." See George G. Andre, *A Descriptive Treatise on Mining Machinery, Tools, and Other Appliances Used in Mining* (New York: E. and F. N. Spon, 1877), I, 29.

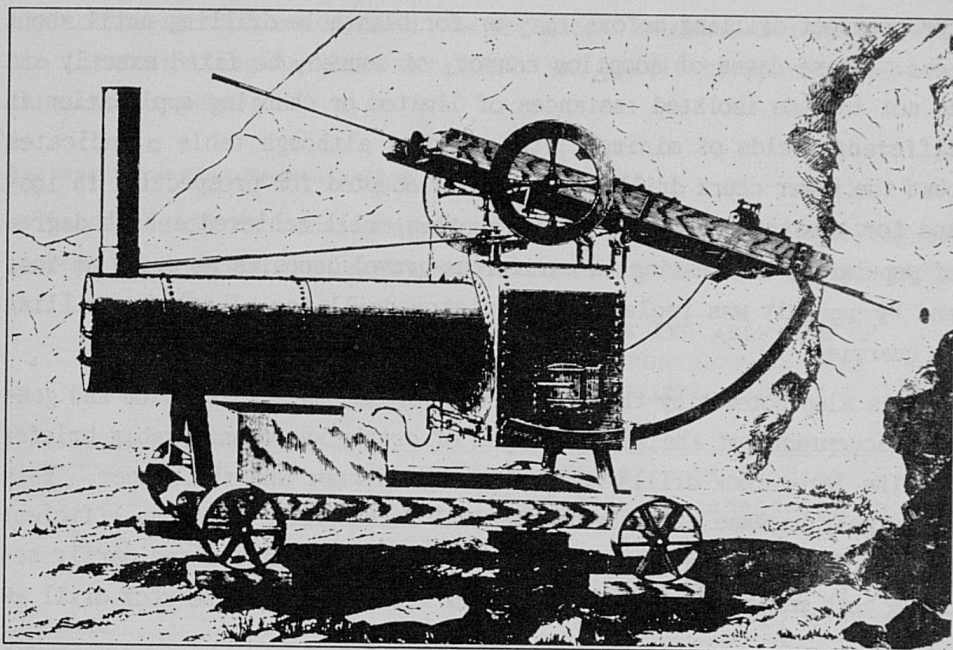


FIGURE 4.— COUCH'S ROCK-DRILLING MACHINE

This ponderous steam-driven machine, patented in 1849, was one of the forerunners of modern rock drills. The machine was provided with means for alternately throwing the drill steel against the rock face and then retracting it — in effect the principle that was applied later in the development of the piston drill. An outgrowth of Couch's work, moreover, was the issuance of a patent in 1851 to one of his associates (J. W. Fowle) on a percussion drill with the drill steel clamped to a piston rod and automatically rotated and with a mechanically operated valve motion. These features were used successfully in the first practical piston drills. Although the original Couch drill was used experimentally there is no record of its commercial application.

was so slow that there was a notable lapse of time between the dates of introduction and of general acceptance of the various types of machines.

The chronology of the development of rock-drill use in underground mines shown in table 1 reveals a lag of almost 20 years between the introduction of the piston drill in 1866 and its general acceptance about 1885. The drifter-type drill patented in 1897 was not accepted throughout the United States until about 1909, although it did achieve wide use in the West as early as 1905. There was a similar time lag before mechanical drills developed primarily for surface operation were generally adopted, as is indicated in table 2.¹⁰ The diamond drill, for example, was first patented in 1863 but was not widely employed for prospecting — its principal function — until the late seventies and early eighties; and the power churn drill which appeared in 1859 was not generally adopted

¹⁰ Although the drills are classified in tables 1 and 2 in accordance with their principal uses in mining, it should be noted that all drills included in table 1 have been used also in surface-mining operations. With the exception of the diamond drill which finds wide use in underground prospecting, the machines listed in table 2 are employed almost solely for surface work.

for prospect drilling before 1903 or for blasthole drilling until about 1912. These dates of adoption cannot, of course, be fixed exactly and do not include isolated instances of limited or changing application in different fields of mining. For example, although table 2 indicates that the power churn drill was generally adopted for prospecting in 1903 and for blasthole drilling in 1912, this drill achieved a high degree of popularity for testing in auriferous-gravel deposits as early as 1901 and by 1910 it was replacing the piston drill for blasthole drilling in quarries.¹¹

It is also noteworthy that the period between the introduction and general acceptance of the various types of drills was considerably briefer for the later rock drills such as the jackhammer and the stoper. This is largely because effective mechanical accessories - such as efficient air-compressing machinery - were then in widespread use and partly because both management and the miner had come to accept the rock drill as

Table 1.- CHRONOLOGY OF INTRODUCTION AND ADOPTION
OF ROCK-DRILLING MACHINES IN UNDERGROUND MINING
IN THE UNITED STATES^a

Type of machine	Date introduced	Approximate date of general acceptance
Piston drill	1866 ^b	1885 ^c
Drifter drill	1897 ^d	1906-9
Plugger drill	1900 ^e	1904-5
Stoper	1905-6 ^f	1908-10
Jackhammer	1909 ^g	1912
Power auger	1893 ^h	1904-07 ⁱ

^aExcludes earlier machines which were not generally accepted, and the diamond drill employed underground for prospecting and infrequently for blasthole work, but which has been used principally for drilling from the surface.

^bHenry S. Drinker, *A Treatise on Explosive Compounds, Machine Rock Drills and Blasting* (New York: John Wiley & Sons, 1883), pp. 322, 207-8.

^cAs early as 1872 the manufacturers of the Burleigh drill advertised that their drills were "now in use in nearly every State in the Union, as well as in Europe and South America" From *Engineering and Mining Journal*, Vol. XIII, No. 14 (Apr. 2, 1872), p. 221.

^dCharles A. Hirschberg, "History of the Water Leyner Drill," *Mines and Minerals*, Vol. XXXI, No. 3 (Oct. 1910), p. 148.

^eH. L. Sinclair, "The Development of the Air-Hammer Drill," *Engineering and Mining Journal*, Vol. LXXXIII, No. 15 (Apr. 13, 1907), p. 715.

^fCharles A. Hirschberg, "Development of the Rock Drill in America," *Engineering and Mining Journal*, Vol. 108, No. 17 (Oct. 25, 1919), p. 679; Sinclair, *op. cit.*, p. 716.

^gHirschberg, "Development of the Rock Drill in America," p. 681.

^hTrade note in *The Colliery Engineer and Metal Miner*, Vol. XIII, No. 9 (Apr. 1893), p. 207; and "The Jeffrey Electric Coal Drill," *The Colliery Engineer and Metal Miner*, Vol. XIII, No. 11 (June 1893), p. 255.

ⁱData supplied by Robert K. Jeffrey, Jeffrey Manufacturing Co., Columbus, Ohio.

¹¹B. G. Cope, "A Comparison of Electric and Gasoline Driven Blast-Hole Drills," *Engineering News*, Vol. 64, No. 28 (Dec. 29, 1910), p. 722.

a practicable tool and because the mechanical weaknesses that had made the first drilling machines unreliable and costly to operate had been largely eliminated.

Factors Retarding Mechanization

The doubts of the management about the advisability of employing new rock-drilling techniques centered primarily about the costs and the profit

Table 2.- CHRONOLOGY OF INTRODUCTION AND ADOPTION OF ROCK-DRILLING AND CUTTING MACHINES FOR SURFACE WORK IN MINING AND QUARRYING IN THE UNITED STATES^a

Type of machine	Date introduced	Approximate date of general acceptance in -		
		Prospect- ing	Blast- hole drilling	Dimension- stone quarrying
Power churn drill	1859 ^b	1903	1912	(c)
Diamond drill	1864 ^d	1880 ^e	(f)	(g)
Hydraulic rotary drill	1888 ^h	1898	(i)	(i)
Track channeler	1863 ^j	(1)	(1)	1880
Wire saw	1900 ^k	(1)	(1)	1928 ^l

^aExcludes surface-drilling equipment for the production of liquid and gaseous minerals.

The channeler and wire saw are not drilling devices in the strictest sense of the term, but they take the place of drills in dimension-stone quarrying and have had a considerable effect on the employment of drillmen in quarries where adopted.

^bJohn F. Carll, "Report on the Oil and Gas Regions," *Annual Report of the Geological Survey of Pennsylvania for 1886* (Harrisburg, Pa.: 1887), pt. II, pp. 597-8. For details of this first power cable-tool rig see "Early Drilling and Production Methods Indicate Mechanical Genius," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), pp. 24-5.

^cOccasionally so used for the removal of waste capping or poor rock near the surface as in slate quarrying.

^dPatented by the French engineer, Leschot, in 1863. An American drill was patented and one built in 1864. In 1867 the Leschot patent rights were secured by American companies which proceeded to develop and manufacture drills under them.

^eFairly complete lines of prospecting drills were available about 1875 and they found extensive use in the next decade.

^fAn early use was for blastholes in Pennsylvania anthracite shaft sinking.

^gThe diamond drill was used in the late sixties to bore shallow "plug-and-feather" holes, as well as for channeling and gadding. Diamond channelers and gadders were quite widely used in the eighties and nineties. Cf. George P. Merrill, *Stones for Building and Decoration* (New York: John Wiley & Sons, 1891), pp. 339-42.

^hAuthorities differ with regard to the date of introduction. Albert G. Wolf in "The Rotary Method of Well Drilling," *Engineering and Mining Journal*, Vol. 108, No. 5 (Aug. 2, 1919), pp. 171-5, gives 1888 as the date of the first well sunk with a hydraulic rotary drill; Howard R. Hughes, "A Modern Rotary Drill," *Transactions of the American Institute of Mining Engineers*, Vol. LI (1916), p. 620, reports the date as 1880.

ⁱNot used for this purpose.

^jMerrill, *op. cit.*, p. 336.

^kApproximate date. See *Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, Bur. Census, 1905), p. 805.

^lThe wire saw fell into disuse after its early employment in the United States. It was successfully reintroduced in slate quarries by the U. S. Bureau of Mines in 1926.

possibilities of such changes. A simple comparison of direct expenditures for labor and supplies - per foot drilled or ton broken with the machine or with hand labor - was not adequate, for other important elements had to be considered in determining the complete cost of machine work. These comprised not only the first cost of the rock drills and the subsequent maintenance expense but also the additional outlay for equipment to supply and distribute power. In 1874, Spilsbury told a meeting of mining engineers that "the expense of this class of machines must be considerably lessened, as at present but few can afford to invest the necessary capital for the air-compressing machinery and drills."¹²

Doubts also arose about the operating efficiency of the early rock drills, and were not without foundation, for the machines were crude, heavy devices, and erratic in performance. Moreover the hard usage a rock drill receives under even ordinary conditions provided a severe test for the new equipment. Because of inherent weakness of the materials and the number of exposed moving parts it was difficult and expensive to maintain in running condition, and many spare drills had to be kept in reserve to assure continuity of work. There were also other difficult problems such as removal of cuttings from the hole and provision of a flexible and automatic feed, and it was many years before the major technical deficiencies were overcome.

The factor of inertia and resistance to sharp change on the part both of miners and management combined with other causes to retard the progress of drill mechanization.¹³ At the time Spilsbury reported on the high cost of rock drills he also noted that "a large number of men in charge of mining operations are greatly prejudiced against the introduction of machinery underground. . . ."¹⁴ Similarly the miners often resented adoption of the rock drill,¹⁵ although where the miners' union was strong, as on the Comstock lode, it "did not prohibit the use of the power drill."¹⁶ The miners' chief concern was the security of employment and the rates of wages rather than the new conditions of work. Some of the workers regarded with amusement the new contraption and the implications it cast upon their physical ability to handle the drilling job. Almost periodically the strong men came up from the mines to demonstrate

¹²E. Gybbon Spilsbury, "Rock-Drilling Machinery," *Transactions, A.I.M.E.*, Vol. III, p. 145.

¹³For a discussion of factors determining the rapidity of mechanization, including the influence of psychological forces, see Harry Jerome, *Mechanization in Industry* (New York: National Bureau of Economic Research, 1934), p. 327.

¹⁴Spilsbury, *op. cit.*, p. 144.

¹⁵B. L. Thane, "Stoping With Machine Drills," *Transactions, A.I.M.E.*, Vol. XXIX (1900), p. 775.

¹⁶Elliot Lord, *Comstock Mining and Miners* (U. S. Dept. Int., Geol. Survey, Monograph No. IV, 1883), p. 365.

that muscle still could hold its own with mechanical contrivances, but, superhammermen though they were the machine continuously won verdicts of greater proficiency.

Extension of Mechanization

Despite all doubts and handicaps drill mechanization gained headway. For example, as early as 1871 the Burleigh drill was available in the West¹⁷ and when the mine superintendents on the Comstock lode "could not hire Chinese miners [they] made cheap servants of steam, compressed air, and dynamite."¹⁸ In driving the Sutro tunnel the early drills (1874) advanced the heading nearly three times as rapidly as hand drillers and at a lower cost per cubic foot of rock removed. The sinking of the Yellow Jacket mine shaft demonstrated the advantages of mechanical drilling in driving a heading vertically,¹⁹ and exploration work in the California and Consolidated Virginia mines in 1878 would not have been physically possible without extensive use of the rock drill. These tests and others in less notable camps indicated clearly that more extensive adoption of the machines was inevitable.

In 1880 there were 257 rock drills in the gold and silver mines in the United States; by 1902 this number had increased to 3,329, of which about two-thirds were used in deep mines that produced three-fourths of the total quantity of ore.²⁰ Of the 122 copper mines reporting to the Bureau of the Census in 1902, 34 were equipped with 900 rock drills and produced six-sevenths of the year's total copper-ore output.²¹ Thus despite the inherent weaknesses of the early rock drill and other objections to its use, the machine had virtually proved its worth by the beginning of the current century. Since then technical progress in rock drilling has continued and has been an important factor in the rapid expansion of the mineral industries. The principal technical changes that have characterized the development of rock drills used for underground and surface drilling are summarized in the two following chapters.

¹⁷A. E. Chodzko, "Machine Mine Rock Drills on the Pacific Coast," *Mining and Scientific Press*, Vol. LXXXI, No. 15 (Oct. 13, 1900), p. 432.

¹⁸Lord, *loc. cit.*

¹⁹*Ibid.*, p. 386.

²⁰*Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, Bur. Census, 1905), pp. 529-30.

²¹*Ibid.*, p. 477.

CHAPTER III

ROCK DRILLS USED UNDERGROUND¹

Before the evolution of large-scale mining and handling techniques at surface operations that became important after 1900, almost all metallic ores were obtained from underground mines. Important technical advances underground therefore had a much greater relative effect on mineral production and represented a larger field of technical progress than in later years. The significance of improvement in rock drills used underground was large, for the changes took place at a strategic point in a production process at a time when that process supplied virtually all of the Nation's requirements for metals.

After the shift from hand to mechanical drills the principal features of rock-drill progress underground were the transition from the piston to the hammer type of drill, the gradual technical improvement of each type, and the increased flexibility of drills in meeting various operating conditions.

THE PISTON ROCK DRILL²

Following a number of early machines that either proved impractical or were not actively sponsored by manufacturers,³ the first rock drill widely used in underground work was the piston drill. This machine was accepted for mining only after some years of trial and development in tunnel building. Construction of the Hoosac Tunnel in Massachusetts (1865-73) provided an excellent opportunity for testing and improving the available rock-drilling machines. Speed in driving this 5-mile railroad bore was held to be of greater importance than low costs, and in seeking to hasten the excavation various rock drills were tried. The machines

¹The emphasis in this chapter is primarily on those rock drills used underground that had an immediate effect on production and output per man. Prospect drilling, which was not extensively pursued underground until the machine drills were rather highly developed, affected production and output per man less directly. For example, it increased ultimate production in relation to labor requirements when substituted for a more primitive form of prospecting (the driving of crosscuts and raises and other forms of development work) that required more labor than drilling.

In addition to the drills discussed in this chapter, the diamond drill is used underground for prospecting. This drill, however, is described in the following chapter with others used principally on the surface.

²The name "piston drill" is a misnomer, for all of the principal types of underground rock drills have some form of piston. The term is probably a contraction of "reciprocating piston drill."

³Early rock drills and rock-drill patents are described by C. C. Hansen in "Rock-Drill History," *Compressed Air Magazine*, Vol. 42, No. 4 (Apr. 1937), pp. 5292-6. More comprehensive accounts will be found in the various editions of Henry S. Drinker's *Tunneling, Explosive Compounds, and Rock Drills*.

were so costly - about \$400⁴ - and broke so frequently that they were soon discarded. In November 1866 the Burleigh drill was introduced and, in an improved form, it was employed from 1868 until the Tunnel was completed.⁵ In the West, mining men were given a striking demonstration of the effectiveness of power drilling with Burleigh drills in the Sutro tunnel on the Comstock lode in 1874.⁶ By that time there were on the market three other makes of piston rock drills - the Rand, Waring, and Ingersoll - and at least two railroad tunnels (the Musconetcong and the Nesquehoning) were being driven with the aid of machines.⁷ The use of the piston rock drill in tunnel driving, however, was merely a prelude to its wider application in underground mining.

Development of the Piston Drill

The principle of the piston drill was essentially similar to that of the hand churn drill - cutting by percussive action. With this type the drill steel was secured to an extension of the piston. As the piston and steel reciprocated and crushed the rock, the cuttings were removed by the pumping or churning action of the steel in the hole.

All of the earliest piston drills were of the same general type. They consisted essentially of a cylinder containing a piston with a rod extending through the front head and terminating in an enlarged section, called the chuck, in which the drill steel was clamped. Compressed air⁸ used as the actuating power was admitted to the cylinder through a mechanically operated valve⁹ that formed an integral part of the rock-drill assembly. The steel was rotated by means of a rifle bar and nut and a ratchet-and-pawl mechanism. The latter engaged the rifle bar so that it was free to turn in one direction only. While the piston to which the nut was attached made either a forward or a backward stroke the nut followed the rifling and rotated the piston slightly, turning the rifle bar on the other stroke. Thus the drill steel was automatically and

⁴Henry S. Drinker, *Tunneling, Explosive Compounds, and Rock Drills* (New York: John Wiley & Sons, 1878), p. 159.

⁵*Ibid.*, p. 180.

⁶"The Sutro Tunnel and its Projector," *Engineering and Mining Journal*, Vol. XXVI, No. 22 (Nov. 30, 1878), pp. 384-8.

⁷The Ingersoll drill was used in the Musconetcong Tunnel and the Burleigh in the Nesquehoning.

⁸Steam was also employed but it was generally restricted to drilling on the surface. Compressed air was used to operate rock drills in 1850 or 1851. J. W. Fowle is credited with this achievement (cf. Drinker, *op. cit.*, p. 164). Fowle's improvement (patented 1851) of the original Couch drill also possessed such essential features of a practical rock drill as automatic rotation of the drill steel and a mechanically operated valve. (Cf. also Robert Peele, *Compressed Air Plant* [5th ed.; New York: John Wiley & Sons, 1930], pp. 1-2. This work also discusses many modern drills.)

⁹The first type was a so-called "tappet" valve. The piston pushed against a lever - the tappet - which moved the valve on its seat so that compressed air was alternately admitted to and exhausted from opposite sides of the piston.

constantly rotated in one direction. This ingenious mechanism or a modification is used today in nearly all underground drills.¹⁰

As the hole was deepened the drill was moved forward. On some of the early models the forward movement (commonly known as the feed) was accomplished automatically by means of a ratchet and threaded bar. However, in 1871 Simon Ingersoll provided drills with a guide shell and a hand-operated feed screw that was more satisfactory than the original positive feed and still is used on many mounted machines. A conical projection on the guide shell fitted into a clamp on a column or bar, or the shell was affixed directly to a tripod. This combination provided a sort of universal joint that made it possible to drill holes in any direction, but the piston drill was most effective in boring vertical down-holes where the weight of the drill steel, piston rod, and piston increased the magnitude of the blow.

Since the effectiveness of the machine depended on delivery of hard blows by a moving body of considerable weight and the impact on the rock and the strain of reciprocation were great, the piston machines were massively constructed in the hope of providing the required sturdiness. Some of the early piston drills and mountings weighed as much as a half ton. These machines frequently broke down and the cost of keeping them in running condition was very high. The first Burleigh machines, for example, could not run over 50 hours without major repairs and four machines were kept in stock for every one in operation at the face.¹¹ Three of the early Ingersoll drills were required to keep one at work.¹² By 1873, however, the drills had been improved so that one machine was used for 3 months without repairs and during "that time it drilled upwards of a mile of ground."¹³

The history of the piston drill is one of continued technical progress. After the early Couch and Fowle patents expired, a number of rock drills embodying improvements in design came on the market. Competition among manufacturers and gradual acceptance of the drill by the mining industry, plus the demand for machines adapted for specific uses constantly spurred the makers to provide better drills.

¹⁰Royal J. Day, "Rotating Mechanisms for Rock Drills," *Engineering and Mining Journal-Press*, Vol. 115, No. 23 (June 9, 1923), pp. 1017-23.

¹¹E. Gybbon Spilsbury, "Rock-Drilling Machinery," *Transactions of the American Institute of Mining Engineers*, Vol. III, p. 147.

¹²*Ibid.*

¹³Letter from the Burleigh Rock Drill Co., *Engineering and Mining Journal*, Vol. XVIII, No. 16 (Oct. 17, 1874), p. 246. The Burleigh Company contradicted the charges of frequent break-downs and high costs made by Spilsbury (see Spilsbury, *loc. cit.*). It is probable that he referred to the first model and they to the "Improved Burleigh" of 1868.

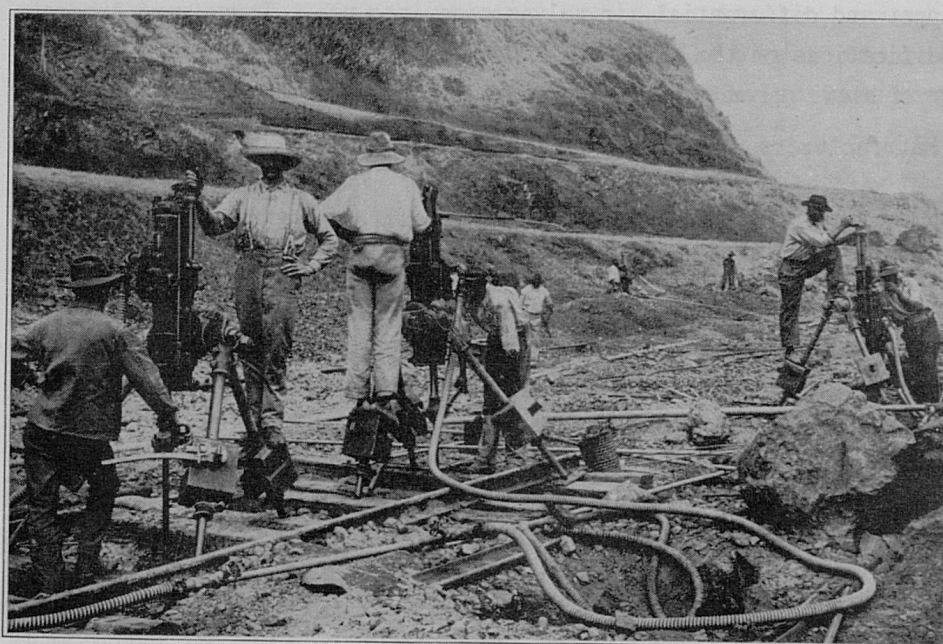


FIGURE 5.— LATER MODELS OF THE PISTON DRILL

About a quarter century ago, when these photographs were taken, the piston drill was highly developed and probably the most widely used machine for drilling blastholes. It made possible about a tenfold increase over hand drilling in output per driller-shift. The machine usually required two men, one of whom had little to do except when setting up or tearing down the drill.

The upper illustration shows a typical underground machine in use in an iron mine. The heavy double-screw column (used as a bar) was necessary to withstand the shocks of the blows transmitted through the rigidly coupled drill steel and piston rod. The lower illustration shows heavy models used for drilling deep holes in excavation for the Panama Canal.

One of the early important improvements was the use of "side rods" about 1875. Before that time the heads (end covers) were firmly bolted to the drill cylinder and were not infrequently broken by the piston's striking them. With the side rods, or long bolts, which carried small coiled springs at the ends, the heads were pulled together against the ends of the cylinder. With this arrangement the springs acted as buffers if the piston struck a head and an inexpensive rod would be broken if the blow was unusually severe.

As the rapidity with which rock could be bored depended partly on the number of blows struck, much attention was given to study of valves in the effort to increase drilling speed. The first step was to enclose all of the valve gear, which eliminated much leakage of air as well as breakage of the exposed parts. In the early eighties the use of the "differential-air" valve came into use. This valve was operated by the steam or air which actuated the drill and had no metallic connection with the piston. Later auxiliary valves embodying the principles of the tappet and differential-air valves came into use. There were numerous modifications of the three principal types, and they increased the number of blows per minute three or four times.

Manufacturers were quick to take advantage of progress in iron and steel metallurgy. An increasing variety of high-tensile-strength steels and alloys became available and by 1897 piston drills weighing 210-250 pounds unmounted were on the market. About 1912 powerful drills weighing one quarter less were manufactured. At the same time there were improvements in air-compressor equipment and working air pressures were increased from 40 to 60 pounds to about 70 to 90 pounds per square inch.¹⁴ This aided in further weight reduction as it was possible to use cylinders of half the diameter and still provide higher drilling speeds and greater mobility than with the early models. The cost of the machines was also reduced.

Disadvantages of the Piston Drill

Despite all of these improvements, the piston drill remained a comparatively cumbersome, heavy, and awkwardly mounted tool. The task of setting up the drill, particularly in a small raise, was long and difficult. In consequence, when it was found that a hole was inaccurately pointed after the machine had been set up it was the usual practice to continue drilling the hole as pointed rather than to spend the time and energy

¹⁴H. W. Seamon, "Relation of Air Pressure to Drilling Speeds of Hammer Drills," *Transactions, A.I.M.E.*, Vol. LXVI (1922), pp. 755-6.

required for resetting the drill. Two men were needed to set up the machine, although with experienced and skillful machine runners and improved models there was little or no work for the second man (a helper commonly called a "chuck-tender") to do while drilling was in progress.¹⁵ Attempts to reduce the weight so that one man could handle the drill so curtailed the drilling speed as to make the lighter drill unsatisfactory, and the miners strongly resisted the use of a one-man drill. Moreover the difficulty and unpleasantness of drilling holes sharply inclined above the horizontal with the piston drill virtually precluded its use for such work. Thus, the piston drill remained essentially a two-man machine and its usefulness was limited to work on the levels and in those stopes where almost horizontal or down-holes could be drilled.

Difficulty in removing cuttings from the drill hole was another factor that limited the drilling efficiency of the piston machine. Holes pointed above the horizontal were drilled dry and if the holes pointed steeply upward the cuttings fell out by gravity. Where the inclination of the holes approached the horizontal or pointed downward, however, the cuttings at the bottom of the hole cushioned the blow of the drill bit unless the drilling process was interrupted and these chips and cuttings were removed with a spoon, swab stick, or blowpipe. In holes pointing below the horizontal, water usually was introduced by the chuck-tender and mud was splashed out of the hole.¹⁶ As the hole grew deeper, however, it became necessary to stop the machine from time to time, withdraw the drill, and clean out the cuttings.

The reciprocating action of the drill steel and the length of the stroke caused considerable friction loss which mounted rapidly when the hole "got out of line" or became crooked and the steel had to be forced around the bend at every stroke. Moreover, much energy was required to overcome the inertia of the moving mass at the end of each stroke.

Despite its shortcomings the piston drill was widely used in mining as the first practical mechanical drill for work underground. Not only did it represent the important transition from manual to mechanical drilling and the development of greater efficiency in the drilling process, but

¹⁵"The One-Man Drill," *Engineering and Mining Journal*, Vol. LXVIII, No. 19 (Nov. 10, 1904), p. 739. "The mine manager . . . is doing his best to get rid of the two-man air drill, especially in stoping. Costs underground have long suffered from that high-priced gentleman, the 'chuck-tender,' or machine helper, whose business it is to tap the steel with a hammer when it sticks in a hole and is in danger of 'fitchering,' to tighten a bolt and do other small services. . . . [He is] absolutely necessary to assist in 'setting up' or 'taking down' the machine . . . in effect, the chuck-tender is paid for a shift, while he is busy actually less than 20 minutes in the hour."

¹⁶The water not only facilitated the removal of the cuttings but also kept the drill steel cool and thus aided in maintaining the temper and cutting edge of the drill bit.

also, until the first decade of the twentieth century, it was virtually the only drilling machine used underground. Since then the piston drill has given way to the hammer-type drill and is today seldom used in either underground or surface-mine operations.

HAMMER DRILLS

The disadvantages of the piston drill were serious enough to cause engineers to cast about for a different kind of drill that would be cheaper to operate, easier to handle in narrow places, and faster in boring through the rock than the piston machine. They turned to one of the earliest principles in rock-drilling techniques - that of the hammer-and-drill. In 1897 J. George Leyner developed a mechanical hammer drill that soon challenged the position held so long by the piston machine.

Hammer-Drill Development

The hammer drill constituted a radical departure from the accepted principles of mechanical rock-drill construction as embodied in the piston drill. In the hammer drill the piston moves freely in the cylinder and strikes the drill steel, whereas in the other the piston is rigidly attached to the steel and they reciprocate together. The work done in drilling a hole is a function of the kinetic energy of the moving drill parts and varies as the product of their mass by the square of their velocity. In the piston drill the inertia of the large mass of the piston, piston rod, and drill steel prevented the attainment of high speeds. The moving part of the hammer drill (the hammer or piston) was smaller than the piston of the other drill and could reciprocate much more rapidly. Thus the hammer drill with its free-moving or floating piston striking light high-frequency blows could perform the same amount of work as the heavier but more sluggishly acting piston drill.

So complete a change in operating principles gave rise to several technical problems upon whose solution depended the success of the hammer-type rock drill. Among these was the necessity of devising a more effective valve arrangement than that of the piston drill; for example, an air-thrown valve was needed that had large openings and was quicker-acting. Materials strong enough to withstand this rapid-fire action of the hammer drill had to be developed as well as some method for cushioning the back-stroke. Two other problems were the rotation of a steel not rigidly attached to a moving piston and removal of the cuttings from the drill hole without loss of drilling time. The latter was of utmost importance to efficient utilization of the hammer drill, which has very small amplitude of movement; for, unless the cuttings were removed and a fresh or

clean rock face presented to the cutting edges of the bit, the chips packed around the bit and prevented effective progress into the rock.

These were difficult problems and a relatively long time elapsed before hammer drills were widely adopted for commercial use. In the first decade of the new century, however, they proved their value and in 1912 W. L. Saunders, a close observer of rock-drilling progress, felt sufficiently sure of the usefulness and importance of the hammer drills to tell the American Institute of Mining Engineers that "a hammer drill is the modern progressive miner. It has practically done away with hand drilling and in doing this it has largely increased the field of service. There is no longer any question about the fact that it pays to use power drills in all classes of mining."¹⁷

Types of Hammer Drills

The early hammer drill was used for all kinds of drilling¹⁸ but special models were later developed for particular purposes. By 1912 three types of hammer drills were in widespread use for special kinds of underground drilling - the stoper for up-holes, the drifter for relatively horizontal holes, and the jackhammer for down-holes.

The Drifter Drill.- Leyner's first drill utilized air blown through the hollow drill steel for expulsion of cuttings, and in 1898 he produced the Water Leyner,¹⁹ a similar drill which was the first to use a combined stream of air and water. Because it was imperfect technically and because no practicable method of rolling the necessary hollow steel was available, the drifter drill, as it is commonly called, was not widely used except in the western mining regions until about 1909.²⁰

The drifter drill is one of the most widely used machines in mining. It is an automatically rotating²¹ mounted hammer drill with hollow drill steel and a piston containing a water tube which projects through the front head of the machine into the hole in the steel. The front head of the drill is constructed so as to permit the introduction of compressed air at a higher pressure than the water which is forced through the water

¹⁷W. L. Saunders, "Rock-Drilling Economics," *Transactions, A.I.M.E.*, Vol. XLVII (1914), p. 156.

¹⁸Charles A. Hirschberg, "Development of the Rock Drill in America," *Engineering and Mining Journal*, Vol. 108, No. 17 (Oct. 25, 1919), p. 679.

¹⁹Charles A. Hirschberg, "History of the Water Leyner Drill," *Mines and Minerals*, Vol. XXI, No. 3 (Oct. 1910), p. 148.

²⁰*Ibid.* The fact that six models of the Leyner drill had appeared by 1905 and that Leyner had enlarged his factory provides the basis for the assumption that the drifter drill had become popular rather early in its life.

²¹The partial rotation of a drill after each blow should not be confused with the feed (manual or automatic) that moves the drill forward in the hole.

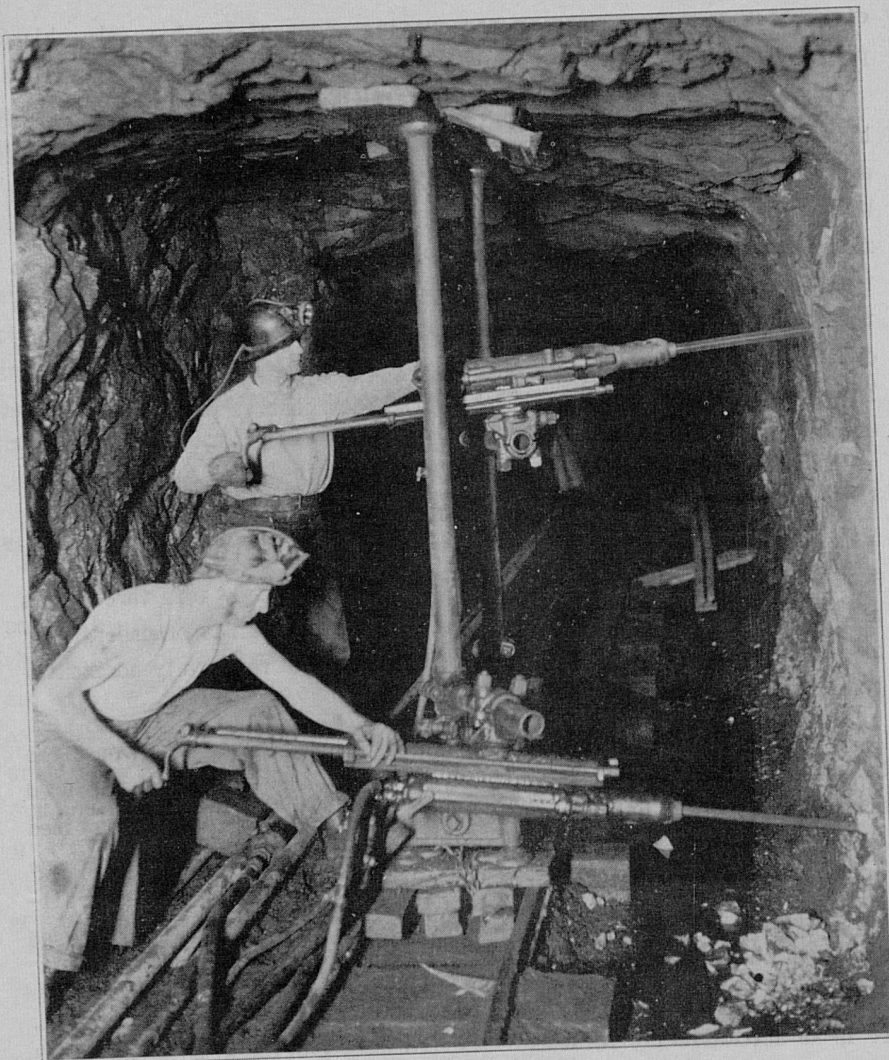


FIGURE 6.- LATE-MODEL DRIFTERS IN AN AMERICAN GOLD MINE

The modern, wet drifter drills illustrated drill about twice as rapidly as the piston machines. They are usually one-man machines. Some models have an automatic feed in place of the screw feed illustrated. The small size of the drill support contrasts with that shown in figure 5.

tube. By the principle of the injector²² the air mixes with the water and forces it to the bottom of the hole. The water wets and settles the greater part of the dust and the air ejects the mixture of cuttings and water from the hole.

²²The injector is a device for introducing water into a steam boiler by the direct action of live steam; the steam is blown through a nozzle that is continually surrounded by water and thus a vacuum is created. The water rushes into the vacuum and the mixture of steam and water is forced along a feed pipe into the boiler.

Rotation of the drill steel always has been automatically effected in the drifter drill. The early models utilized substantially the same rifle-bar and ratchet-and-pawl system as the piston drills, but in the hammer drill the rotation was imparted first to a chuck-sleeve or bushing that turns the steel. Some of the more recent models have been constructed with an independent air engine within the body of the machine to rotate the drill steel. Although this engine adds about 20 pounds to the weight of the machine it has increased drilling speed by greatly reducing the considerable friction loss in effecting rotation by the method first described and has added further to the drill efficiency by providing a rotation completely independent of the hammer movement.

The early models of the drifter drill were fed forward by hand with a feed screw and crank mechanism identical to that employed on the piston drill. Recently automatic feeds have been developed for which increased drilling speeds are claimed.

Although lighter than the piston machines the first drifters were still relatively heavy pieces of equipment, weighing about 150 pounds unmounted. Because the reaction to its light blows was much less than to the heavy blows of the piston machine, however, lighter supports could be used. Moreover, after it had been mounted - first in a shell and then on a tripod, column, or bar - and set up for operation it required less work than the piston drill. The drill steel of the drifter could be changed without loosening or tightening nuts, and if the hole were free the change took but a minute or two. Even the earlier models of the drifter drill could be operated by one man, although a helper was usually employed. The drifter also used less compressed air than the piston drill.

Every effort continued to be made consistent with good design to reduce the weight of the drill. There are now three standard sizes of drifters as well as heavier special models for long-hole work. The standard modern drills weigh 125 to about 180 pounds and have cylinder diameters of 3 to 4 inches. The heaviest machines used in very hard rock and large tunnel jobs generally are two-man drills; the intermediate size is often run by one man, or by one man with a helper serving several drills; the smallest size is universally a one-man drill.

Comparisons of efficiency of the piston and the drifter drill usually resulted in favor of the latter. Drill steel of smaller diameter could be used with the drifter because the blows of the floating piston were lighter. This one factor in itself meant greater footage per machine-shift. As the hole became deeper the rate of drilling with the piston drill diminished perceptibly because of the added weight of the longer

drill steel and the increasing friction of the steel against the side of the hole. The rate of advance with the drifter machine varied but little throughout the length of the hole, provided of course that the bits were of the proper gage and not dulled, and that the hole was free.²³

When the mounted hammer drill first appeared the piston machine was already rather highly developed, and it continued to be improved. Moreover, the mine operator was reluctant to scrap old equipment until the new drill had passed the trial stage, and was unwilling to undertake the additional expense of providing a water supply. In certain instances the miners resented the one-man drill because of its possible effect upon employment opportunities. The principal reason for the slow displacement of the piston drill, however, was the long time that elapsed before a satisfactory hollow drill steel was available for use in the drifter drill. These difficulties were gradually overcome, and today the drifter drill is used in all fields of mining. In underground work it is mainly employed for boring horizontal or approximately horizontal holes, as well as for driving drifts and tunnels. It works well in hard rock and since the addition of the independent rotation it has been found particularly well suited to soft or seamy rock. Its wide application at surface operations is discussed in the section on surface drills.

*The Stoper*²⁴.— The stoper — a hammer drill mounted on an air feed-leg — was introduced about 1906 by C. H. Shaw of Denver²⁵ and rapidly achieved wide popularity, especially for the drilling of holes inclined above the horizontal and for work in stopes and raises. Hand-held pneumatic drills²⁶ were called stopers too and were used quite widely at the beginning of the twentieth century. These were soon discarded, however, because the task of holding the drills for up-hole work was so severe that many drill runners would not use them.²⁷

The modern stoper is an air-actuated hammer drill with a pneumatic feed cylinder that holds the drill steel up against the working face. This cylinder — usually $2\frac{1}{2}$ to 3 inches in diameter — is provided with a piston attached to a rod terminating in a pointed shoe. In many drills

²³A drill hole is said to be "free" when it is straight, not rifled, and contains no excessive amount of cuttings. Under such conditions, the drill runner can easily turn the drill by hand or withdraw it without difficulty.

²⁴The name applied to this type of machine was probably due to the fact that it performed its best work when drilling up-holes and was, therefore, used primarily in stopes.

²⁵Hirschberg, "Development of the Rock Drill in America," p. 679.

²⁶See the discussion of "hand-held hammer drills" later in this chapter.

²⁷H. L. Sinclair, "The Development of the Air-hammer Drill," *Engineering and Mining Journal*, Vol. LXXXIII, No. 15 (Apr. 13, 1907), p. 715. "It was next to impossible to get men who would hold the machine over their heads and drill uppers. One could not blame the drill runners, as it was certainly an awful task to set a man at, and only the very strongest could stand it for any length of time."

the hammer both strikes and acts as a valve and the machine is, therefore, called a "valveless" drill. Generally, to prevent cuttings from working into the drill and to prevent the unshanked drill steel from following the hammer down, a small piece of steel called the "anvil block" is interposed between the hammer and drill steel.

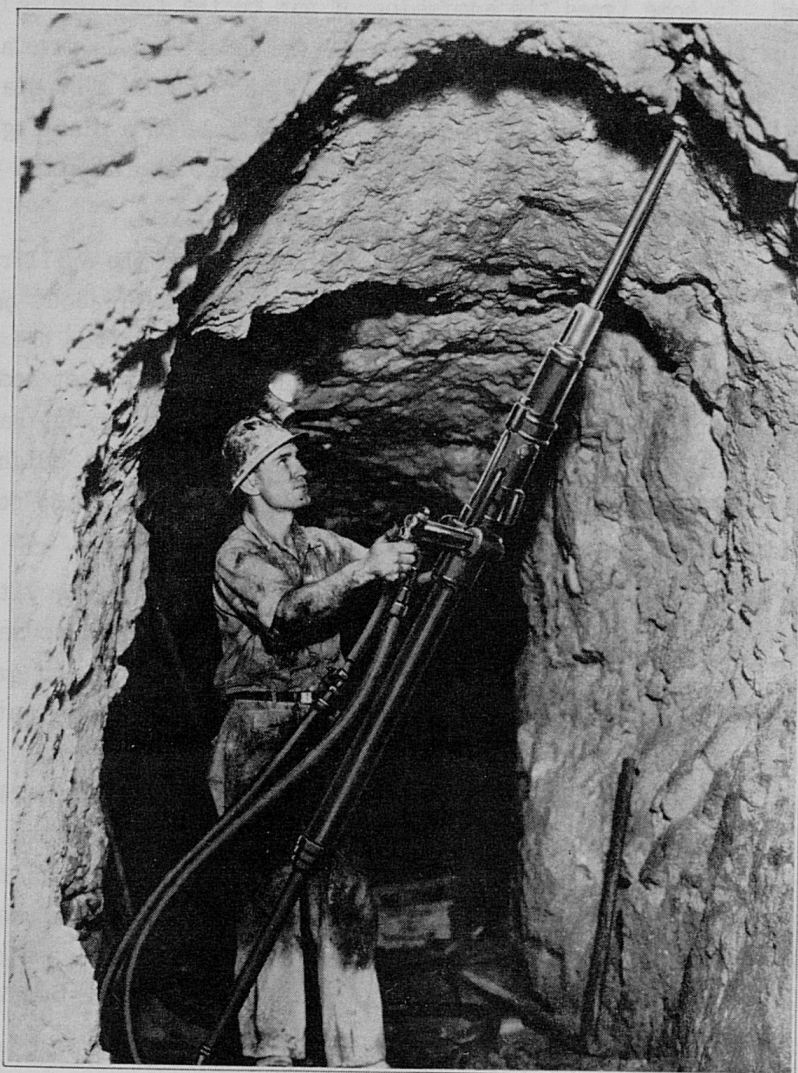


FIGURE 7.— AUTOMATIC-ROTATING WET STOPER

This type of hammer drill was developed about 30 years ago and was quickly accepted because it greatly simplified and lightened the task of drilling holes that were inclined above the horizontal. As it is self-supporting and of moderate weight, it has always been a one-man machine and generally averaged a high footage per shift compared with other underground drills.

In drilling upward-pointing holes the cuttings fall out by gravity. The high cutting speed of the stoper aggravated the dust hazard when the holes were drilled dry. Wet stopers became available about 20 years ago but there was some objection to their use at first because of the annoyance caused by water and mud falling on the drill runner. The addition of automatic rotation to the wet stopers overcame that objection and the dust menace has been greatly reduced where such models are used.

To set up the stoper, the drill is inserted in the chuck and the pointed shoe at the end of the piston rod is placed against some sort of solid footing - the wall, muck pile, or a temporary platform. As the air valve is opened the drill is raised on the feed-leg until the steel comes into contact with the rock. Further opening of the valve begins the actual drilling. In some types the admission of air to the feed-leg is independent of that to the drill proper; some of the latest models have a pair of such feed-legs with independent controls which provide a substantial support for the drill, make it easier to start a hole on a slanting surface, and permit the operator to perform other incidental duties while the drill is running.

As first constructed the stoper was hand-rotated, and the drill runner constantly revolved the whole machine through an arc of about 90 degrees by means of a short arm projecting at right angles from the drill cylinder. In 1921, however, the familiar rifle-bar and ratchet-and-pawl system was applied to the stoper. It became quite popular but has not been universally adopted because it adds considerably to the weight and initial cost of the machine; hand-rotated stopers weigh 60 to 90 pounds, self-rotating models 80 to 120 pounds.

The problem of keeping the drill hole clear of cuttings, so vital to the commercial development of the drifter drill, presented no serious obstacles to the use of the stoper. In up-hole work the force of gravity causes the cuttings to drop out of the hole and there was no great need for hollow steel. The dust that resulted from drilling with solid steel, however, was a serious hazard to health. The dry stoper was nicknamed the "widow-maker" by the drill runners because of the numerous cases of pneumoconiosis (a disease of the lungs caused by habitual inhaling of minute mineral or metallic particles) resulting from its use. To overcome the dust hazard an external spray of water that played on the collar of the hole was used but it was both inconvenient and ineffective and the miners would not use it unless closely supervised.

Soon after a commercially feasible method of rolling hollow drill steel was developed a water attachment similar to that used with the wet drifter was adapted to the stoper. Hand-rotated wet stopers proved unpopular because the water dripped on the hands and arms of the drill runner and the water hose made turning the drill harder. The heavier self-rotating type, however, gained headway despite the fact that its use presented certain difficulties. The use of a wet stoper involves the additional burden of dragging a water hose to or with the machine and providing a water supply in stopes. In steep or narrow raises, the

water line and the greater weight of the drill add materially to the amount of labor and the difficulty of carrying and setting up the machine. Furthermore, the machine runner inevitably is splattered with mud and water that drip from the hole, and consequently he must stop frequently. Because of the inconvenience and loss of time the operators sometimes prefer to "drill dry and eat the dust", especially in those mines in which payment is made on a basis of footage drilled per driller-shift. It is encouraging to note, however, that growing realization of the danger of dust to the health of the worker as well as of the increased drilling speed obtained where wet stopers are employed²⁸ has evoked a decided trend away from dry drilling.

The drifter and stoper were quite similar technically yet their histories and fields of application have been quite different. The drifter was first introduced in 1897 and the stoper about 1905-06, but the latter was generally accepted before the drifter because of the difficulty in developing a satisfactory method of removing cuttings from drifter-drilled holes and the more pressing need for an up-hole drilling machine. The piston drill could bore both horizontal holes and uppers but it was quite unsatisfactory for the latter.

The stoper is used almost exclusively for up-hole drilling and the drifter for horizontal because of the differences in the kind of mounting. The pneumatic feed of the stoper is an integral part of the drill and holds the steel up against the working face. The drifter, on the other hand, is placed in a cradle or shell that is mounted on a column or bar, and the drill steel is fed forward to the face by a crank-and-screw mechanism or by an air-actuated automatic feed. Occasionally the stoper is used to drill horizontal holes by mounting on a bar or by simply laying it flat with the foot resting against some stop.

Hand-Held Hammer Drills.—More closely akin to the stoper than the drifter drill were the light hand-held hammer drills,²⁹ the plugger, and the jackhammer.³⁰ They were developed from the early pneumatic chipping and riveting hammers in common use about 1900. The efficiency of these pneumatic tools was due to the fact that the nonrotating reciprocating hammer was so light that high speed could be obtained without great air consumption and little power was wasted in overcoming inertia.

²⁸Lucien Eaton, "Rock Drills and Accessories," *Engineering and Mining Journal*, Vol. 134, No. 2 (Feb. 1933), p. 68.

²⁹About 1884 Sergeant had built a hammer drill and before 1890 Shaw had experimented with the same type but as hollow steel was then unknown they found no application in mining.

³⁰In this report the term "plugger" refers to the hand-held, hand-rotated hammer drill; "jackhammer", to the automatic-rotating, hand-held hammer drill.

The Plugger.- The hand-rotated plugger was used principally for block-holing,³¹ and light work that did not require holes of more than 3 to 4 feet. It³² weighed 14 to 65 pounds, had a cylinder diameter of $1\frac{1}{16}$ to 2 inches, and usually was less than 2 feet long.

Either solid or hollow steel $\frac{7}{8}$ to 1 inch in diameter was used with the plugger rock drill. Where hollow steel was used the holes were kept clear of cuttings by discharging exhaust air at the bottom. This drill was also equipped with a simple device to permit live air to enter at the bottom of the hole and remove chips not cleared by the exhaust air. It was a popular machine³³ and the forerunner of both the stoper and the jackhammer.

The Jackhammer.- The plugger, stoper, and drifter together furnished the mining industry with a combination of hammer drills that could be adapted - with some slight inconvenience, perhaps - to any conditions encountered in underground rock drilling. There persisted, however, a demand for a machine light enough for one man to operate and less restricted in its field of application than either the stoper or the plugger. The jackhammer, introduced in 1909, filled this demand so satisfactorily that it rapidly became the most popular type of drill for down-hole drilling underground in rock and ore, for shaft sinking, for quarrying, and for coal mining.

The jackhammer is a hand-held hammer drill having the common rifle-bar rotation and usually is motivated by compressed air. Heavy models are used for holes as deep as 15 to 20 feet. The standard present-day jackhammer has a cylinder diameter of $2\frac{1}{2}$ to $2\frac{3}{4}$ inches and weighs 40 to 50 pounds - considerably less than the early models which usually weighed about 100 pounds. Other models weighing from 25 to 115 pounds are available for special kinds of work. The lightest machines are used for block-holes, hitch cutting, etc.; the heavier models for heavy drilling tasks in extremely hard rock, for shaft sinking, and for some quarry work.

The problem of the removal of cuttings, especially in down-hole work where the jackhammer is most useful, already had been solved in the drifter drill. The earliest jackhammers, like the pluggers, used air to blow out the cuttings, but about 1911 the wet machine came on the market. It used hollow steel $\frac{7}{8}$ to $1\frac{1}{4}$ inches in diameter and a water-air jet like

³¹Block-holing is a method of breaking large boulders or rocks by firing a charge of high explosives in a shallow hole.

³²The earliest of these drills, called a "plug" drill, was employed in quarries to drill holes a few inches deep in which were placed the "plugs-and-feathers" that were used to separate blocks of stone. The steel was turned with a wrench.

³³An editorial, "The Hand-Hammer Drills," in the *Engineering and Mining Journal*, Vol. LXXX (Sept. 9, 1905), p. 450, reciting some of the characteristics of the hand-hammer drill, said that this drill had "come to stay."

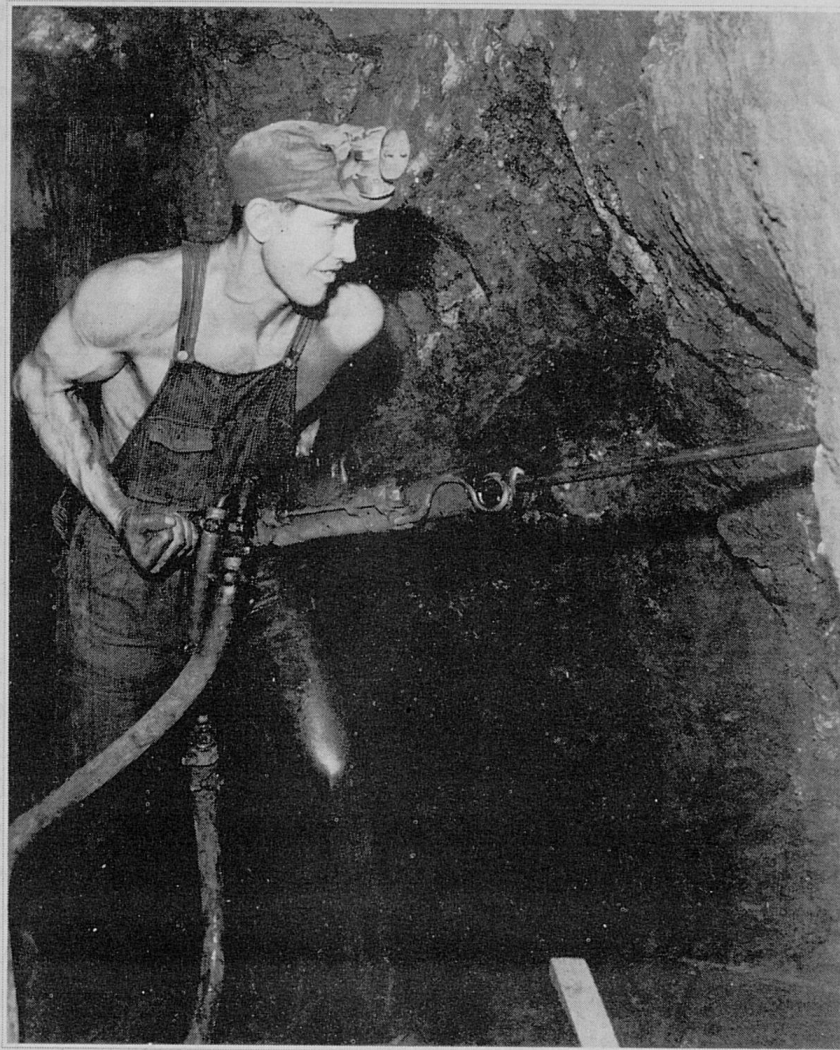


FIGURE 8.— A WET JACKHAMMER IN AN UNDERGROUND MINE

This machine has the widest utility of the hammer-drill group. Though intended as a down-hole drill it is sometimes used unmounted to drive horizontal passages. When the drill is so used considerable strength and endurance are required.

With simple changes the jackhammer may be converted in a few minutes into a light drifter or stoper and it thus serves as an all-purpose tool for the small mine or prospect where the ground is not so hard as to require a heavier or more powerful drill.

that of the drifter. In shallow work, however, such as block-holing, dry drilling is still common practice.

The mobility of the jackhammer, from which results a great part of its popularity, is due not only to its lightness but also to the fact that it need not be mounted for either down-hole or breast work. It is equipped with a bar handle by which the operator holds the machine when drilling or while carrying it from place to place. If necessary, however, it can be placed in a shell and mounted on a column or bar like the drifter or piston drills or on an air feed-leg like a stoper.

In addition to the standard models, there is a light jackhammer that weighs about 40 pounds and uses solid twisted auger steel. This drill, which combines the percussive action of the hammer drill with the rotary motion of the auger, has been employed widely in certain soft ore, coal, and nonmetal mines.

The advent of the jackhammer was a milestone in the evolution of underground drilling equipment and provided overwhelming evidence of the advantage of the machine over human muscle for work underground. The frequent arguments and contests between the advocates of mechanical drilling and hand drilling were finally settled in August 1912, when the last match between hand and power drilling was staged at Calumet, Mich. An observer reported that "a three-man double-jack team of the best drillers in the copper country was pitted for a money prize against a small hammer drill of the Butterfly type [so-called from the fluttering action of the thin plate valve]. This machine was operated by one man. The drilling was in a block of Cape Ann granite, 60 inches thick. The three-man drilling team started with a $1\frac{1}{4}$ -in. bit and finished with a $\frac{7}{8}$ -in. bit. The one man with the Butterfly used a 2-in. starter and finished with a $1\frac{1}{4}$ -in. bit. It required 14 min. for the machine to drill entirely through the block (60 in.), while the hammer-and-drill squad put in a 49-in. hole in the same time. The machine did 20 per cent. more work with one-third the labor cost. As a matter of fact, no such rate of hand drilling . . . could be maintained over a working shift, while there is no reason why the machine drill should not keep up its speed indefinitely."³⁴ The superiority of the hammer drill was no longer open to question.

THE POWER AUGER DRILL

The mechanical auger is the power-propelled counterpart of the manual auger drill. Like its predecessor it has operated most effectively in relatively soft formations and has not been used in hard rock. Its application has been limited to such soft materials as coal, soft iron ore, clay, slate and gypsum, cement rock, and soft limestone.

The introduction of electricity into mines about 1890 aided mechanization of the auger drill since the electric motor was an ideal prime mover for a rotating device. Late in 1893 electric augers were put into use in coal mines.³⁵ They were reported to have been especially designed

³⁴Saunders, loc. cit.

³⁵Fred J. Platt, "Electric Mining Machinery," *The Colliery Engineer and Metal Miner*, Vol. XVII, No. 11 (June 1897), p. 485. Cf. also trade note in *The Colliery Engineer and Metal Miner*, Vol. XIII, No. 9 (Apr. 1893), p. 207; and "The Jeffrey Electric Coal Drill," *The Colliery Engineer and Metal Miner*, Vol. XIII, No. 11 (June 1893), p. 255.

for "anthracite mining , taking down roof, or *general rock work*" and to have been tested on "rock" and sandstone.³⁶ Compressed-air models were available by June 1895.³⁷ Like other drills the power auger did not at once attain widespread use and in 1897 an observer stated that the "use of power drills in coal mines where electric and compressed air plants are installed has not in the past received [the] consideration warranted."³⁸ It was not until 1900 and 1903 that the electric and compressed-air types were introduced into other than coal mines.³⁹

The twisted or spiral steel of the power auger is attached to a rotating rod, and the drill bores by cutting and scraping. The chips are removed from the hole by the screw action of the steel. The necessary rotary motion is initiated by either a compressed-air engine or an electric motor. The lighter models may be held by one man and are fed forward by pushing against the drill. Heavier types generally are mounted on a tripod, column, or bar or (as is frequently the case in coal mining) are placed directly on the coal-cutting machine or upon a separate truck. In such instances the feed is effected by moving the drill up to the face or by means of a slotted (splined) threaded shaft in which the drill steel is clamped.

Where conditions for its use are favorable the power auger has advantages over the usual hammer drills. These are in large measure inherent in the rotary compared with the percussive method of boring. In general, mechanical augers are also lighter than the corresponding unmounted and mounted hammer drills, for it is possible to use the simple, compact, and highly efficient electric motor or the relatively efficient rotary air engine for the power-auger drive. The power consumption of mechanical augers is also much lower than that of hammer drills. For example a mounted air-driven auger drill requires about one-third to one-half as much air as a light mounted drifter and somewhat less than a medium-weight jackhammer. The electric motor is correspondingly more efficient than the compressed-air engine.

Important betterments in the power auger were a reduction in weight of the motors and an increase in their safety, reliability, and efficiency. The earliest models required mountings, and two men or a man and boy ordinarily were used to run them, but later models were one-man drills.

³⁶"New Electric Coal Drill," *Engineering and Mining Journal*, Vol. LVII, No. 23 (June 9, 1894), p. 536. Underscoring supplied by authors.

³⁷This information was kindly supplied by Robert K. Jeffrey, Jeffrey Manufacturing Co., Columbus, Ohio.

³⁸"Power Coal Drills," *The Colliery Engineer and Metal Miner*, Vol. XVIII, No. 2 (Sept. 1897), p. 80.

³⁹See ftn. 37.

There are now light hand-held types, as well as a powerful model for drilling horizontal large-diameter blastholes.⁴⁰ Auger steel generally is larger in diameter than that used for the drifter drill and is obtainable in sizes large enough to bore a 5- or 6-inch hole. The quality of auger steel, moreover, has been greatly improved. Detachable bits were provided for the auger drill even before power was applied to it and about 20 years before such bits were used with percussive drills.⁴¹

A substitute for the power auger adopted for use in some metal and nonmetal (including coal) mines is a light hammer drill of the jackhammer or stopper type using auger steel. The cutting is done by both percussion and scraping and this drill will penetrate harder ground than the simpler power auger. Its special field is in those mines equipped only with a compressed-air system where dust is not a hazard and where a dual-purpose drill is desired. Although ordinary hammer drills were first used for such work, later models were developed that rotated more strongly and rapidly and struck a lighter blow than the standard machines.

Data on the effectiveness of the mechanical improvement of the drill auger are not available but the general effect of these changes can be illustrated by a few examples. In 1870 tests made in some English coal mines with the manual threaded-bar auger showed that one man could accomplish 4 to 12 times as much with this machine as with a jumper or hand churn drill.⁴² Twenty years later, when the hand drill-auger was quite commonly used in coal mines in this country, it was claimed that an improved model "will drill 5 or 6 holes with the expenditure of less labor and time, than will be expended in drilling one hole by the old [hand-churn] method."⁴³ Early electric-powered models showed further important gains over the most effective hand machines. At one colliery the cost of taking down rock in a heading with an early electric auger was reported as \$3.74 per yard compared with \$6.00 with the hand auger.⁴⁴ Later types of portable electric or compressed-air augers operated by a man and boy could drill a hole 6 to 7 feet deep in about $1\frac{1}{2}$ minutes, while by hand it would have required 20 to 40 minutes.⁴⁵ Modern power augers have still higher drilling speeds.

⁴⁰"Auger Drills 50-Ft. Horizontal Holes," *Engineering and Mining Journal*, Vol. 134, No. 2 (Feb. 1933), p. 85.

⁴¹"The Cyclone Mine Drill," *The Colliery Engineer and Metal Miner*, Vol. XIII, No. 3 (Oct. 1892), p. 64.

⁴²"Boring by Machinery," *Engineering and Mining Journal*, Vol. X, No. 15 (Oct. 11, 1870), p. 228.

⁴³"Bittenbender's Improved Mine Drills," *The Colliery Engineer and Metal Miner*, Vol. XII, No. 1 (Aug. 1891), p. 16.

⁴⁴Platt, *loc. cit.*

⁴⁵"Power Coal Drill," *Mines and Minerals*, Vol. XXV, No. 5 (Dec. 1904), p. 236.

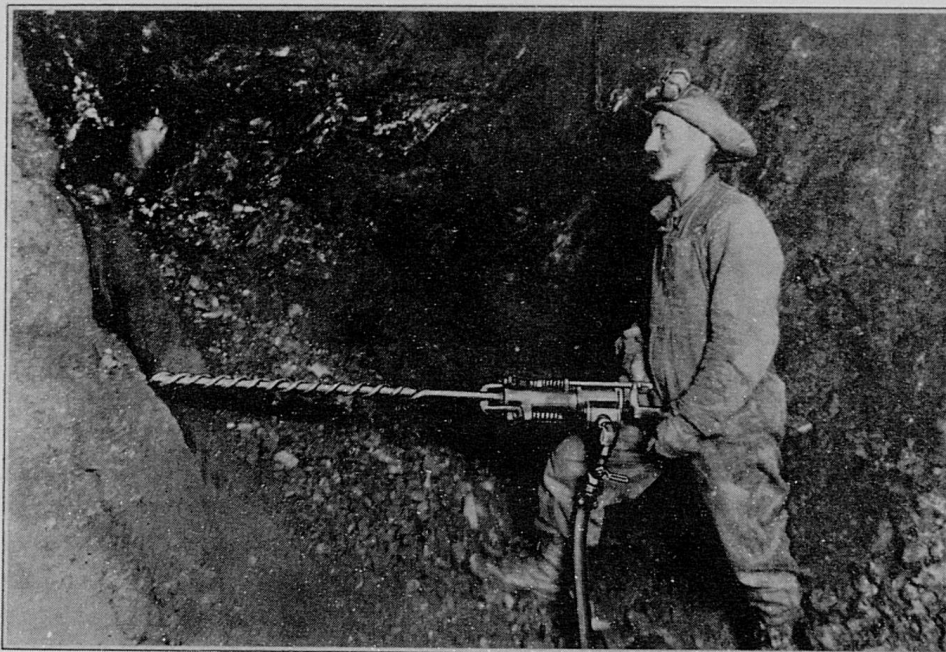


FIGURE 9.— A JACKHAMMER AUGER IN AN IRON MINE

The ordinary auger drill bores by a scraping action and this limits its application to relatively soft materials. The field of usefulness of the rotary borer was expanded to include moderately hard rocks such as iron, phosphate, salt, and other ores (where the dust hazard was slight) by combining the percussive motion of the jackhammer with the rotary bit motion. At first the regular types of hand-held hammer drills were used but later special models which had a stronger rotation and struck lighter blows were developed. Under certain conditions this type of machine is displacing the ordinary electric or air-driven auger drills.

CHANGES IN MOTIVE POWER, MATERIALS, AND PARTS

Since 1912, advances in the art of mechanized rock drilling underground have been confined largely to improvements in the existing types of drilling machines through the development of new materials and parts, through stronger construction, and through changes in kind and amount of motive power employed. With the aid of such improvements great strides have been made in accelerating the rate of drilling and in reducing expenditure of both time and of energy. The net results of these changes have been translated into savings in repairs and indirect labor costs as well as into lower direct costs of drilling per foot of hole.

Changes in Motive Power

Early in the history of the mechanical rock drill it was apparent that the kind and amount of power consumed by a rock drill were very important factors in the effectiveness of the machine, and much effort has been made to improve drill motivation. The first powered rock drills were actuated by steam,⁴⁶ and though fairly satisfactory for tunnel work they

⁴⁶ A number of hand-powered percussive and rotary drills have been patented but none became commercially significant.

could not be used widely in underground mines.⁴⁷ Air-compressing machinery was available when the first practical rock drill came on the market and it was a simple step to substitute compressed air for steam. The increased demand for air compressors that followed this development led to improvements in their design, capacity, and efficiency along with those in the rock drill. The rock-drill manufacturer early began to build compressors and today the leading drill manufacturers are among the outstanding constructors of air-compressor equipment.

From the beginning there has been an almost constant tendency toward the use of increased air pressures with rock drills. Until recently the possibilities of using air pressure of about 100 pounds or more per square inch were largely limited by the weakness of the materials used in the construction of drilling machines and drill steels, and by the great emphasis placed on reduced weight. To be strong enough to operate under relatively high pressure the earlier drills had to be very heavy, and a higher drilling rate was obtained only at the expense of considerably more steel breakage, of rapid dulling of the steel, and of higher repair costs.⁴⁸ Improvement of the quality and strength of drill steel and the development of strong but light materials for drill construction opened new possibilities for accelerating the speed of drilling by applying higher air pressures.

Many attempts have been made to actuate rock drills by electric power. Between 1900 and 1910 seven or more such drills came upon the market and a few managed to obtain a temporary foothold. Although they required only about one-third the power of the compressed-air piston drill no marked success attended the attempts to convert the rotary motion of the electric motor into the reciprocating action essential to the operation of percussive rock drills. The maintenance cost was excessive and much time was lost from break-downs. Several pulsator-type piston drills, known as electric air drills, appeared about 1902.⁴⁹ The first were unsuccessful, but experimentation with them continued and by 1914-15 they were being used rather widely, and it was reported that they consumed less power and drilled more rapidly than the ordinary pneumatic machines.⁵⁰

⁴⁷"Rock Drills," *Mines and Minerals*, Vol. XXV, No. 10 (May 1905), p. 497.

⁴⁸F. M. Hitchcock, "Air Required to Operate Rock Drills," *Mines and Minerals*, Vol. XXV, No. 10 (May 1905), p. 487.

⁴⁹This machine consists of two units: a small electric air compressor and a simplified rock drill without valves, side rods, and other minor parts. The compressor was connected by two short hoses to the drill whose piston was actuated by the pulsations of compressed air. Since the air was not exhausted but was used merely as an elastic power-transmission medium in a closed circuit the power requirements were low.

⁵⁰David W. Brunton and John A. Davis, *Safety and Efficiency in Mine Tunneling* (U. S. Dept. Int., Bur. Mines, Bull. No. 57, 1914), pp. 111-2.

The initial cost of these drills was high, electric-transmission lines had to be provided for their use, and the closely coupled compressor-drill combination was so bulky and awkward to handle that its use was limited to work on the levels. Most of these machines were discarded within a few years.⁵¹

Changes in Materials and Parts

Significant progress in reducing the weight of rock drills and increasing their durability has been made by changing and improving the materials and the methods of treating the metals for rock-drill manufacture. In the first rock drills, for example, cast iron had been used extensively. Its resistance to shock was low, and strength was attained only by making the parts very heavy. Designers very early began to replace cast iron with steel. This was an important forward step but even the steels employed varied in quality and it was not until about the turn of the century that materials of relatively uniform quality and characteristics were available. Subsequently a wide range of alloys was developed, and it became possible to select a material best suited to a specific purpose. The modern drill is composed almost entirely of steel castings and drop forgings; and the moving parts such as hammers, anvil blocks, rifle bars, etc., are made of alloy steels.

Exact specifications for composition and heat treatment of the metal used in each part of the drilling machine have been set up to allow for the strains and stresses to which the particular part may be subjected. Care is exercised to make all parts within narrow tolerance limits, and they are tested with precision instruments. This was important not only in reducing the weight of the drills but also in permitting changes in structural design. Various drill accessories have also been improved and standardized. The important improvements introduced in this respect have not only reduced the cost of drilling but also increased the productivity per driller-shift.⁵²

*Improvements in Drill Steel*⁵³.— "Drill steel is the spearhead of the entire blasting process. Without dependable drill steel, the most powerful

⁵¹Some unsuccessful attempts have been made to use the explosive power of gasoline in motivating rock drills.

⁵²George H. Gilman, "Heat Treatment of Rock-Drill Steel," *Transactions, A.I.M.E.*, Vol. LXVI (1922), p. 779.

⁵³Hollow drill steel used in hammer drills is usually $\frac{7}{8}$ of an inch to $1\frac{1}{2}$ inches in diameter but solid steel may be as large as 2 inches in diameter. The length of the steel may be as much as 40 feet - depending upon the character of the work for which it is intended. Various cross-sectional shapes are employed, but only three are used extensively. Round steel is used with the drifter drill; the stoper uses quarter octagon (square steel whose corners are slightly beveled) and hexagonal; hexagonal steel is customarily employed with the jackhammer but sometimes round steel is used.

drill would be crippled."⁵⁴ Even in days of hand drilling, mining engineers, superintendents, and drillmen recognized the importance of the steel, but it was not until the adoption of machine drills increased wear and tear on the drill steel that much attention was given to its composition and manufacture and treatment. Poor-quality steel not only impaired the performance of the drill but also lowered the over-all efficiency of the mine; the breakage of steel in a hole, for example, necessitated the boring of a new hole and caused further loss of time by disrupting the process of orderly mining.

To be most satisfactory a drill steel should combine very different qualities. The shank should be tough enough to resist bending and to withstand the shock of 1,600 to 2,200 blows per minute delivered with the force due to 80 to 105 pounds of air pressure, yet not so hard as to cause excessive wear on the hammer face. On the other hand, the bit end of the steel should be extremely hard in order to resist wear and to assure maximum penetration.⁵⁵ In addition, the steel should be easy to forge, and its carbon content such that it can be hardened easily.

Difficult as it was to combine the two primary requisites of hardness and toughness in a single piece of solid steel the problem was complicated even further by the advent of hammer drills and the use of hollow drill steel. Separation of the piston from the drill steel and increased frequency of the blows altered the nature of the stresses imposed upon the steel, and the hole through the drill steel reduced its strength.

Hollow steel, unknown when the Leyner hammer drill was invented, was needed in order to utilize its water-air jet method of removing cuttings. The first product was crude and most unsatisfactory. Short pieces of solid steel were bored and then welded to a hollow iron rod. About 1908 the boring tool used in making gun barrels was employed and pieces a few feet long could be made with some degree of success but the cost was high. The problem of making long bars with a smooth well-centered hole was one with which the drill builder could not cope and it became the task of the steel maker.

Over a period of years several methods of rolling hollow steel were developed and improved.⁵⁶ About 1913, Swedish and American metallurgists

⁵⁴C. H. Vivian, "Rock-Drill Steel," *Compressed Air Magazine*, Vol. 41, No. 4 (Apr. 1936), p. 4991.

⁵⁵For a discussion of qualities essential in bits and shanks, see Frank H. Kingdon, "What is the Ideal Drill Steel?" *Engineering and Mining Journal*, Vol. 111, No. 16 (Apr. 16, 1921), pp. 668-9; also Royal J. Day, "Rock Drill Steel," *Engineering and Mining Journal-Press*, Vol. 115, No. 15 (Apr. 14, 1923), pp. 670-3.

⁵⁶For an account of the history of drill-steel manufacture see Vivian, *op. cit.*, pp. 4991-7. Cf. also P. A. E. Armstrong, "Drill Steel From Hollow Ingots," *Chemical and Metallurgical Engineering*, Vol. 24, No. 22 (June 1, 1921), pp. 960-4; and N. B. Hoffman, "Rock-Drill Steel," *Mining and Metallurgy*, Vol. 17, No. 175 (July 1921), pp. 31, 34.

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investigated the possibilities of making hollow steel by rolling pierced billets of steel over metal cores. The metal ingots were heated and reduced in rolling mills to billets about 4 inches square, which were cut into suitable lengths and pierced with a central hole into which the core was inserted. The billets were then reheated and rolled down to the required size. After they were cooled the core was withdrawn. The method proved quite workable even when lead or iron cores were used, but it was not until the invention in England of the austenitic process⁵⁷ in 1926 that it became really satisfactory. Austenitic steel is elastic and tough and elongates under tension so that a core made from it can be readily withdrawn from the rolled bar. The smooth straight hole of constant diameter left is a decided improvement over the irregular holes that resulted when either other metals or sand was used to support the billet walls during the rolling process. Moreover some of the chromium in the core is diffused into the drill steel at high temperature and materially increases its resistance to corrosion.

Great strides have been made in drill-steel metallurgy, as well as in the processes of its manufacture. Extensive research showed that the most vital points for improvement in the production of good drill "bits"⁵⁸ were composition, heating, and hardening.⁵⁹ Accordingly, many efforts were directed to determining the most desirable constituents of drill steel and the amounts of each ingredient to be included. Recent analyses of various commercial drill steels show that their content of certain ingredients falls within a relatively narrow range and that impurities in the steel have been largely eliminated.

Along with advances in the methods of manufacture and in the metallurgy of drill steels there were important developments in the techniques of sharpening, hardening, and tempering. Drill sharpeners, oil and gas furnaces, and automatic heat-treating machines employed in these processes are more accurate and rapid than even the best manual methods. The use of such technical equipment has made possible a decrease in steel consumption and an increase in the effectiveness and productivity of rock drills.⁶⁰

That "good drill sharpening and hardening are essential factors in securing efficient drilling"⁶¹ is axiomatic. When this work was done by

⁵⁷Austenite is a solid solution of iron and carbon. For the purpose named it was alloyed with chromium and nickel.

⁵⁸Here used to mean the implement; the bit, shank, and intervening material.

⁵⁹See George H. Gilman, "Drill Bits and Drill Steel for Metal Mining," *Engineering and Mining Journal*, Vol. 103, No. 19 (May 12, 1917), pp. 823-32.

⁶⁰George J. Young, "A Review of Drilling, Part III," *Engineering and Mining Journal*, Vol. 112, No. 11 (Sept. 10, 1921), p. 420.

⁶¹*Ibid.*

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⁶⁰George J. Young, "A Review of Drilling, Part III," *Engineering and Mining Journal*, Vol. 112, No. 11 (Sept. 10, 1921), p. 420.

⁶¹*Ibid.*

Table 3.- AMOUNTS AND PROPERTIES OF SOME DRILL-STEEL CONSTITUENTS^a

Constituent	Content (percent)	Properties
Carbon	0.70 -1.00 ^b	Gives strength and hardness
Manganese	0.25 -0.40 ^c	Facilitates forging and increases tensile strength
Sulphur	0.015-0.025 ^d	Impurity; makes steel brittle when hot
Phosphorus	0.01 -0.025 ^d	Impurity; makes steel brittle when cold
Silicon	0.10 -0.20 ^e	Impurity; retards absorption of carbon

^aData are from George H. Gilman, "Drill Bits and Drill Steel for Metal Mining," *Engineering and Mining Journal*, Vol. 103, No. 19 (May 12, 1917), p. 829; Frank H. Kaiser, "Suggestions for Selecting and Testing Drill Steel," *Engineering and Mining Journal*, Vol. 103, No. 20 (May 19, 1917), p. 875.

An ordinary straight carbon steel suitable for drilling in average ground and with the air pressures ordinarily employed would have, in percentages: carbon, 0.85-0.90; manganese, 0.3-0.4; phosphorus and sulphur, less than 0.03 each; and silicon, 0.1-0.2.

^bCarbon content varies slightly with size, shape, and make. These are representative American steels. The carbon content of Swedish steels ranges from about 0.65 to 1.05 percent.

^cSome as low as 0.15 percent.

^dSome as high as 0.04 percent.

^eSome lower than 0.10 percent.

hand the variation in bit size and temper often was so great that the drill runner was apt to use a steel long after it had been dulled rather than search or wait for a sharp piece. Quite frequently too the mine would not have enough steel to permit the drillman to take enough for the day's work to his place when he came on shift. Drilling with dull steel not only impeded the rate of cutting into the rock but also increased steel breakage by causing severe vibrational and torsional strains to be set up in the shank.⁶² At the present time the tendency is toward mechanical methods of steel maintenance. The machine most widely used for this purpose is the power drill sharpener which was introduced as early as 1902⁶³ and first adopted in larger mines. Today only small mines do not utilize such machines. Where a group of nearby mines is under one management a central steel-sharpening shop is sometimes established. It was claimed that the earlier sharpener could do the work of two blacksmiths and two helpers and sharpen about 50 bits per hour of running

⁶²Gilman, "Heat Treatment of Rock-Drill Steel," pp. 784-5. See also S. S. Clarke, "Comparative Tests on Drill-Steel Breakage," *Mining and Metallurgy*, Vol. 14, No. 324 (Dec. 1933), pp. 493-5.

⁶³"Drill Sharpening Machine," *Mining and Scientific Press*, Vol. LXXXVI, No. 15 (Apr. 11, 1903), p. 225.

time.⁶⁴ About 10 years later the machines were capable of sharpening 200 to 400 bits per shift or about two and one-half times as many as a good blacksmith could hand dress in the same time.⁶⁵ Still later models could produce about 375 bits of uniform gage, sharpness, and hardness per 8-hour shift, and machines making shanks could handle 250 to 350 pieces of steel of varying bar diameter.⁶⁶ The latest types are reported to forge new bits up to $3\frac{5}{8}$ inches in diameter at the rate of 30 to 60 per hour, to sharpen dull bits at the rate of 30 to 60 per hour, and to make 25 to 50 shanks per hour.

To insure proper hardening and tempering of drill steel automatic heat-treating machines and oil and gas furnaces with pyrometric control have been developed. More and more mines are installing such equipment today, particularly where detachable bits are used.

The quality and efficiency of drill steels doubtless will be improved further. The use of alloy steels, for example, is in a stage where extensive progress seems probable. Tests more than 20 years ago showed that such steels have greater tensile strength than straight carbon steel, permit the use of lighter sections and smaller bits, and result in increased boring speed in rock.⁶⁷ Proper heat treatment of alloy steels is more complex than that of conventional carbon steel, and methods have not yet been developed which would permit such steels to be treated in ordinary mine shops. Further experiments with methods of preparing and treating conventional drill steel have given some evidence of possible lower costs and better performance with its use, but these methods have not yet been widely accepted in the United States. Among these investigations may be mentioned those of sharpening of bits by hot milling⁶⁸ and with improving their wearing power by welding hard-alloy tips to the edges of the bits. This latter method gives some promise of success although difficulty was experienced in making a shockproof bond between the hard alloy and the steel. In "long-hole" work - such as prospect drilling with a drifter - where the depth of hole that could be bored depended on gage loss one observer reported that the depth bored per bit was increased to six to eight times that of the ordinary bit by using "Stellite", a cobalt-chromium-tungsten alloy.⁶⁹

⁶⁴ *Ibid.*

⁶⁵ Richard T. Dana and W. L. Saunders, *Rock Drilling* (1st ed.; New York: John Wiley & Sons, 1911), p. 50.

⁶⁶ Robert S. Lewis, *Elements of Mining* (New York: John Wiley & Sons, 1933), p. 128.

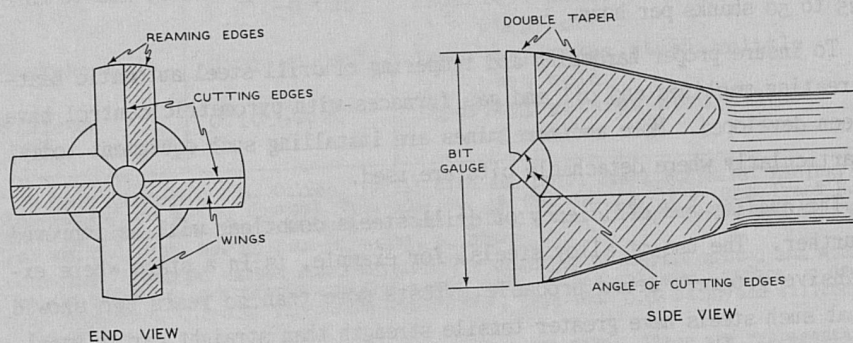
⁶⁷ Carroll R. Forbes and Joseph C. Barton, "Comparative Tests of Hammer Drill Bits," *Transactions, A.I.M.E.*, Vol. LVIII (1918), pp. 3-24.

⁶⁸ Wing G. Agnew, *Hot Milling of Rock-Drill Bits at the Mines of the Vinegar Hill Zinc Company, Platteville, Wisconsin* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6907, mimeo., Oct. 1938).

⁶⁹ Lucien Eaton, "Rock Drills and Accessories - II," *Engineering and Mining Journal*, Vol. 134, No. 3 (Mar. 1933), p. 109.

Changes in the Shapes of Drill Bits.— The shape of the bit may also affect significantly the amount of work a rock drill will perform in a specified period. Through careful analyses of certain drills and various kinds of rock some success has been achieved in redesigning the shapes in which bits are formed so that they will more completely meet the requirements made of them.

Figure 10.— A 4-WING CROSS BIT FORGED ON HOLLOW DRILL STEEL



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Rock-drill bits of this general type have been the most widely used with the hammer and piston drills. The length of cutting edge, or bit gage, depends upon the depth of hole to be drilled and upon the diameter of the steel. For holes deeper than the length of drill feed (which usually is about 2 feet) progressively longer pieces of drill steel are required. The bits at the ends of these steels must be progressively smaller than the starter because the wings are continuously worn away by the abrasive action of the rock as the hole is deepened. The smallest bit, however, must be larger than the drill steel to allow for free ejection of the cuttings. As the size of hole has a pronounced effect upon drilling speed, the tendency is to use the smallest possible bits. In American mining practice $\frac{1}{8}$ inch is a common gage change though some mines have found $\frac{1}{16}$ inch satisfactory.

The angle of the cutting edge usually is 90° and common wing tapers are 5° and 14° . The wings are often $\frac{1}{4}$ to $\frac{5}{8}$ inch thick. To be effective, bits must be symmetrical and accurately shaped. This is now generally accomplished in a power sharpener that can forge several hundred bits per shift. Also, with hollow steel, the hole must be kept fully opened.

Detachable bits have much the same shape and appearance as the one illustrated above. The greater number of those now in use are provided with coarse internal threads that match an external thread on the drill rod.

Any bit used in rock drilling should keep the hole round and free and accomplish as much drilling as possible before resharpener. The various parts of a standard, 4-point cross bit are shown in figure 10. As the cutting edges of the bit break off particles from the rock mass and the drill advances into the hole the reaming edges perform the first-named function. The ability of the bit to "mud"⁷⁰ freely and wear and perform well depends to a great extent on the penetration which, in turn, is governed by the cutting angle and the length of the cutting edges. If

⁷⁰To "mud" is to throw the cuttings back from the bottom of the hole when the bit is advancing into the rock.

the bit does not penetrate the rock sufficiently the entire steel rebounds and much energy is lost; if the bit penetrates too much a strong cushioning effect results and the speed of drilling is retarded. In American mines today the 90° cross bit with a 5° and 14° double taper is used very widely. The double taper introduced about 1918-20 was an important advance in drill-bit design and added greatly to the strength of the wings and retarded loss of gage. These bits can be accurately made only by a power sharpening machine.

Many different designs of drill bits have been developed, but recent efforts toward standardization have resulted in elimination of many forms. The three most popular shapes are the 4-point or cross bit, the Carr bit,⁷¹ and the 6-point rosette bit that is used only with hammer drills. Many other forms are still used, of course, but not so widely as the three mentioned. Along with the standardization of bit design there has been some standardization in size and section of drill steel.

Detachable Bits.—Despite the vast improvements made in commercial drill steels the problem of achieving a compromise material suited to both the shank and the bit had not been entirely solved. This has resulted in separating the shank and the bit so that each might be made of the most suitable material. The detachable bit weighs about $\frac{1}{4}$ to $\frac{1}{2}$ of a pound and now is made of high-carbon steel in sizes and shapes to fit drill steels of various weights and sections.

The idea of a detachable bit is not new. As early as 1865 a patent was granted for a detachable "three-bladed hand-drill bit",⁷² and Leyner applied for a patent on a taper-fit rock-drill detachable bit in 1903. Since then many other patents have been issued for a variety of detachable bits for both hand and machine drills, but it was not until about 1918 that a usable form was developed,⁷³ and several years elapsed before large-scale trials were made.

There are today several major types of such bits in use in the United States, and many other kinds are being tried at various mines. The bits must act as an integral part of the steel, and they differ in the manner in which they are attached to the drill rod or shank. An early type now little used was attached by means of a very closely fitting

⁷¹This is a modification of the chisel bit used in hand drilling. Because of its full-reaming edges it does not lose gage rapidly, is fast-cutting and useful in hard homogeneous rock.

⁷²McHenry Mosier, *Progress Report on Investigation of Detachable Rock-Drill Bits* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6877, mimeo., Feb. 1936), p. 2.

⁷³Chauncey L. Berrien, "Development and Installation of the Hawkesworth Detachable Bit," *Transactions, A.I.M.E.*, "1930 Yearbook," Vol. XCI (1930), p. 139. See also: Felix Edgar Wormser, "The Hawkesworth Detachable Drill Bit," *Engineering and Mining Journal-Press*, Vol. 114, No. 6 (Aug. 5, 1922), pp. 262-4.

tongue-and-groove joint; another was threaded and held to the rods by a coupling much like that used with pipe; others have internal threads to match the external thread at the end of the drill rod. Another type that is beginning to find favor because of its full-reaming edges has a straight tapered recess and is held in place by a driving fit on the correspondingly tapered drill rod.⁷⁴ In the threaded varieties the end of the rod makes close contact with the bit at the bottom of the threaded recess or where the skirt of the bit rests on a shoulder on the rod. Nearly all types of detachable bits have a double taper but they differ somewhat in wing shape and cutting-edge design.

Although some mines were fitted out with detachable bits about 15 years ago and some construction contractors adopted them it is only within the past 5 years that they have come into fairly widespread use. Now, many of the large mines in the country have adopted the detachable bit, and many more operators are testing the possibilities of decreasing drilling costs through their more extensive utilization.

In most mines where detachable bits have been applied, savings were effected in drilling time and in the handling of steel. The metals used for detachable bits need not combine the characteristics required of the steel for the drill rod and may be high-carbon or alloy steel that can be hardened to a considerable degree. Before it is dulled or loses its gage such a bit can cut more than the conventional bit forged on a regular drill steel. Also, the rod to which the detachable bit is attached may be made of material selected for toughness and resistance to fatigue without regard for the qualities required for the bit, thus reducing breakage and the attendant loss of steel.

Since the detachable bit is lighter and usually will drill more than the conventional steel, some of the time spent in changing steel may be saved. Greater saving arises from the use of sharp bits, of which the drill runner may have an ample supply and which are easy to change. As a result he is less apt to use a bit after it has become extremely dull and lost its gage. Moreover, the strains imposed on the shank and on the machine itself are less severe so that the possibilities of sticking or breaking the steel or injuring the drill are considerably reduced. The light detachable bit has made possible still another saving by reducing the number of nippers⁷⁵ needed. In addition to labor saving, the use of

⁷⁴McHenry Mosier and Wing G. Agnew, *Mount Weather Testing Adit, Progress Report 1* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3439, mimeo., Feb. 1939), pp. 7-9.

⁷⁵The "nipper" is the workman who carries the sharpened drill steel from the blacksmith shop to the drillers and returns the dulled steel.

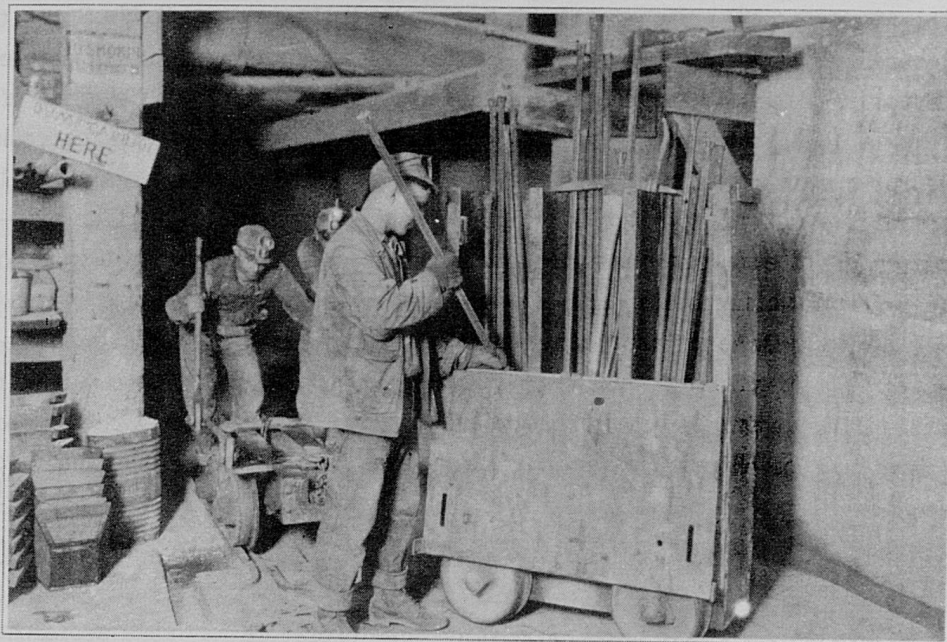


FIGURE 11.— HANDLING DRILL STEEL UNDERGROUND

One of the greatest savings in the use of the detachable bit is the reduction in "nipper" labor (the "nipper" is the workman who distributes sharp, and collects dull, drill steel) and that of others who transport drill steel from the blacksmith shop to the working face. In hard rock a drifter drill dulled 50 or more pieces of steel per shift; these would weigh about 800 pounds whereas an equivalent number of detachable bits and a drill rod would weigh about 50 pounds and could be carried by the driller as he went to his working place.

the separable bit reduces greatly the weight of drill steel in circuit, for only one set of rods is required by the miner instead of several sets of steel.

Detachable bits may be used three or more times before the steel lost in drilling and grinding (the usual method of sharpening) makes them too small for use. Sharpening by forging is now being employed satisfactorily, and the bits are heat-treated as is the conventional steel.

Many mines, however, have found that some conditions do not favor the adoption of detachable bits. Where costs of transportation and distribution of drill steel are low, or the sharpening shop is well organized and efficient, or the rock of such quality that the footage drilled per bit is quite high the use of the detachable bit may offer few advantages. Results were not always favorable, moreover, with the bits that were in use a few years ago. One observer reported that the drilling capacity of the detachable bit was about 20 percent less than that of the standard bit and that the saving in drilling cost was due entirely to the reduction in steel-handling expense. This saving, however, was offset by the royalty incorporated in the cost of the detachable bit. He concluded that

the field for this bit was limited to moderately hard rock.⁷⁶ Current general experience, however, indicates that under many conditions the separable bit is superior to the standard bit. An interesting example of this is found in the Tri-State zinc-lead mining district where the rock is often cherty and highly abrasive and about 50 pieces of standard steel ordinarily were required per drilling-machine shift. The earlier experience with detachable bits was not satisfactory as the bits lost gage so rapidly that often only one regrind was possible. A study of the mechanics of drilling in the flinty rock led to the use of a modified wing-design bit and it was found highly advantageous to use this bit without regrinding until the wings were worn down to little more than the rod diameter. The cost per foot of drilling with the standard detachable bit was very slightly below that of drilling with the ordinary [integrally-forged] bit, but the modified type showed a saving of more than one-third.⁷⁷

To provide a factual basis upon which mine operators may make decisions as to the use of detachable bits in their mines, the U. S. Bureau of Mines is gathering data and making studies in mines where such bits have been used. Six reports describe and summarize the findings of the Bureau's investigations up to May 1939.⁷⁸ These reports show that detachable bits have been adopted to a very wide extent. In some of the very large as well as in small mines they are used for all kinds of drilling but in other mines they are used for special tasks only or are being tried experimentally. A growing volume of evidence as to the advantages of detachable bits justifies the belief that further improvement and increased use will constitute a significant aspect of future technical progress in mining.

⁷⁶Eaton, "Rock Drills and Accessories - II," p. 108.

⁷⁷C. W. Nicolson, "Recent Improvements in the Mining Practice of the Tri-State District," *Mining Technology*, Vol. 2, No. 3 (May 1936), A.I.M.E. Tech. Pub. No. 905, pp. 5-6.

⁷⁸Mosier and Agnew, *op. cit.*, 12 pp.; McHenry Mosier and W. G. Agnew, *Bit Gage v. Drilling Speed* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3447, mimeo., May 1939), 4 pp.; McHenry Mosier, *Progress Report on Investigation of Detachable Rock-Drill Bits* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6877, mimeo., Feb. 1936), 9 pp.; McHenry Mosier, *Progress Report No. 2 on Investigation of Detachable Rock-Drill Bits* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6911, mimeo., Nov. 1936), 20 pp.; McHenry Mosier, *Progress Report No. 3 on Investigation of Detachable Rock-Drill Bits* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6936, mimeo., Apr. 1937), 27 pp.; and McHenry Mosier, *Progress Report 4 on Investigation of Detachable Rock-Drill Bits* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6951, mimeo., July 1937), 37 pp.

CHAPTER IV

DEVELOPMENT OF SURFACE-DRILLING TECHNIQUES

A vastly greater tonnage is now produced from surface than from underground mine workings. The trend toward open-cast mining and quarrying has been an outstanding tendency in which technological advances in rock drilling on the surface have played an important role. In common with underground drilling, surface drilling is done either for prospecting or blasthole boring, although surface drills must be able to bore deeper holes of larger diameter for efficient blasting than underground drills.

Two broad classes of rock drills are employed on the surface - those designed primarily for use underground and a specialized group of machines intended for surface work. The drills described in chapter III - the piston and the hammer drills, and especially the drifter and the jackhammer - have been adapted for surface mining and quarrying. In some instances special mountings have been developed to make them more suitable for surface work where they are used mainly for blasthole drilling and for relatively short-hole prospecting. Other machines were developed primarily for surface work.¹ The machines in this group, the power churn drill and various types of the rotary drill, are large and powerful and usually require some sort of rig.² Their main function is to drill long or large-diameter holes, or both. With minor exceptions - notably the diamond drill - they are used very rarely underground.

The large surface drills frequently are used to prospect an area before a shaft is sunk for an underground mine. The ability of these drills to bore long holes and to produce fairly accurate samples of the ground passed through is of great value in determining the best shaft location. Where the nature of the overburden and depth of the deposit from the surface will permit exploitation from open pits, as in strip metal and coal mines and rock quarries, large surface drills are employed both for prospecting and blasthole boring after mining operations have begun. In the latter task these big drills generally are supplemented by some kind of smaller hammer drill.

¹Mining is only one of the fields to which surface-drilling techniques are applicable. Others include canal building, sinking artesian wells, the construction of dam foundations and abutments, highway and railway construction, and many more uses. The first surface drills were devised for use in canal building and well sinking.

²A rig is a framework or derrick (the engine necessary to run the drill) and hoisting tackle to raise and lower the drilling tools, casing, etc.

There is a third type of machine used in dimension-stone quarries where the peculiar needs have led to the development of special types of cutters employed almost solely in producing building and ornamental stone. Along with these machines, the channeler and the wire saw, some type of drill generally is employed.

As has been noted, nearly all the drills employed today for surface mining originally were intended for application under different conditions. The stimulus to develop these machines for use in surface mining arose from the growth of the mining industry and the need for more effective drilling techniques. Before 1865 all surface blasthole drilling in the United States was manual. The successful use of power churn drills in the oil fields of Pennsylvania, however, demonstrated the efficacy of drilling machines for deep-hole work. The rapid growth of the oil and gas industry in the latter part of the nineteenth and the beginning of the twentieth century was accompanied by remarkable advances in surface-drilling techniques, so that when improved methods of drilling were required in open-pit mining and quarrying the equipment was available. Such a need arose with the growth of quarrying and the discovery of large ore deposits close to the surface when underground mines could no longer supply the growing metal requirements of our expanding industrial economy.

Open-pit mining in the United States was not new but it has been only since the last decade of the nineteenth century that strip metal mining has become really important. There were some open-pit iron mines in New York, New Jersey, Pennsylvania, and Michigan before 1870 but they were generally small both in size and production. The modern open-pit iron mine may be said to date from the opening of the Mesabi Range in 1892. Strip mining of copper on a large scale did not begin until about 1906.

Another result of our expanding industrialism has been the increasing importance of rock quarrying. Road building became important, and the trend in construction shifted from wood to steel and concrete. The demand for crushed and broken stone grew sharply and necessitated radical technical changes in the quarrying industry as drilling techniques (for prospecting and particularly for blasthole boring) were invested with a new and vital importance. Previously crushed stone had been used principally for flux and lime, necessitating the breaking of the rock into special sizes or lumps. The new uses for crushed stone in the preparation of concrete and cement, however, required much smaller sizes of stone and new methods of quarrying. For the production of such stone

in large quantities it was found that promiscuous shattering of complete hillsides was more desirable than the prevailing methods of breaking rock. Early drills such as the piston, hand churn, spring pole, and other types could not accomplish the heavy drilling for which these large-scale methods called. Recourse was had, therefore, to portable models of the powerful drills that had been employed for sinking the first oil wells.

Large-scale quarrying and mining brought about the wider use of surface-drilling techniques in still another manner. These enterprises entailed a large capital investment to cover the increased outlays for development and plant. More consideration was given to the probable ultimate production of a mine or quarry and this required accurate sampling of underlying strata and delineation of the deposit. The available drills were widely used to obtain this information and their utility for this purpose has been improved steadily.

The remainder of this chapter describes drills used in surface work. Those used for prospecting are described first, followed by a discussion of blasthole drills.

PROSPECTING DRILLS³

For prospecting purposes a drill that can produce a good sample of the rocks penetrated, bore deep holes, and work at any angle is preferred. The importance of securing accurate information about subsurface strata has been, and still is, great enough to warrant the expenditure of much effort to develop drills to meet these basic requirements. Two types of drills designed originally for other purposes have been thus adapted - the power churn drill and the various forms of the rotary drill. Each of these major types has features that make it suitable for prospecting in a particular kind of terrain.

The Power Churn Drill⁴

Early in the nineteenth century there appeared in the United States a series of drills known as "hand machine drills." These were drop drills essentially similar to the heavy hand churn drills described in chapter II. The cutting tool was raised by hand with a rope and permitted to drop back into the hole. In 1838 John A. and J. M. Singer conducted a fairly successful experiment with a large drop drill on the Illinois

³As is noted in the last part of this chapter, some of the drills used for prospect drilling are also used for blasthole boring.

⁴Also known as the well, percussion, cable-tool, or rope drill.

and Michigan Canal. The machine was patented in 1839, and about 10 or 12 were put to work on the canal.⁵ Drills of the spring-pole type - the predecessor of the power churn - were used between 1806 and 1820 to sink deep wells at Charleston, W. Va.; Louisville, Ky.; and St. Louis, Mo. It was not until the early sixties, when small steam power plants and semiportable drilling machines became available and were successfully applied to drilling oil wells in Pennsylvania, that the possibilities of power churn drilling in mineral exploration became apparent. Difficulties of the early power churn drills in drilling even shallow holes in badly caving ground or in making satisfactory progress in hard strata were largely overcome by improvements in adapting them for oil-field drilling. These improved drills could be used satisfactorily for prospect drilling, and today the power churn drill is employed widely in sampling mineral deposits where the rock is soft enough to be broken by the chipping action of the bit and where casing or drivepipe is used as an added precaution in loose or unconsolidated strata.

The early power churn-drill outfit consisted essentially of four separate units - a steam boiler, a simple engine, a wooden derrick, and a string of drill tools. The engine could be used to raise or lower the drilling tools and the "sand pump", or to actuate a walking beam⁶ - the counterpart of the spring pole - that imparted an up-and-down motion to the tools suspended from one end. The drill operated by percussive cutting and could be used only for boring vertical holes. The string of tools for deep drilling generally comprised a set of jars, a drill stem, and a cutting bit. The jars - sometimes omitted when drilling was done through hard rock - were a pair of sliding links that produced a sharp shock as they met on the upward stroke and loosened the bit if it stuck fast in the hole.

To increase the force of the blow a heavy bar (called the auger stem) was generally inserted between the jars and the drill stem. Another bar (the sinker bar) was sometimes added above the jars to keep the drill line taut. Manila rope was used for the drilling line which was attached to the tool string by a rope socket.⁷ At the surface the rope was fastened in a swivel clamp attached to the temper screw⁸ that hung from the walking beam. Some adjustment of stroke length was obtained by connecting

⁵ Henry S. Drinker, *A Treatise on Explosive Compounds, Machine Rock Drills and Blasting* (New York: John Wiley & Sons, 1883), p. 189.

⁶ A massive lever that was pivoted at one end, or, later generally near the middle.

⁷ In place of the rope or cable, wooden rods similar to those of the primitive spring-pole drill found extensive use abroad and in the sinking of water wells in this country but now are seldom employed.

⁸ A screw device several feet long by which the tools are lowered as the hole is deepened.

the pitman⁹ at different points on the engine crank. The torsion in the rope was, as a rule, adequate to accomplish rotation of the drill bit, but in shallow holes it was sometimes supplemented by manually twisting the drilling line.

Holes ordinarily were drilled dry or with just enough water to facilitate periodical removal of cuttings, usually with some form of sand pump or bailer. The bailer consisted of a hollow cylinder a few feet long with a simple valve at one end and was attached to a small rope or "sand line" that passed over a sheave on the derrick to a drum or reel. When it was lowered into the sludge at the bottom of the hole the valve opened and permitted the cuttings to enter the cylinder; as it was raised the valve closed and held the cuttings. In soft or unconsolidated strata requiring continuous removal of cuttings the hydraulic or jetting system was widely used.

Several basic changes in the structure of the drill outfit made the jetting system applicable to power churn drilling. The cutting bit was altered to allow the passage of water to the face by making the upper part of the bit hollow and perforating the lower half with two or more holes. A string of hollow rods long enough to extend well above the top of the hole replaced the drilling line. The top of this rod string was connected to a pump with a swivel coupling so that water might be forced down the hollow rods and through the bit to the bottom of the hole to carry the cuttings up the hole outside the hollow rods.

In this method of boring, the excavation was accomplished in loose material by the water jet and the bit usually was rotated to keep the hole straight. Pipe or casing somewhat larger in diameter than the drill bit was driven down as the hole was deepened. This casing held up the walls of the hole and prevented caving that would give an irregular sample of the strata penetrated. When the ground could not readily be washed the drill pipe and bit were given a churning motion and cutting proceeded by percussion. In the Mesabi type of this drill, developed in the early nineties for prospecting soft iron ores, the rig differed from the ordinary cable tool in that a walking beam was not used. The rope holding the drill pipe passed over a sheave hung from a tripod or derrick and wound once or twice around a drum or reel (usually called a "cathead") that was revolved continuously by the engine. As the free end of the rope was pulled tight and loosened, the string of tools alternately rose and dropped. Drilling was ordinarily vertical, but inclined holes could be bored by starting the casing at an angle.

⁹A rod that connects the rotating member of the engine with the walking beam.

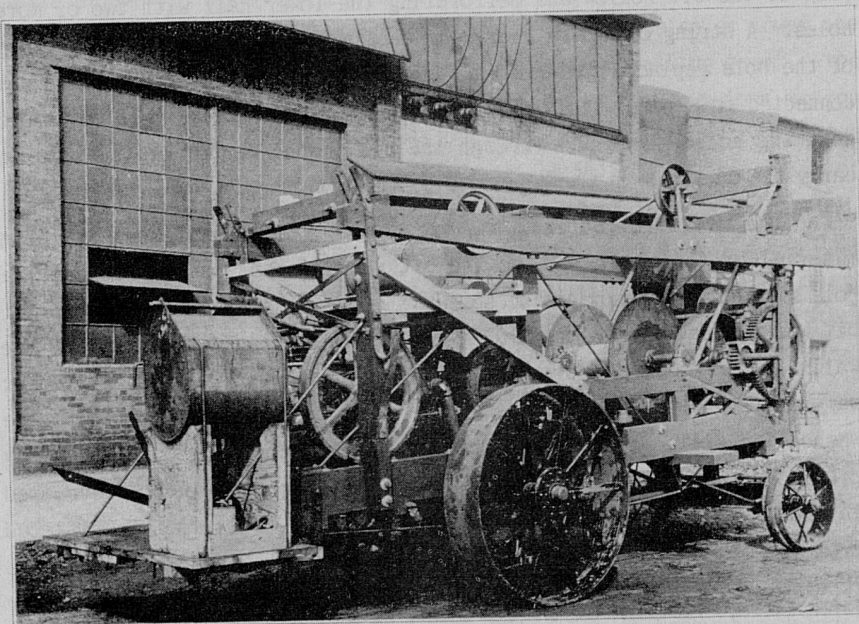
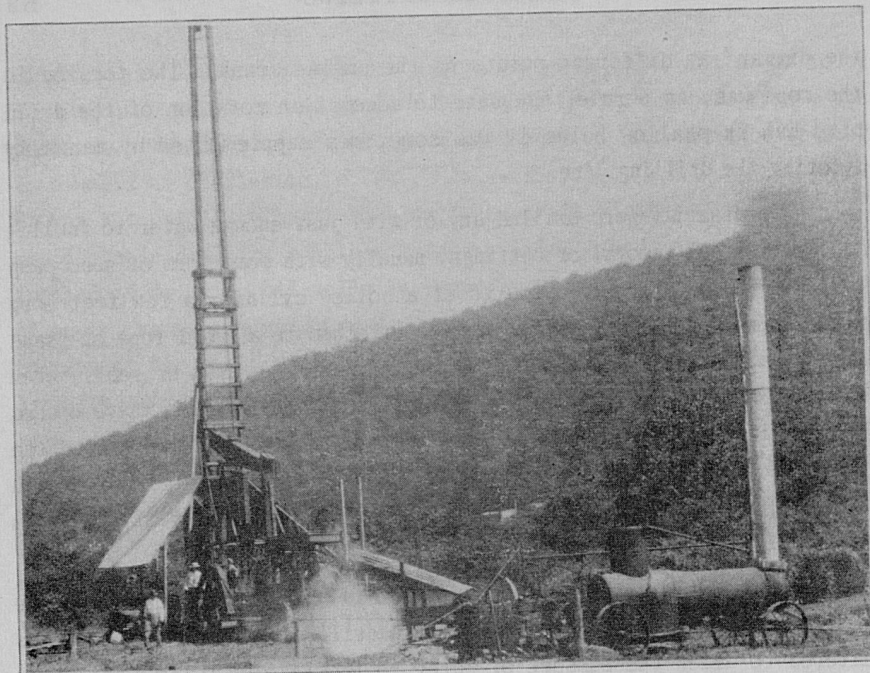


FIGURE 12.— TWO STAGES IN CHURN-DRILL DEVELOPMENT

The upper photograph shows a well-drill outfit commonly used up to the turn of the century. In the foreground is a portable locomotive-type boiler; to the left is the engine over which may be seen the massive wooden walking beam and the wooden derrick which could be dismantled and re-used. The derrick was usually a square frame tower.

The lower photograph shows an early, self-contained, portable churn drill driven by a gas engine. These models were horse-drawn or fitted with traction wheels. The type shown was used for blasthole and prospecting work in the first decade of this century.

Another variant of cable-tool drilling suitable for small-diameter shallow holes in easily broken ground was the self-cleaning or hollow-rod method that worked by percussive cutting. As in the wash-boring process, the rods were hollow and the bit had small openings and also a valve that opened on the down stroke. Water poured into the hole made a sludge that was forced through the bit into the rods and out at the surface by the sudden compression from the fall of the rods.

Modern Churn Drills.—The modern power churn drill consists of a source of power, a walking beam, a hoist operated by suitable clutches, and a drill line of manila or wire rope connected to a string of tools by a rope socket. For deep holes 2,000 feet or more, a steel derrick that is quickly and easily assembled and dismantled has replaced the wooden framework that could be used but a very few times. Easily transportable, high-pressure, oil- or gas-fired boilers are used with much-improved steam engines or the drill may be powered with an electric motor or with gasoline or Diesel engines. Changes in power transmission and control have added speed and efficiency and have simplified operation.

The basic tools used in churn drilling have changed but little over an extended period, although there have been several improvements and additions. The tools have been made larger in diameter, longer, and heavier so that a much more powerful blow could be struck. The first important advance was the invention of jars about 1831.¹⁰ As deeper holes were bored a whole series of special tools was developed to recover drilling tools and drilling line broken or lost in the hole. Manila rope has been generally replaced by steel cable, although it had great elasticity that made drilling "on the spring of the rope" an important feature of the drilling method; also, the shocks of the impact of the tools on the rock were not transmitted to the derrick or walking beam. As greater depths were attained the rope had to be larger to carry the load, and it took more power to move it. Besides, it rotted quickly and was rapidly worn by the sludge; in holes where there was much water, friction especially retarded penetration. Substitution of a steel cable permitted use of greater engine speed and heavier tools and increased the speed of drilling and the possible depth of hole.

Improvements also were made in the rig required for power churn drilling. At least as early as the late eighties completely self-contained

¹⁰Dr. J. P. Hale in the section on "Salt" in M. F. Maury and Wm. M. Fontaine, *Resources of West Virginia* (Wheeling, W. Va.: The Register Co., 1876), pp. 286-7, stated that "in 1831 William Morris invented a simple tool [that] has always been called here 'Slips,' but in the oil regions they have given it the name of 'Jars.' It is a long double-link, with jaws that fit closely, but slide loosely up and down. . . . Billy Morris never patented his invention This tool has been adopted into general use wherever deep boring is done, but few know where the slips or jars came from."

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and portable churn-drill rigs were available.¹¹ These were lightweight, horse-drawn machines and used animal or steam power. Some had hollow rods and were used for holes only a few hundred feet deep, principally small-diameter water wells. Their development was similar to that of the standard cable-tool rig, and they were widely used in shallow-hole work because of their mobility. This equipment was steadily improved and for a number of years all-steel portable rigs, driven by gasoline, Diesel engines, or electric power and mounted on wheels or caterpillar treads have been available (see figure 27). As the units have increased in size there has been an increase both in length of stroke and in frequency of the blows, and machines are available which can drill a 6-inch hole 2,500 feet or more in depth.

Rotary-Type Drills

Unlike percussive power churn drills, rotary-type drills cut by abrasion. The drilling bit is made in a wide variety of sizes and is attached to a string of jointed pipe or rods held at the upper end in a rotating device driven by an engine. As the hole deepens, the drill rod or pipe is lengthened by additional units. Some fluid ordinarily is employed for the removal of cuttings, and under certain conditions the hole may be lined or partly lined with a string of casing. Several machines employing the principle of the rotary drill are used for mineral prospecting, especially the diamond, calyx, and hydraulic rotary drills. The diamond drill is most useful in hard rock and in boring long holes at any angle. The latter two are useful primarily for boring in unconsolidated strata and in softer and medium-hard rocks. In general they bore only nearly vertical down-holes but make holes (and cores) many times the size of those ordinarily obtained with the diamond drill; also in the softer rocks they may secure greater core recovery at a somewhat lower cost. Although these two types of drills have many similarities, their principal features are discussed separately.

The Diamond Drill.—The diamond drill is the earliest type of rotary drill and uses an annular bit set with diamonds and procures a core from the strata penetrated. It was patented in 1863 by R. Leschot, a French civil engineer, and was originally intended to be used only for blast-hole boring in the Mont Cenis railway tunnel. In 1864 a patent for a diamond drill was granted to F. K. Copeland, an American, who was said to have originated the idea of using this machine for mineral prospecting. Copeland transferred his patent to an American company which at once

¹¹"Portable Rock Drilling Machinery," *Engineering and Mining Journal*, Vol. XLVII, No. 9 (Mar. 2, 1889), p. 207.

proceeded to manufacture drills. In 1867 M. C. Bullock obtained the Leschot patent rights for two American companies with which he was associated and subsequently manufactured diamond drills under his own name. Bullock and Copeland are credited with having quickly developed the machine into a useful tool. By 1870 they were being distributed here and abroad and at least by 1871 were being advertised in technical journals; an extensive line of drills was displayed at the Centennial Exposition at Philadelphia in 1876.¹²

One of the earliest uses (about 1864) of the diamond drill was in dimension-stone quarrying to bore shallow, closely spaced holes into which were driven wedges to split off blocks of stone. For this purpose as well as for blastholes, solid bits were generally used. For prospect work, a hollow or annular bit was employed to form a core. The earliest prospect work with the diamond drill appears to have been done about 1869. In that year, holes were bored about 225 feet deep in the southeastern Missouri lead district, about 100 feet deep on the Marquette iron range, and one hole in Colorado to a depth of 417 feet. About 1870 a hole over 700 feet deep was drilled in the anthracite regions. This hole is of special interest, for Tecklenburg states that this was probably the first in which was obtained a full cross section of the strata penetrated; it was important to the development of deep-boring techniques because the frequent and serious rod breakages (common gas pipe was used as drill rods at that time) encouraged Bullock to invent a special set of tools to recover broken rods and bits.¹³ After 1870 the amount of prospect drilling greatly increased and in 1872 the drill was used successfully for boring blastholes in shaft sinking.¹⁴ Although the principal field of this drill has been exploratory work, it has been used to some extent for blastholes.

An important feature of diamond-drilling equipment is a core barrel carrying a diamond-studded bit. The rotary movement and the pressure communicated to the drill rods enable the bit to scrape or abrade a ring in the rock, leaving a central core that projects into the barrel. At

¹²Writing about 1889, Tecklenburg said that the diamond drill had developed in the preceding 20 years a broader field of application in the United States than in any other country and that by 1874 there were nearly 50 companies and contractors engaged in diamond drilling. He also made the striking comment that "under American conditions the underlying basis for preferring the diamond drill to others is probably to be seen in the saving of labor which, as is well known, is so costly in the United States that the thoughts and efforts of all industrial inventors are directed primarily toward the greatest possible reduction in manual labor." (Authors' translation.) From Th. Tecklenburg, *Handbuch der Tiefbohrkunde*, Band III, "Das Diamantbohrsystem" (Leipzig, Germany: Baumgärtner's Buchhandlung, 1889), p. 92.

¹³*Ibid.*, pp. 93-4.

¹⁴Eckley B. Cox, "A New Method of Sinking Shafts," *Transactions of the American Institute of Mining Engineers*, Vol. I, p. 271. The deepest hole was 334 feet.

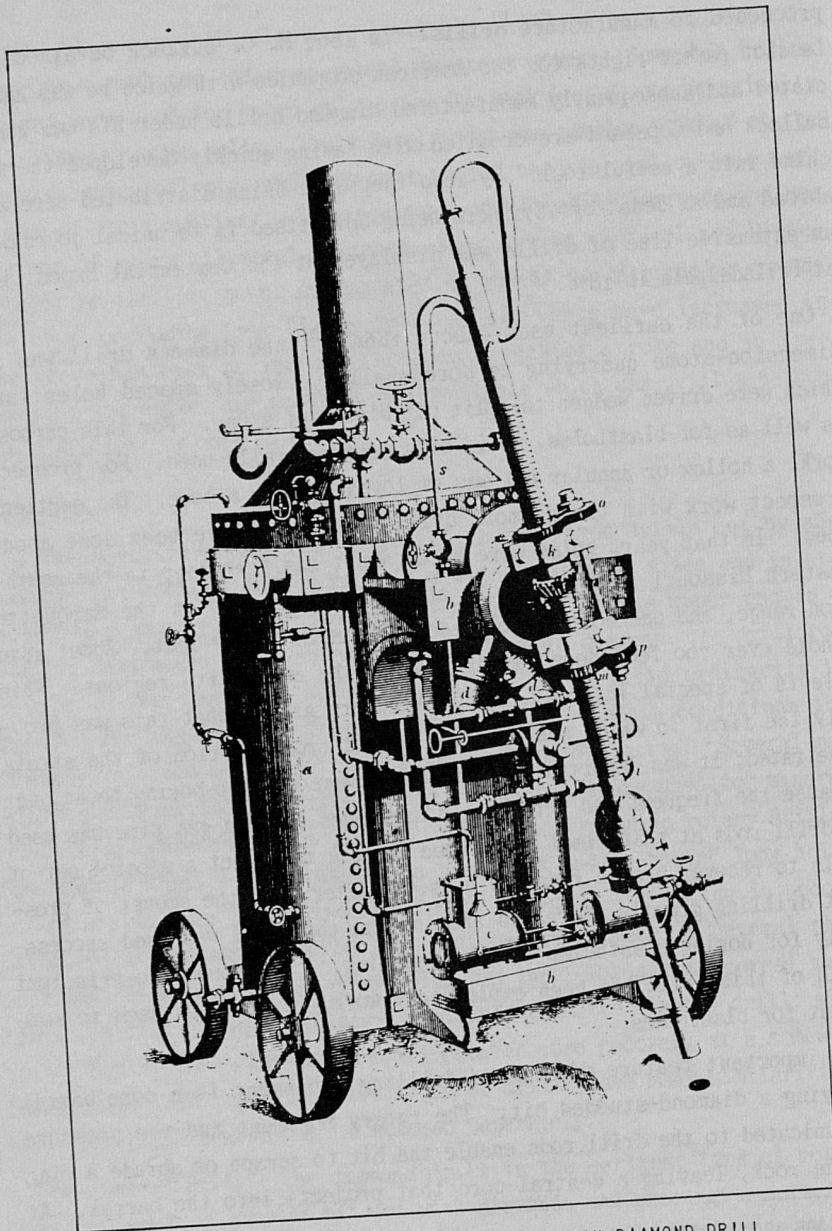


FIGURE 13.— AN EARLY PORTABLE AMERICAN DIAMOND DRILL

This odd-appearing contrivance is a prospecting drill of 1874, said to be good for 1,000-foot holes. It cost over \$3,000.

The bit, which could cut a 1-inch core, is shown at the lower end of the rods. The swivel head could not be opened and the whole machine had to be moved so that the rods could be raised or lowered. Only one set of feed gears was used; to change feed rates different gears had to be inserted. The machine was driven by the oscillating steam engine which may be seen just below the swivel head. Above the engine is the hoisting drum that carried the rope for handling the rods. The water pump was mounted on the cast-iron frame that carried the steam boiler.

intervals the drill column is pulled from the hole, and the core brought to the surface with the rods.¹⁵ For use in mineral prospecting, the core barrel is generally 1.5 to 3 inches in diameter and 5 to 10 feet long, but for deep holes it may be longer than 10 feet, usually in 10- or 20-foot sections flush-jointed so that several may be connected.

In early models of the diamond drill a single-tube core barrel was used. The diameter of the barrel corresponded very closely to that of the bit, and the core was retained in the barrel by means of the core lifter - a split-ring core spring. When the vibration of the core barrel was very severe it caused the core to break and wear away. The core barrel itself was also apt to grind the stationary core around which it revolved so that water descending under pressure through the drill rod could wash away these crushed particles. Thus the information that was obtained about the penetrated strata frequently was incomplete and even misleading, especially if the ground being drilled was soft or somewhat shattered.

The double-tube core barrel consisted of an outer tube similar to the original barrel and, next to the core, an inner "floating" tube suspended on ball bearings in such a way that the outer tube was free to rotate independently of the inner one. The descending water passed through the annular space between the two barrels and did not come in contact with the core, except where it passed between the core and the bit, so that the washing action of the water had no effect upon the core. Owing to independent rotation of the two tubes the core wedged itself so firmly that the inner barrel remained stationary, except, of course, for the slow downward movement of the whole string of rods. In this way the grinding action of the core barrel was eliminated. The core lifter is attached to the core barrel just above the bit or placed in the inner cylinder to eliminate all friction between the core and the core spring.

Use of the double-tube core barrel produced a better core, especially in soft ground. The arrangement, however, was less sturdy than the single barrel and it was claimed that progress was slower because of the more careful handling required. The single-cylinder core barrel continued to be used in drilling through firm ground where the danger of core loss was slight.

Actual cutting of the rock in diamond drilling is done by a diamond-set steel bit, which is usually hollow¹⁶ and is made of semiannealed steel

¹⁵The earliest models had no mechanical means for removing the rods from the hole and it was necessary to move the drill. By 1872 the swivel head had been hinged so that it could be swung out of the way and the drill had been equipped with an integral hoist operated from the drill engine through a suitable clutch.

¹⁶Although the first diamond drill used an annular bit, solid bits either convex or concave were employed for some of the early blasthole and prospect drilling.

hard enough to wear well yet soft enough to permit the diamonds to be set in it. Usually six to eight black diamonds or carbons (carbonados) are used in each bit, half set on the outside edge of the bit and half on the inside. Such bits cut an annular groove in the rock, permitting removal of a core, as already noted; where no core is required, a solid bit with diamonds set across the whole face sometimes is used. The bit is kept cool and the fine cuttings are washed out of the hole by a current of water that is forced by a pump through the hollow rods and returns to the surface through the space between the rods and the walls of the hole.

Because of high prices¹⁷ wear and breakage of stones is a major item of drilling expense, and engineers made determined efforts to find substitutes for the black diamond. In many districts, particularly where formations are comparatively soft, the use of bort is fast becoming general. Bort is an imperfect gem stone or brilliant and is as hard as the black diamond but its structure is crystalline, and it fractures more easily. In some instances it has been found more economical to utilize low-grade carbons. Various other substitutes such as tungsten carbide or volomite, and aluminum oxides of various types have been tried but have not proved satisfactory under all drilling conditions.

It frequently happens that the driller must stop work to "fish" for a bit or part lost in the hole. About 85 percent of these fishing jobs involves the recovery of lost bits. The tools used on such jobs include tapered and bell taps, rod spears, corkscrews made of heavy spring steel, and other tools of special design. These auxiliary tools are so effective in recovering lost equipment that the loss of a hole owing to inability to clear it is a very rare occurrence.

The diamond drill employs one of two types of feed mechanisms, the screw or differential feed and the hydraulic feed, both of which are positive in action and are mounted on swivel heads, making it possible to drill in any direction. In the differential or screw feed (used with the first diamond drills) the rotating feed screw turns in a specially designed nut which is also rotated in the same direction by means of gears so fitted that the screw is fed forward a fraction of an inch with each revolution. Most drills carry three sets of gears, only one of which is engaged, thus providing three feed rates. Many gear combinations

¹⁷The price of black diamonds has risen tremendously since they were first used. About 1870-80 the price ranged from about \$5 to \$12 per carat. In 1931 small scrap diamonds were about this price while carbons of 1 carat to over 1½ carats cost \$115 to \$175 per carat, the price increasing progressively with the size. In 1933, when most drilling was stopped, the prices were about 45 percent lower. See W. Rex Storms, "Diamond-drill Bits and Carbon," *Engineering and Mining Journal*, Vol. 134, No. 3 (Mar. 1933), pp. 96-8.

may be obtained, allowing a wide range of feed rates (1 inch for 50 to 2,400 revolutions of the screw) suitable to rocks of all degrees of hardness.

The hydraulic feed was introduced about 1872 and has been substituted for the screw feed where very deep holes were to be drilled. The mechanism is essentially a hydraulic jack in the form of a cylinder containing a hollow piston and rod by means of which the progress of the drill rods and bit is controlled. Water under pressure from an auxiliary pump is admitted to or released from the cylinder so that the piston, rod, and an internal hollow driverod are moved in the desired direction. The drill column is clamped in the driverod and rotated by bevel gears as in the differential feed machine. In some models the single hydraulic cylinder was replaced by a pair connected by yokes. By controlling the flow of water from the lower side of the piston the pressure exerted by the bit on the bottom of the hole can be governed very precisely; thus the rate of drilling can be controlled, and the speed of rotation kept constant. The action of the pressure-control valves is managed so easily that the full pressure of the piston may be quickly applied to move the drill rods downward or upward. The task of raising the string of drill rods is also greatly facilitated by reversing the feed.

The hydraulic is in some respects superior to the screw feed although it requires a higher degree of skill to operate. With the latter, the rate of feed is constant but the pressure may vary widely and perhaps endanger the bit, but with the hydraulic mechanism, however, the pressure is kept constant so that the advance varies almost directly and automatically with the hardness of the rock. Thus the drill runner can quickly and easily adjust the rate of advance independently of engine speed, a feature of much value where there are frequent changes in rock hardness. The hydraulic feed is also better suited to carry the weight of the drill rods, which in a deep hole may weigh several tons. Until 1874 the deepest hole drilled by this type of machine was 1,142 feet.¹⁸ The hydraulic feed had then been in use about 2 years, and its particular value recognized, but it had not then been determined if it "will answer for deep borings."¹⁹ By 1909, however, it was reported that a hydraulically fed diamond drill in Upper Silesia had bored a hole 7,347 feet in depth,²⁰ and in 1938 a hole had been bored to a depth of 10,718 feet on

¹⁸Oswald J. Heinrich, "The Diamond Drill for Deep Boring, Compared With Other Systems of Boring," *Transactions, A.I.M.E.*, Vol. II, p. 253; see also Supplement, p. 261.

¹⁹*Ibid.*, p. 251.

²⁰Frank A. Edson, *Diamond Drilling With Special Reference to Oil-Field Prospecting and Development* (U. S. Dept. Com., Bur. Mines, Bull. No. 243, 1926), p. 2.

the Rand.²¹ Despite the various advantages of the hydraulic feed, it is not utilized under all conditions. For drilling shallow holes or in underground work where light, compact equipment is essential, the screw feed is generally employed.

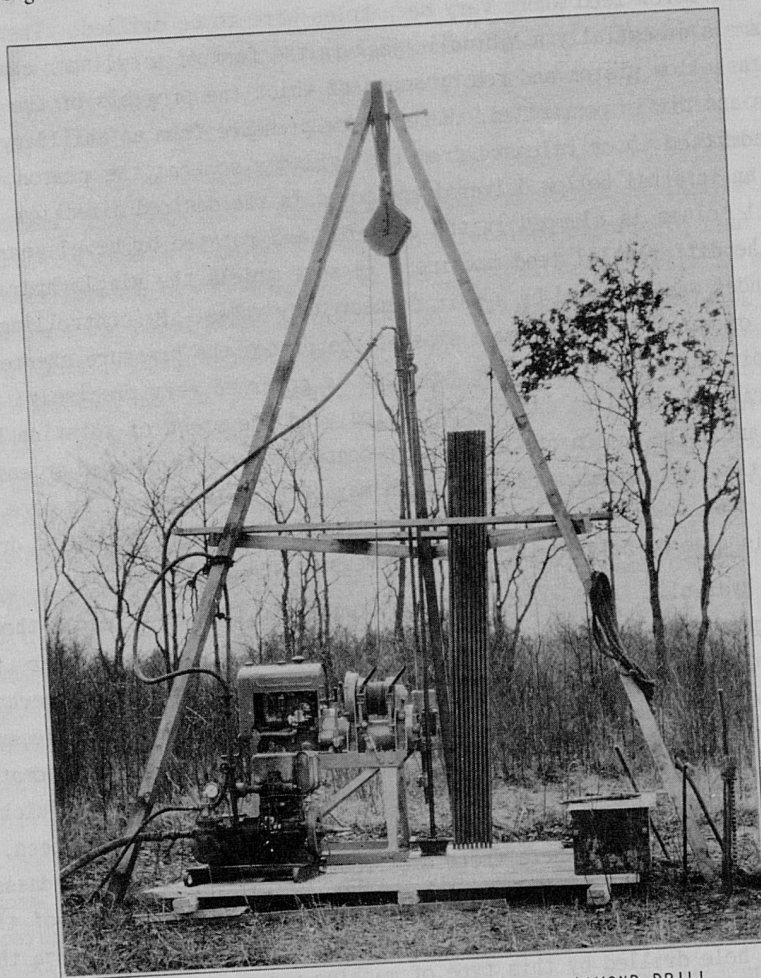


FIGURE 14.— A RECENT ONE-MAN PORTABLE DIAMOND DRILL
The simplicity and completeness of this skid-mounted, gasoline-driven screw-feed drill are evident when it is compared with the 1874 model shown in figure 13.

Diamond drills are manufactured in various sizes. The drill of standard design bores holes that are $\frac{1}{2}$ to about $3\frac{1}{8}$ inches in diameter. For underground prospecting, small screw-fed diamond drills, sometimes mounted on columns and operated by one man, bore $\frac{1}{4}$ to $\frac{13}{16}$ -inch holes to

²¹The Rand hole is described in "New Central Wits. Reef Correlation," *The South African Mining and Engineering Journal*, Vol. XLVIII, pt. II, No. 2351 (Feb. 19, 1936), p. 779. A $\frac{13}{16}$ -inch core was taken.

depths of 300 to 500 feet. The cores yielded by the new small machines may range from $\frac{13}{16}$ to $\frac{1}{8}$ inches in diameter.

The rate of drilling with the diamond drill depends primarily on the hardness and homogeneity of the rock and on the depth of the hole. In clay, shale, or slaty rock the pressure must be light to avoid pulverization of the core, and in shattered rock it is sometimes advisable to raise the rods after every foot drilled. In hard rock, slower speeds and higher pressures are used. With increasing depth of hole there is a decrease in rate of advance for the total or over-all time because of the time lost in lowering and withdrawing the rods. The time devoted to actual drilling may range from about 40 to 75 percent of the total time, averaging about 60 percent, and speeds from about $1\frac{1}{2}$ to 10 feet per hour while drilling. Drilling rates have increased because of higher rotating speeds which now range from about 300 to 800 revolutions per minute compared with about 150 to 200 with the early types. Other technical advances have been notable improvements in drill rods (preventing much lost time due to breakage), in the strength of construction, in the driving engines, and in increased specialization in design.

The Calyx Drill.—The calyx drill was first used in coal prospecting in the Australian bush and by 1898²² it was employed for borings in England. Within a few years it was applied for mineral prospecting and for water-well drilling in the United States.²³ For several years this drill was widely used but its rather limited field of application and improvements in competing types of drilling machines have relegated it to the background. Recently, there has been renewed interest in the use of the shot drill, a modified form of calyx drill, for the boring of very large (60- to 66-inch) holes.

The calyx outfit consisted of an engine and hoist, with a tripod or derrick, and the drill and drill rods which were chain- or belt-driven from the engine.²⁴ The drill rods were hollow and water was forced through them by a pump; in small models they were rotated by bevel gears as in the diamond drill. Pressure was applied to the bit by a cable attached to a yoke on the drill column and wound on small drums manually turned with a worm gear. In larger models and in deep holes the weight

²²Francis H. Davis, "Davis Calyx Drill" (plus discussion following article), *Transactions of the Institution of Mining Engineers*, Vol. XV (Newcastle-upon-Tyne: 1898), pp. 363-77. Cf. also "The Davis Calyx Drill," *Engineering and Mining Journal*, Vol. LXV, No. 8 (Feb. 19, 1898), p. 223.

²³R. B. Brinsmade, "Mining Practice in Southeast Missouri," *Mines and Minerals*, Vol. XXII, No. 4 (Nov. 1901), p. 148; and "Drilling Without Diamonds," *Mines and Minerals*, Vol. XXV, No. 7 (Feb. 1905), p. 347.

²⁴For a detailed description of early American types see L. V. Emanuel, "Core Drilling With The Davis Calyx Drill," *The School of Mines Quarterly, a Journal of Applied Science*, Vol. XXIII, No. 3 (New York: Columbia University, Apr. 1902), pp. 219-33.

of the boring column was generally adequate to produce the necessary pressure. The feed rate was adjusted by means of the hoist that carried the cable from which the boring tools were suspended. Another type of machine used a rack-and-pinion with a hand-ratchet lever. Although this arrangement permitted delicate adjustment, great pressures could not be exerted because the leverage was small.

The ordinary (or Davis) bit used in the softest material was annular and much like the "saw" bit occasionally employed with the diamond drill; the principal difference was in the shape and length of the teeth. This bit cut with a peculiar chipping action not unlike that of a stonemason's hammer and chisel. The teeth were forced into the rock and, as the rods turned, the torsion broke chips from the rock and the bit teeth sprang forward to a new seat. Because of this action the rotative (peripheral) speed was lower than that of the diamond drill. To cut rock harder than that in which the toothed bit was effective, the shot bit was developed.²⁵ It was also an annular steel bit and had one or more slots cut into the side so that the small, hard, chilled-steel shot came in contact with the rock below and immediately outside the bit and cut by pressure and abrasion. Peripheral speeds may be higher than with the toothed bit.

The calyx drill is a coring machine and gets its name from the annular space left between the relatively small drill rods and the larger tube inserted in the column above the core barrel. The cuttings are carried upward by the high velocity of the current of fluid moving through the small space (about $\frac{1}{8}$ to $\frac{1}{4}$ inch) between the core barrel and the hole walls, and drop into the calyx because of the sudden decrease in velocity at the enlarged space at its mouth. Core barrels are much like those used with the diamond drill. Inclined down-holes may be bored with either type of bit although the limit for the shot drill is about 45° from the vertical.

The driving mechanism in the larger of the modern calyx drills differs from that of the diamond drill. The top section of the drill rod is square - or nearly so - and passes through a hole in a heavy steel or cast-iron disk that rotates on roller bearings and has a ring gear on its under side. A pinion driven by belt or a chain drive from the engine turns this disk; the rotary motion is communicated to the drill column by

²⁵Davis cannot be credited with this innovation, for it had been used, presumably with a rotary or diamond drill, several years before he described the calyx drill. "The Shot Process of Drilling," *Engineering and Mining Journal*, Vol. LV, No. 21 (May 27, 1893), p. 485, states: "In this method of drilling through rock steel shot are poured inside of the drill pipe, into a ring or channel made in the rock by a few revolutions of the pipe. . . . [Shot was used as a substitute for diamonds which cost 3 to 4 times as much as they had a few years earlier.] The National Boring and Drilling Co., which owns the process recently put down near Scranton, Pa., a test boring 8 inches in diameter 390 ft. deep."

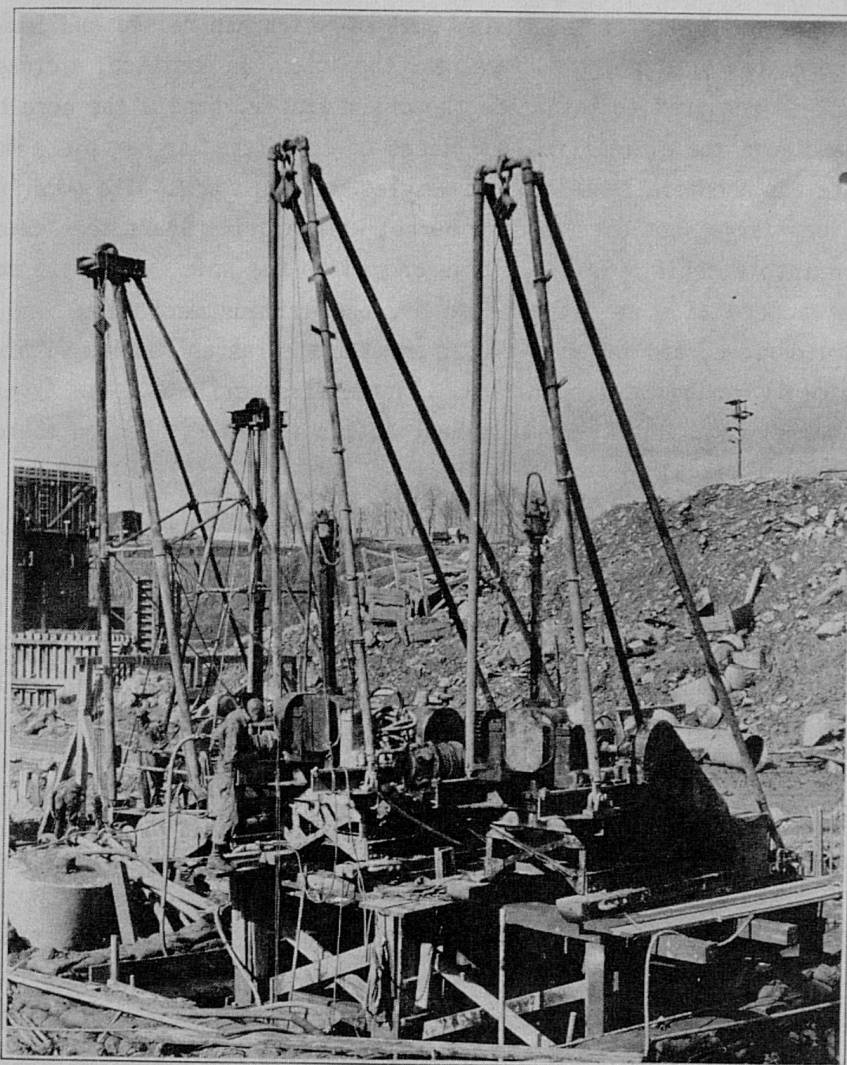


FIGURE 15.— A BATTERY OF CALYX DRILLS

The machines shown were used for geological exploration at TVA dam sites. They cut cores 36 and 72 inches in diameter, using shot as an abrasive. A piece of 36-inch core is shown at the lower left of the photograph.

arms or "keepers" that rest against the flat sides of the top drill-rod section and fit into the hole in the rotary or turntable. Thus the rods may slide freely as they are revolved and the rate of feed may be governed as already described.

A very large and unique coring device - which may be called the Newsom drill after its inventor - holds much promise for the future.²⁶ It

²⁶To date, two deep and very large-diameter holes have been successfully bored. See J. B. Newsom, "Shaft Boring Found Inexpensive and Safe," *Engineering and Mining Journal*, Vol. 137, No. 9 (Sept. 1936), pp. 443-8. Cf. J. B. Newsom and C. F. Jackson, *Shaft Sinking with a Shot Drill, Idaho Maryland Mine, Grass Valley, Calif.* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 8923, mimeo., Oct. 1936); and "New Advance Scored in Boring Holes of Large Diameter," *Engineering and Mining Journal*, Vol. 139, No. 10 (Oct. 1936), pp. 39-41.

consists essentially of two units, both of which are raised and lowered by a separate hoist on the surface near the hole. In addition, a crane or derrick is required to set aside the drill proper, handle the core barrel, and move the extremely heavy pieces of core (the largest piece moved to date was about 14 feet long and weighed over 20 tons). The borer unit is a very large shot bit and core barrel with a drive shaft that extends upward into a cabin. This cabin is wedged to the hole walls with screw jacks and contains an electric motor, the driving mechanism, and the control devices, and is large enough so that the runner remains within it and closely governs the operation. In the first drill of this type the core barrel and lifter were combined, but in the latest design there is a separate core lifter.

The large rotary borer is not a prospecting drill but replaces the rock drill in shaft sinking. Because of its great size and weight (the device is nearly 30 feet high and weighs about 15 tons) it cannot be used underground. The calyx or shot drill, however, has been used for boring holes as large as 20 inches in diameter underground and has recently been employed to provide ventilation openings between the bottom levels of a deep mine.²⁷

The Hydraulic Rotary Drill.—The hydraulic rotary drill was developed, and is now widely used in drilling for oil and gas.²⁸ In the eighties²⁹ such a drill was employed to sink a well in Louisiana, but it was not until 1901 that the hydraulic rotary drill, after repeated failures of pole-tool and cable rigs, succeeded in penetrating the soft strata of the Gulf coastal plain in the spectacular Spindletop oil field near Beaumont, Texas. After this success the possibilities of the rotary method were recognized³⁰ and within the next decade about 10,000 wells were drilled with this machine. Because certain types of rocks greatly reduce the effectiveness of the rotary drill it has only occasionally been used for metal prospecting.³¹

²⁷Michael P. Tierney, "The Calyx Core Drill," *Mining Congress Journal*, Vol. 24, No. 11 (Nov. 1938), pp. 14-9.

²⁸For a description of rotary drilling in oil and gas production see O. E. Kiessling and Others, *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-10, July 1939), pp. 80-5.

²⁹The exact date of the first American application is in doubt. Albert G. Wolf, in "The Rotary Method of Well Drilling," *Engineering and Mining Journal*, Vol. 108, No. 5 (Aug. 2, 1919), p. 171, states that the first well was drilled in 1888 by B. Andrews, Sr., of New Orleans. Howard R. Hughes, in "A Modern Rotary Drill," *Transactions, A.I.M.E.*, Vol. LI (1916), p. 620, gives 1880 as the date.

³⁰Isaiah Bowman, *Well-Drilling Methods* (U. S. Dept. Int., Geol. Survey, Water Supply Paper No. 257, 1911), p. 30.

³¹Van Dyke Copper Prospects With Rotary Drill," *Engineering and Mining Journal-Press*, Vol. 120, No. 9 (Aug. 29, 1925), p. 344. The rotary drill has been used also in exploring saline deposits in Nevada.

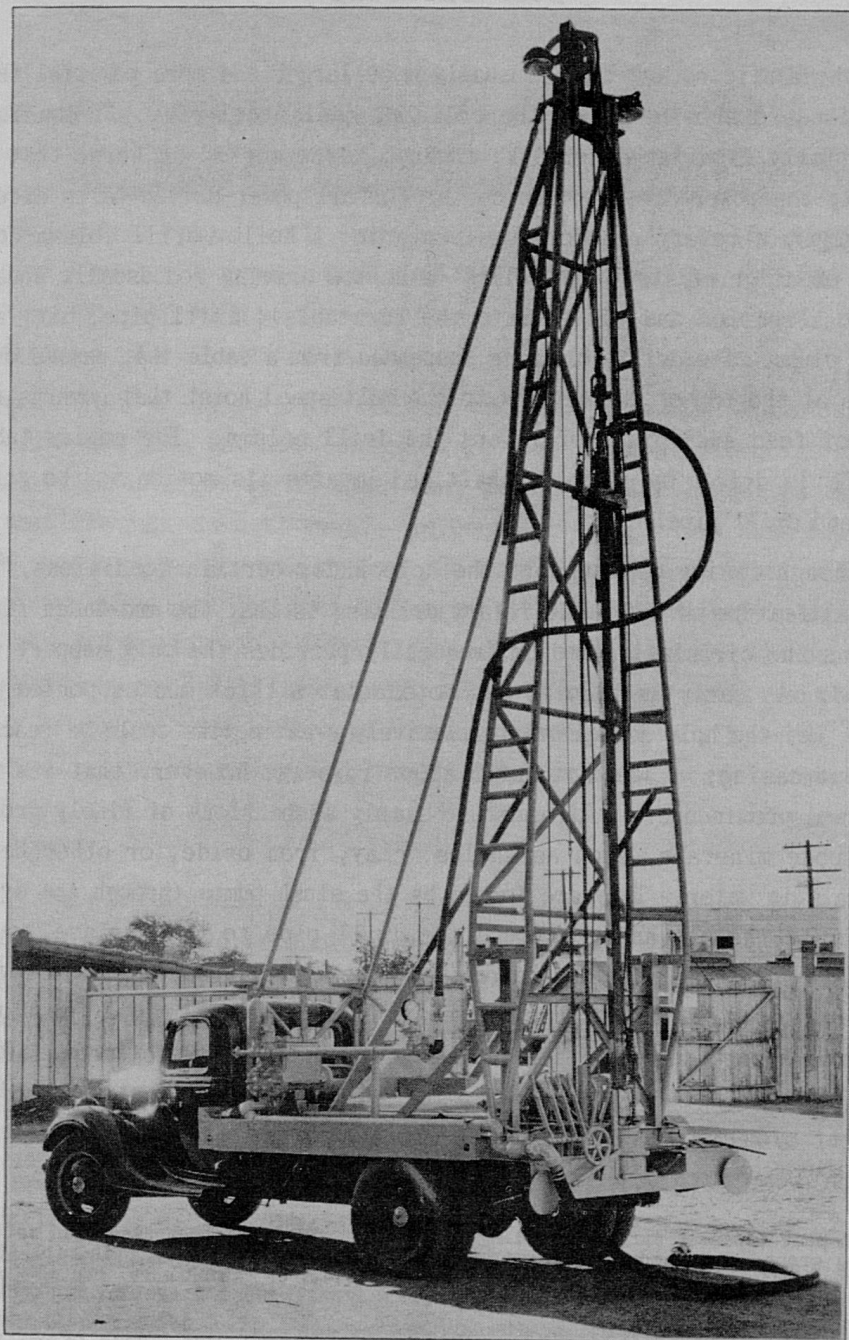


FIGURE 16.- MODERN PORTABLE HYDRAULIC ROTARY DRILL
USED FOR PROSPECTING

Although intended primarily for seismographic prospecting for gas and oil, this rotary drill may be used for any drilling in soft to moderately hard strata. Machines about this size can drill 5-inch holes about 1,000 feet deep. Larger portable drills with greater range are also available and are increasingly popular.

The draw works and power plant of the large hydraulic drills used in drilling for oil and gas wells are replaced by the truck engine with independent power take-offs to drive the drill, the slush pump (seen directly behind the truck cab in the photograph), and the hoists which are mounted directly below the welded, tubular-steel, folding derrick. The cathead, which is equivalent to the turntable of large units, is at the center rear of the truck just below the usual tool string. In some models a hydraulic feed may replace the gravity feed for drilling in harder formations.

The hydraulic rotary rig is usually much larger and more powerful than the standard shot drill or the ordinary cable-tool rig. It consists essentially of a large derrick; engine; "draw works" or hoist that is usually the power-distribution center for all power-driven parts except the pumps; a rotary platform or turntable; a hollow drill column composed of a "grief stem" or "kelly" (a hollow driving rod usually square in cross section and fitted into the turntable); drill pipe; bit; and slush pumps. The drill column is suspended from a cable that passes over blocks at the top of the derrick to the multispeed hoist that governs the rate of feed and raises or lowers the drill column. The rotary table usually is driven by chain or shaft and imparts its motion to the grief stem and drill pipe.

Although casing may support the hole under certain conditions,³² a special feature of hydraulic rotary drilling is that the mud-laden fluid used as the circulating medium frequently provides the only support required. As early as 1889 it was noted that a thick mud supported the walls³³ of the hole so well that relatively great depths could be reached without casing; it was not until about 1910-15, however, that its use attained prominence. Such muds are simply suspensions of finely ground insoluble minerals, such as shales, clay, iron oxide, or other heavy minerals in water. They are forced by the slush pumps through the drill column to the bit and up around the drill pipe to the surface, where they are collected in pits and re-used after settling or being otherwise treated to remove the drill cuttings. The fluids have several functions, the most important³⁴ of which are to carry cuttings to the surface, keep the bit cool, prevent caving, seal the pores of permeable strata, and to prevent blow-outs as the weight of the heavy mud column³⁵ counteracts pressures met upon penetrating oil and gas formations.

³²With most types of surface-drilling equipment, casing has been used when soft or caving ground was encountered and drilling continued with a smaller bit. This practice evolved from the use of hollow sycamore logs or "gums" more than 130 years ago in drilling salt wells on the Kanawha River in West Virginia. See Hale, *op. cit.*, pp. 281-7.

³³Wolf, *loc. cit.*; also I. N. Knapp, in "The Use of Mud-Laden Water in Drilling Wells," *Transactions, A.I.M.E.*, Vol. LI (1916), pp. 571-2, stated that the success of the hydraulic rotary method was dependent on the proper use of mud-laden fluid and that this method was the only one successful in wells over 200 feet deep in the soft coastal plain sediments. He also said that the use of mud-laden fluid was suggested by Fauvelle, a French engineer, in 1833. A translation of Fauvelle's paper is given in the *Journal of the Franklin Institute*, Vol. XII, 3d ser. (1846), pp. 369-72.

³⁴Lester C. Uren, *Petroleum Production Engineering* (2d ed.; New York: McGraw-Hill Book Co., Inc., 1934), p. 230.

³⁵Mud-laden fluids are occasionally used with standard cable-tool rigs. For description of such unusual application see: James O. Lewis and William F. McMurray, *The Use of Mud-Laden Fluid in Oil and Gas Wells* (U. S. Dept. Int., Bur. Mines, Bull. No. 134, 1916), pp. 12-3; J. A. Pollard and A. G. Heggem, *Mud-Laden Fluid Applied to Well Drilling* (U. S. Dept. Int., Bur. Mines, Tech. Paper No. 66, 1914), 21 pp.; A. G. Heggem and J. A. Pollard, *Drilling Wells in Oklahoma by the Mud-Laden Fluid Method* (U. S. Dept. Int., Bur. Mines, Tech. Paper No. 68, 1914), 27 pp.; and A. Beeby Thompson, *Oil-Field Exploration and Development* (New York: D. Van Nostrand Co., 1925), II, 682-8, 640-3.

A fishtail bit that could scrape its way through soft material was first used in rotary drilling, but in 1908 the cone bit was invented.³⁶ This bit made it possible to drill much harder strata and greatly increased the usefulness of the rotary drill. It consisted of cone-shaped, hardened steel wheels with toothed surfaces mounted radially on pinions so that they could revolve freely as the drill column was rotated. Bits of this type and modifications, such as the roller and disk bits, cut by attrition or disintegration.

Early types of the rotary drill were designed primarily for coring. In one form the bits and core barrels were like those of the Davis calyx; when the core barrel was filled, heavy pressure would be put on the bit so that the (inside-set) teeth were bent far enough inward to hold the core as the rods were pulled from the hole. Special fishtail and cone bits have also been designed for coring,³⁷ and used mainly in drilling oil and gas wells. Of special interest in recent years has been the notable progress in the development of portable rotary drills mounted on heavy trucks. Such models have been used widely for shallow-hole work, especially in seismographic prospecting, and more recently they have been employed in drilling to considerable depths in oil- and gas-field development.

Although development of the hydraulic rotary drill was a tremendous advance in oil-field technology and made possible the boring of holes nearly 3 miles deep³⁸ - roughly twice the greatest depth reached by the cable-tool drills³⁹ and one and a half that by the diamond drill⁴⁰ - it has not been used extensively in other branches of mining.

BLASTHOLE DRILLS

Blastholes must be drilled for virtually every type of surface-mining operation.⁴¹ The kind of drill employed is determined by the character and hardness of the rock, the topography of the area, the type of

³⁶Hughes, *op. cit.*, p. 621.

³⁷For a description of rotary core barrels see John R. Suman, *Petroleum Production Methods* (1st ed.; Houston, Tex.: Gulf Publishing Company, 1921), pp. 36-40.

³⁸One well at Kern County, California, was drilled to a depth of 15,004 feet in 1938. See Kiessling and Others, *op. cit.*, p. 92.

³⁹A deep test well on the Goff farm in West Virginia reached a depth of 7,386 feet early in 1918. It was then said to be the deepest well in the world. See *Mineral Resources of the United States, 1918* (U. S. Dept. Int., Geol. Survey, 1921), pt. II, p. 1010.

⁴⁰See pp. 61-2.

⁴¹Blasthole drilling is not limited to mining. Railway, highway, canal and dam construction, and excavation for building foundations, for example, are often in rock and the techniques employed are those of open-cut mining and quarrying. There is some evidence that mining and quarry procedures have evolved to some extent from those first utilized in public works. Early steps were made toward mechanization of the drilling process with the use of the crude Singer drop drill in the 1840's in canal work and the piston drill was first used in railway-tunnel building in the sixties.

operation, and other considerations. To facilitate discussion, drills used for blasthole boring in general-type quarries are first described, and descriptions of drills used for the same purpose at dimension-stone quarries and at open-cut metal mines follow.

The distinction between the two types of quarry operations is made on the basis of the differing products and the consequent difference in working methods. The ordinary general-type quarry plant may produce cement materials, crushed stone, fluxing stone, road metal and railway ballast, and other types of crushed or broken products. It is concerned primarily with dislodging and shattering rock that usually must be crushed and sized further before it is ready for use. The dimension-stone quarry, on the other hand, produces blocks of stone for building and ornamental purposes, and the principal problem is to break the rock along predetermined lines or to confine the breakage to lines of weakness inherent in the particular rock mass. Shattering or even promiscuous cracking of the rock must be avoided. In consequence, the techniques and tools employed in drilling in the two types of quarries are dissimilar.

Blasthole Drilling in General-Type Quarries

Drilling in general-type quarries may be divided into two categories, primary drilling for blasting to dislodge the rock and secondary drilling (or "block-holing") for blasting to break the boulders dislodged in the primary blast into sizes that can be conveniently loaded.⁴²

Among the factors that must be considered in choosing a blasthole drilling technique are the hardness of the rock, the presence or absence of crevices or pockets, the degree of fracture, and the dip and bedding of the strata. The height of the working face also influences the effectiveness of the drilling process employed but, unlike the factors enumerated above, may be controlled to some extent by the operator. Before rock drills were introduced, the height of the working face depended largely on the depth to which holes could be drilled by hand. The development of mechanical rock drills, however, gave the operator a wide choice as to the height of the bench worked provided the deposit was relatively thick. Thinness of deposits and limited range of available drilling equipment were factors that curtailed the element of choice.

⁴²Several other methods are also employed for secondary breaking, such as sledging, "mudcapping", and "steel balling." Mudcapping is the process of breaking rock by placing an explosive on top of the rock or boulder instead of in a drilled hole and covering it with a damp cohesive material (mud or clay) to hold it in place until detonated. Although this is a quick method, it is inefficient in the use of explosives. Steel balling consists of dropping a ball of steel or cast iron onto the boulder from a height of 20 feet or more. Such a ball usually is raised and dropped by a power shovel.

If but one type of machine was available, the height of the working face was limited to that at which the given type of machine could function most effectively. Introduction of the piston drill into quarry work, for example, increased the height of a workable face to about 15 or 20 feet - about the limit to which the early piston machine could drill satisfactorily under ordinary conditions. On the other hand, if the height of the working face was rigidly fixed, the kinds of drills that could best be used were those that would function most effectively at that height. Finally, wide alternatives regarding the height of bench existed only at operations where the beds worked were relatively thick.

The general adoption of power surface drills for work in quarries was a very slow process. Perhaps the major deterrent was lack of capital required to purchase the drills and to provide auxiliary equipment and accessories. Tradition and local custom also were not changed readily, and the early machines frequently could not be used where quarry conditions or the types of products desired were unusual. Not until after the turn of the century, when the rapidly rising demand for cement and crushed stone necessitated greatly increased daily output, did the adoptions of mechanical drills increase extensively.

Motive Power.- The piston drill was probably used in quarries as early as the seventies but was rare until the next decade.⁴³ From the beginning of and well into the present century, steam powered the drills used for surface work, although the use of compressed air and other actuating forces increased steadily. Steam was employed because portable or stationary boilers of suitable size were widely available, and the capital outlay was much smaller than for an air-compressing plant. Nor was there objection to steam as in underground mines. Further, a somewhat smaller volume of steam than of air was required to actuate the drill⁴⁴ and if there were no line losses less fuel was needed to run the drill with steam. In practice, however, small boiler plants were inefficient and losses of steam very high. Even with insulated pipe lines, condensation losses, in cold weather especially, were large. Furthermore, the drilling machine sometimes was damaged by sudden expansion and was difficult to handle because of the heat, so that small, hand-held drills could not

⁴³"A Big Blast," *Engineering News and American Railway Journal*, Vol. XXII, No. 38 (Sept. 21, 1889), pp. 288-9. This was, as the writer called it, a "notable" event. Although there had been other and larger quarry blasts, 20,000 to 25,000 tons were estimated to have been broken in this particular blast and it was thought to have been the first time that rock drills were used to drill holes 30 feet deep. Mechanical drilling was undertaken because the quarry owners foresaw the need of mass production due to the rapidly growing use of rock for "stone roads" and railway ballast.

⁴⁴Drill designers estimated about 10 percent less. See Richard T. Dana and W. L. Saunders, *Rock Drilling* (1st ed.; New York: John Wiley & Sons, 1911), p. 33.

be used. These and many other disadvantages⁴⁵ encouraged operators and technologists to seek better methods of power transmission and use.

Electricity appeared as an economical and convenient source of power with low transmission losses. The electric drill was one of the first attempts to utilize electric power in mines, and they were in use in a limestone quarry as early as 1893.⁴⁶ The actual power requirements of these drills were not great compared with those of air or steam drills but they were heavy, heated rapidly, and lacked power on the backstroke. Percussive and hammer-type electric drills were tried but were discarded for the reasons cited on pages 38-9.

The success of compressed air in underground mines and its advantages over steam brought about its adoption in quarries. The striking results that followed successive changes from hand to piston drilling with steam and then with compressed air are illustrated by reports for an Ohio quarry early in the nineties and are summarized in table 4. At this

Table 4.- COST OF DRILLING AND REAMING WITH HAND, STEAM, AND COMPRESSED-AIR DRILLS AT AN OHIO QUARRY^a

Date	Method	Feet drilled			Cost in cents per foot	
		Total	Top hole	Side hole	Total	Drilling only ^b
Sept. 1891	Hand	6,238	4,447	1,791	8.6	7.6
Sept. 1892	Steam piston drill	7,503	5,629	1,874	6.5	4.7
Sept. 1893	Compressed-air piston drill	10,401	8,007	2,394	4.3	2.5

^aCompiled from "Improvements in Quarrying Machinery," *Engineering and Mining Journal*, Vol. LIX, No. 18 (May 4, 1895), p. 416.

^bThe article states that "all blacksmith work, all fuel and oil for hoists and pumps, etc. are charged against the drills." The figures (costs) were for reamed holes ready for blasting. "Taking out the cost of reaming and making fair allowance for oil, coal, boiler attendance, etc., properly chargeable against the hoists, pumps, etc., since they ran full time and the drills but 17 days (for 4 drills) the cost of drilling is" as given in this column. Reaming, or enlarging the drill hole, was probably done by the Knox system of elongating the hole along the line of the desired break.

time manufacturers claimed that with the improved compressors there "is secured at the drill end of the transmitting pipe 88% net efficiency, while under the same conditions steam would give about 40%."⁴⁷ The

⁴⁵For a detailed discussion of the comparative merits of steam and compressed air, the reader is referred to Halbert P. Gillette, *Handbook of Rock Excavation* (rev. ed.; New York: McGraw-Hill Book Co., Inc., 1918), pp. 232-5.

⁴⁶"Electric Drills in Quarry Work," *Engineering News and American Railway Journal*, Vol. XXIX, No. 21 (May 25, 1893), p. 494. This was a solenoid type of machine similar to the ordinary piston drill and was tripod-mounted. The piston was made of a soft steel that was attracted and repelled by a current of electricity that alternately passed through coils of wire placed at the ends of the cylinders. The stroke length was about that of the regular piston drill but the number of strokes per minute was much higher and it was reported to drill rapidly.

⁴⁷"Improvements in Quarrying Machinery," *Engineering and Mining Journal*, Vol. LIX, No. 18 (May 4, 1895), p. 416.

change in motive power brought about a pronounced increase in drilling effectiveness that is discussed later in this study.

The Piston Drill.— Usually only shallow holes of small diameter were bored with the hand hammer-and-drill. With the hand churn drill, larger and deeper holes were put down. Although hand drilling was used widely until the first decade of this century for drilling primary blastholes, the outstanding superiority of the piston drill for that purpose became more and more evident. This machine drilled holes 5 inches or more in diameter to a depth of 15 or 20 feet and not uncommonly to 30 or more. As the larger holes held more explosive than the hand-drilled ones they could be spaced farther apart and resulted in more rock broken per foot of hole; the greater depth attained increased the height of bench two or three times that prevalent with hand drilling. Nevertheless, the use of the piston drill presented special problems for large-scale production operations at deposits thicker than the average drilling depth.



FIGURE 17.— EARLY PISTON DRILL IN A QUARRY

The tripod on which this early (about 1885) drill is mounted was invented in 1871. The tripod made this machine highly useful in quarry work but it was not widely adopted until the eighties.

Drilling requirements also were affected by increased use of the power shovel. By 1893 the power shovel was being used in quarry stripping,⁴⁸ and not later than 1901 it was applied to the loading of broken stone. The early shovel was not the efficient, mobile, full-swinging type in

⁴⁸E. A. Herrmann, "Steam Shovels and Steam Shovel Work," *Engineering News and American Railway Journal*, Vol. XXIX, No. 17 (Apr. 27, 1893), p. 387. Cf. continuation of this article in Vol. XXIX, No. 24 (June 15, 1893), p. 562.

widespread use today but one of small dipper capacity and slow speed that worked from a railway track and could swing through only about a half circle. Even with its limited-action radius and crew of 2 or 3 men to operate and fire the boilers and 4 to 6 pitmen to move track and perform other tasks it was said to do the work of 60 to 120 men.⁴⁹ To utilize such a machine efficiently the quarry manager had to provide large quantities of stone broken to a size that the shovel could handle. The piston drill served this need by its ability to drill holes about 20 or more feet deep. If the rock deposit was thicker than the maximum practical drilling limit of the piston drill, the quarry had to be worked on a multiple-bench system. This method necessitated employment of much hand labor for clearing the benches and for track work, and often interfered with the continuous operation of the shovel.

Use of the power drill also raised added problems of secondary drilling. Even with hand drilling, some rock fragments were too large to be handled and with the greater hole spacing and burden⁵⁰ of power drilled holes the number and size of the fragments increased. To reduce them to shovel size much hand labor was needed for block-holing. Of greater consequence was the hindrance to steady shovel operation created by the need for frequent secondary blasting. With hand loading, the quarry tracks were laid out with numerous loading points, and if secondary blasting stopped work at one place the total production was not materially affected. But if a large mass were in the way of the shovel loading had to cease while the boulder was being drilled and blasted, and the output suffered.

The Portable Churn Drill.— The problem of increasing the bench and quarry height and providing an ample supply of properly broken stone ahead of the power shovel on a single level was not solved until the portable power churn drill was brought into use for drilling relatively large-diameter deep holes. A good illustration of how progress in drilling solved the multiple-bench problem was afforded by a railway construction job that involved quarrying on a large scale. The building of a large railroad yard in 1903⁵¹ was not proceeding with the desired rapidity. An excavation averaging 75 feet in depth was being made (mostly in shale so soft that piston drills were not satisfactory) and drilling was accomplished with three-man hand churn drills putting down 20- to 30-foot holes. Three benches were therefore necessary. Although 300

⁴⁹*Ibid.*, Vol. XXX, No. 5 (Aug. 3, 1893), p. 91.

⁵⁰Generally speaking, the shortest distance from the hole to the quarry face.

⁵¹"Construction Work On The Pennsylvania R. R. Between Harrisburg and Gallitzin," *Engineering News*, Vol. L, No. 13 (Sept. 24, 1903), pp. 273-8; and W. R. Hulbert, "The Work of Well-Drilling Machines On The Pennsylvania R. R. Low-Grade Freight Line," *Engineering News*, Vol. LV, No. 15 (Apr. 12, 1906), pp. 419-20.

to 400 laborers were employed for drilling, they could barely keep 10 steam shovels at work. The contractor then adopted the small (4- to 8-horsepower) wagon-mounted well churn drill that could drill $4\frac{1}{2}$ - to 6-inch holes 250 to 400 feet deep. These machines bored 20 to 80 feet in 10 hours and averaged 48 feet. In soft soapstone as much as 100 feet was attained, but in hard limestones the rate was as low as 5 or 10 feet. The contractor reported the actual cost of power drilling to be about one-third that by hand. The greater advantage, however, was the shift to a single-bench type of operation, and the 17 churn drills in use broke more than enough rock to keep 22 shovels loading continuously.

The success of the churn drill at the operation cited above encouraged the contractor to employ it later on a much more difficult quarrying job.⁵² In this case, the rock was a hard gneiss and mica schist, with many seams and widely varying dip. The topography was so rugged that the drills had to be lowered to drilling sites quarried in the rock by hand, and the rock-cut was as deep as 135 feet. In spite of all these difficulties the churn drills averaged $19\frac{1}{2}$ feet in 10 hours with a range of 11 to 60 feet in holes 75 to 128 feet deep. On the same job piston drills were used to put in "toe" or "snake" holes⁵³ up to 35 feet in depth and averaged 40 to 60 feet in 24 hours. The use of churn drills at this operation might appear uneconomical because roads had to be cut for their transport and because four men, sometimes with horses, were required to supply two drills with bits. Nevertheless great economies were reported from the greater efficiency of blasting with deep holes instead of 25- to 30-foot hand-drilled holes, and from the reduction in hand labor required for clearing benches that accompanied the shift from the use of the multiple to the single bench.

In 1905 at least one quarry was drilling 18-foot holes with the power churn drill and current advertisements of drilling equipment indicate that greater depths were attained.⁵⁴ By 1908, steam-driven churn drills were boring blastholes over 100 feet deep in limestone quarries,⁵⁵ and in the next 2 years electric- and gasoline-driven drills came into use.⁵⁶

⁵²"The Pennsylvania Railroad Low Grade Freight Line from Harrisburg to Atglen, Pa.," *Engineering News*, Vol. LIV, No. 28 (Dec. 28, 1905), pp. 877-80. Well drills were in use here at least as early as July 1, 1905.

⁵³Nearly flat holes bored into the quarry face at the floor level.

⁵⁴Burton G. Cope, "Blasting in Quarries," *Rock Products*, Vol. IV, No. 7 (Oct. 1905), p. 31. See also well-drill advertisements which appear for the first time in this issue.

⁵⁵"Big Racine Quarry," *Rock Products*, Vol. VIII, No. 4 (Oct. 22, 1908), pp. 25-6.

⁵⁶"An Electric Driven Well Driller for Making Large, Deep, Blast Holes," *Rock Products*, Vol. IX, No. 1 (July 22, 1909), p. 40. See also B. G. Cope, "A Comparison of Electric and Gasoline Driven Blast-Hole Drills," *Engineering News*, Vol. 64, No. 26 (Dec. 29, 1910), p. 722.

These changes in motive power were part of the advance in drill construction and efficiency that included a wide variety of technical improvements. The wide use of the power churn drill for blasthole drilling in quarries filled a long-felt want,⁵⁷ and the rapid expansion of the crushed-stone industry was the main factor in the development of the portable churn drill as a blasthole drilling machine.

Although the outstanding development in quarry practice between 1905 and 1917 was the shift from the multiple-bench (in which the stages were usually not much over 20 feet high) to the single-bench operation (in which the stages were the height of the quarry face and frequently exceeded 100 feet), the widespread adoption of this system and of the power churn drill was a gradual process. It already has been noted that there was a pronounced lapse of time between the introduction of any drilling device and its general acceptance. For example, the churn drill for quarry blasthole work came into use about 1905, but nearly 4 years later an editorial writer remarked that the "newest innovation" in deep drilling in quarries was the use of the well drill.⁵⁸ In the following 6 months, trade publications reported other installations and one observer stated a year later that the tripod-mounted piston drill was being rapidly displaced by the churn drill. It was not until 1919 that many hundreds of churn drills were reported in use. While the churn drill was being accepted more generally, the piston drill began to compete with it for use in moderately deep drilling. About 1909 the improved piston drill was mounted on a truck or movable frame and there was added a small derrick with hand or power winch to handle the long, heavy drill steel. Holes about 5 inches in diameter and 40 to 50 feet in depth could be bored, and it was claimed that "the labor cost [was reduced] 75% as compared with the ordinary methods of operating."⁵⁹

Neither the heavy wagon-mounted piston drill nor the churn drill was suitable for secondary drilling. Even the regular piston drill was not well-adapted for this work, although some of the lighter models were so used. In the 10 years following 1903, secondary drilling was performed with the plugger drill, and later with the faster- and harder-hitting jackhammer.

⁵⁷"Rock Drilling," *Rock Products*, Vol. VIII, No. 10 (Apr. 22, 1909), p. 28.

⁵⁸"What Is the Blasting Limit?" *Rock Products*, Vol. VIII, No. 6 (Dec. 22, 1908), p. 20.

⁵⁹"An Electrically-Operated Quarry and Plant for Production of Broken Stone at Gary, Ill.," *Engineering News*, Vol. 62, No. 17 (Oct. 21, 1909), p. 423. See also "A Traction Rock Drill for 5-in. Holes 50 Ft. Deep," *Engineering News*, Vol. 65, No. 20 (May 18, 1911), pp. 600-1, in which it was said that this drill could do the work of 5 tripod-mounted drills with 10 men. The forerunner of this type was described in Frank Richards, "A Novel Locomotive Rock Drill and a Remarkable Drilling Record," *Engineering News*, Vol. 62, No. 23 (Dec. 2, 1909), p. 610. Though the earlier drill was crude, it was said to have accomplished more with two men than four tripod drills with eight men.

Other developments tended further to circumscribe the use of the piston drill. It had long been the custom to use this drill for toe holes to aid in fragmentation and to make a regular quarry floor. About 1910, however, good hollow drill steel could be obtained in lengths greater than the 4- to 8-foot pieces previously available; and the light one-man jackhammer using such long steels came into use where relatively short holes were required. There was also a revival of "tunnel" blasting⁶⁰ - a method suitable where rugged topography rendered it difficult or impossible to move the large and heavy blasthole drills from hole to hole, where hard or broken ground seriously reduced the rate of churn drilling, or where large rock masses were desired for harbor, jetty, or dam building. In the restricted space of these tunnels the piston drill could not be used advantageously but the jackhammer was particularly effective. Where more complete fragmentation was desired, particularly in quarries where the benches were more than 100 feet high, a combination method of power churn drilling with "coyote holes" was introduced in 1926⁶¹ and is still being utilized successfully in many quarries.

The Drifter Drill.- The drifter hammer drill, which had displaced the piston drill almost completely in underground work, also made progress against the piston drill at surface operations. It was not until reasonably satisfactory methods of manufacturing long, hollow drill steel were developed, however, that the drifter began to replace the piston drill in quarrying. Moreover, surface work required heavier, more powerful machines than those used underground, and such models had to be developed and tested. Thus it was about 1917 before drifter drills were available for boring 30-foot holes having a 2-inch diameter at the bottom.⁶²

Following the practice already established with piston drills, drifters were mounted on wagonlike frames which expedited moving and setting up the drill. The derrick mounting appeared in the early twenties and significantly increased the efficiency of the drifter for quarry work.⁶³

⁶⁰Known also as "coyote-hole" or "gopher-hole" blasting. In this quarrying method a small tunnel 3 by 4 feet in cross section is driven into the quarry face at about the floor height. The length of this opening is always less than the face height and depends on the character of the rock, the degree of fragmentation desired, etc. From the end of the tunnel, crosscuts are driven in opposite directions and approximately parallel to the quarry face. The explosives are usually placed along these crosscuts.

Although this method had been employed in Great Britain about 30 years earlier, its first use in the United States was in the winter of 1877-78 at a limestone quarry in eastern Pennsylvania.

⁶¹"Well Drill and Coyote Hole Blasting in Combination," *Rock Products*, Vol. XXIX, No. 11 (May 29, 1926), pp. 33-7.

⁶²Joseph H. Walshe, "Deep Hole Quarry Drilling with Hammer Type Drills," *Rock Products*, Vol. XXVIII, No. 11 (May 30, 1925), pp. 46-7.

⁶³"Developments in Machinery and Equipment - Drilling and Blasting," *Rock Products*, Vol. XXVIII, No. 26 (Dec. 26, 1925), pp. 168-9.

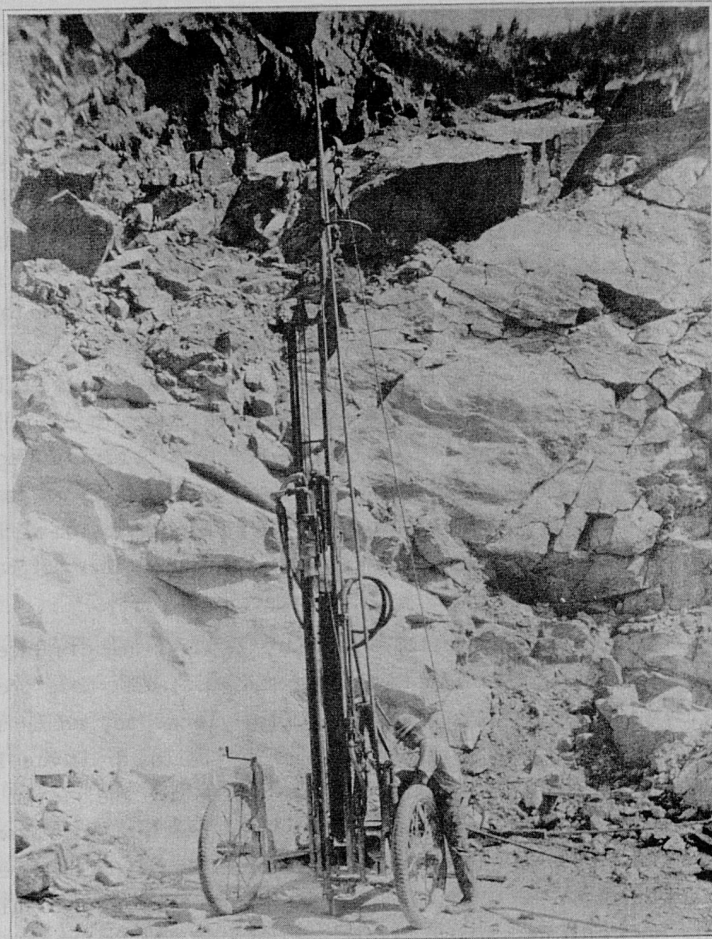


FIGURE 18.— DERRICK-MOUNTED DRIFTER DRILL

This machine competes with the churn drill for blasthole work in stone quarries and open-cut mines. It has high mobility and very high drilling speed and the drill, as well as long drill steel supported by the ring at the top of the steel derrick, is easily handled with a small power hoist mounted on the machine frame.

Some models have a power screw feed and the derrick frame may be inclined so as to drill holes in any direction. The earliest models of wagon-mounted piston drills were said to have done as much work as four tripod-mounted piston drills. Late hammer types will accomplish about double that amount.

There were several types similar in principle. One consisted of a substantial, wheeled derrick about 16 feet high and a heavy drifter mounted on a slide carried by the vertical uprights of the derrick. The drill was raised and lowered with a wire rope attached to a power winch; a second winch was provided to handle the drill steel. The feed was effected by gravity and controlled with the winch, and it was claimed that this model could drill 40-foot holes with a 3-inch bottom diameter.⁶⁴ Later

⁶⁴Walshe, *loc. cit.*

types were provided with an air engine-driven screw feed which allowed a wide range of pressures. Thus the driller could take advantage, as with the hydraulic-feed diamond drill, of changes in rock characteristics and could keep the machine operating at its optimum rate. Improvement in both the drilling mechanism and the rig makes the later models very different from the early piston-type wagon. Steel has replaced wood, the drill-supporting frame may be inclined so that holes may be bored at any angle, rubber-tired wheels are swiveled so that they may be turned out of the way or the rig easily brought into any desired position, simple manifold connections are provided for air and water, and all control valves are within reach of the operator's hand. The modern derrick-mounted drifter is a one-man drill. Although it generally drills holes only about one-half the diameter of those of the churn drill its light weight and high speed make it perhaps the most effective drill available for holes within its depth range.

The outstanding drills in modern quarrying are the churn drills and the derrick-mounted drifter drills. Rock characteristics permitting, each has inherent advantages and its special sphere of usefulness; the power churn drill for faces about 40 to 100 feet or more in height and the derrick-mounted drifter for the lower faces of about 12 to 40 feet. For intermediate depths of from 25 to 50 feet, each drill finds strong advocates among quarry engineers.

Drilling and Cutting in Dimension-Stone Quarries

The quarrying of building stone is among the oldest of the American mineral industries and dates from the second half of the seventeenth century.⁶⁵ With the growth of cities, the exhaustion of easily available timber, and the need for permanence and durability in building construction, dimension-stone quarrying expanded rapidly in the first half of the nineteenth century. Until a practical power rock drill was developed it remained essentially a hand operation. Early quarry methods are still in use but have been modified somewhat by the use of machines that were adapted from those designed for underground mining or were especially developed to meet the needs of the dimension-stone quarryman.

Hand Drilling.—Although blasting is not employed so extensively as in general-type quarries, it came into use (with gunpowder) possibly as

⁶⁵The early history of this industry was described by George P. Merrill, "The Collection of Building and Ornamental Stones in the U. S. National Museum: A Handbook and Catalogue," *Annual Report of the Board of Regents of the Smithsonian Institution, 1886* (Washington, D. C.: Government Printing Office, 1889), pt. II, pp. 285-91. (The same account may be found in the different editions of Merrill's *Stones for Building and Decoration*, the first of which was published in 1891 by John Wiley & Sons, New York.)

early as the fifteenth century and still finds some application, particularly in granite, massive sandstone, and slate quarries. This method ordinarily is used for what may be called primary breaking, such as the severing of a large mass from a ledge or rock deposit. This differs from the heavy, shattering blast of the general-type quarry. The blast-holes, moreover, are smaller, and only light charges of low explosives are used to initiate fracture along inherent or predetermined lines.

Secondary breaking, or the reduction of rock masses to commercial sizes or those suitable for cutting or dressing, still is usually accomplished by the use of "plugs-and-feathers",⁶⁶ a method followed in this country as early as 1730.⁶⁷ Holes for the plugs, placed a few inches to several feet apart, usually were only a few inches deep, although in some sandstones and granites the length of hole nearly equaled the desired thickness of the block. A pair of feathers was inserted into the hole with the large end toward the bottom and a plug placed between them. A workman passed along the line of holes and gave each wedge a hammer blow until the block was split or freed from the bed.

The shallow holes required for the feathers usually were drilled by one man, but the deeper ones - particularly in the harder rocks - required three men, one turning and two striking. The familiar hammer-and-drill (or as sometimes called in quarrying, "hammer-and-jumper") was used, and the footage drilled per man-shift was often four or five times higher than that in mining. This was because most of the plug holes were much smaller in diameter (three-quarters of an inch being a common size), because they were shallow and little time was needed to clean out the cuttings, and because the rocks, excepting perhaps the granites, were softer and much more homogeneous than those generally found in mining. On the other hand, many more holes had to be bored than in mining; in primary breaking, especially, a row of holes was needed on two and frequently on three or four sides of the block. Explosives could be used only sparingly, as shattering caused a great loss of stone. Thus drilling was a major operation in quarrying; when done by hand the principal quarry labor cost was for drilling. This provided a great incentive to mechanization of that operation.

Rotary Drills and Modifications.- The rotary drills, except the hydraulic, heretofore described have been employed in removing overburden or in quarrying proper at dimension-stone quarries. Except perhaps in slate

⁶⁶"Feathers" are thin, half-round pieces of iron or steel slightly tapered lengthwise. The "plug" is a thin wedge that is driven between two feathers.

⁶⁷Merrill, *op. cit.*, pp. 314-6. It was also stated that "so much did the adoption of this simple method facilitate granite working that the price of the cut material dropped within the space of a few months over 60 per cent."

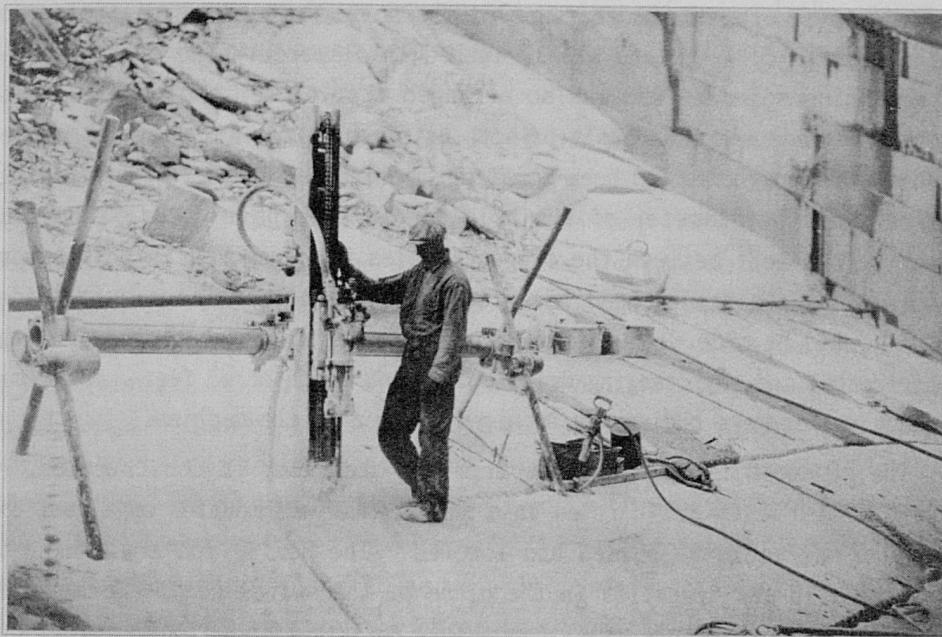


FIGURE 19.— A MODERN BAR CHANNELER IN A GRANITE QUARRY

Channeling in hard rock such as granite is effected by drilling a series of closely spaced holes and subsequently breaking or chopping out the web between the holes with a flat bit or broaching chisel. In this picture holes are being bored beneath the quarry-bar; at the right and in the foreground are completed channels. Behind the operator may be seen a light plug hammer drill used to bore shallow holes for the plugs-and-feathers with which secondary breaking is accomplished. Tripod-mounted piston drills were used first but about 50 years ago the quarry-bar was invented and greatly lightened the laborious task of primary cutting. Channeling in granite could scarcely have been done by hand and a comparison of hand and machine work is not possible, but the machine can do at least as much as 20 hand drillers.

quarrying, stripping or the removal of overburden at quarries is not so important as in the other branches of open-cut mining. Thus in this section have been described only those rotary and other drills used principally in quarrying proper.

The diamond drill probably was the first power drill employed⁶⁸ at quarries, and the early machine was intended only for shallow plug-and-feather holes. Within a few years, improved models for "gadding" and "channeling" were developed⁶⁹ and found considerable application before 1880,⁷⁰ particularly in marble quarrying. Such machines used a steam boiler and engine mounted on a truck that traveled on rails. The drill proper was essentially the same as the screw-feed type described on

⁶⁸About 1864 in Vermont.

⁶⁹To free a block from the quarry floor it is generally undercut and wedged off with plugs-and-feathers. The drilling of the holes - generally horizontal - is called "gadding" and the making of a continuous narrow cut - usually vertically on the sides of a block - is called "channeling."

⁷⁰*Tenth Census of the United States: 1880*, Vol. X, "Special Reports on Petroleum, Coke, and Building Stones" (U. S. Dept. Int., Census Office, 1884), "Building Stones of the United States," pp. 33-8 and plates XX, XXVI.

pages 60-1. The diamond bit was of the solid type with small holes for the passage of water and was $1\frac{3}{4}$ inches in diameter. The channeler had two boring spindles and was so arranged that either two parallel cuts could be made simultaneously or both bits could work in the same groove. When a pair of holes had been bored the machine was moved forward slightly less than the diameter of the hole and another pair bored. The rock partitions left between the original holes were removed in this second operation, the boring head being confined to the partition by a guide. Cuts could be made with this machine at angles up to about 45° from the horizontal and, by changing drill rods, to a depth of $9\frac{1}{2}$ feet. A fireman and a runner were ordinarily required to operate the machine.

The gadder differed somewhat from the channeler in construction. A single feed screw was carried in a swivel that was mounted on a vertical column and could be raised and lowered. The boring rod could also be inclined in any direction in the plane of the swivel head. Such a combination of movements made it possible to drill in any direction, but the special field of operation of the gadder was in the undercutting of primary blocks. The depth of holes was usually about half the block width, although both the depth and the number of holes varied with the character and kind of rock.

Diamond rotary machines were an important addition to the quarryman's equipment; the gadder remained in use for 20 years or more.⁷¹ The boring did not fracture the rock and so reduced the amount of waste; also the rate of channeling and gadding was 10 to 20 times that of hand work.

An early⁷² example of the use of large blastholes was the employment of a crude forerunner of the rotary or calyx drill in some Connecticut sandstone quarries. "These holes, which are made by a crude machine driven by cranks like an ordinary derrick, are 10 inches in diameter and about 20 feet deep."⁷³ Charges of 25 to 75 pounds of black powder were used to free the large blocks, which were broken in turn with large iron wedges driven into a channel cut by hand several inches deep.

The shot drill is little used in quarrying at present except for slate where holes up to 36 inches in diameter are bored to receive the standards that carry the guide pulleys of the wire saw (see page 89). An unusual but particularly interesting application at a Massachusetts granite quarry has been noted by Bowles. A shot drill at this quarry cuts 52-inch

⁷¹*Special Reports of the Census Office, "Mines and Quarries: 1902"* (U. S. Dept. Com. and Labor, Bur. Census, 1905), p. 805.

⁷²F. W. Sperr said the device had "long been in use" See *Tenth Census*, Vol. X, section on "Building Stones of the United States," p. 33.

⁷³Merrill, *op. cit.*, p. 312.

cores from a series of holes across the center and ends of the quarry. The cores are quartered and formed into corner curbstones smoother and truer in shape than those hand-hewn.⁷⁴

Piston Drills.— With the development of the tripod-mounting about 1871 the piston drill was applied to quarry work and was at once widely accepted, especially in granite quarries where many relatively deep holes were drilled. By 1886 it was said that "the old-time method of drilling by means of a flat pointed drill . . . which is held by one workman while others strike upon it . . . has been largely superseded by steam-drills [pistons] of various kinds."⁷⁵ This ordinary tripod-mounted mine drill was much faster than the hand hammer-and-steel. Although it could work in any direction, its size and weight rendered it unsuitable for short holes, and it was difficult to direct with precision where numerous holes were to be bored in line; also, it could not be brought close enough to the quarry floor to serve well in undercutting. These difficulties were overcome by the development in the early eighties of a "quarry-bar" and a "gadder." The former is simply a pipelike bar 10 to 12 feet long supported by A-frames at the ends. Modern quarry-bars are provided with a rack that aids the movement of the drill on the bar and permits exact hole spacing and alignment. The gadder was an adaptation of the diamond gadding machine. It consisted of a low, heavy carriage with an upright standard adjustable to any angle. A piston drill was attached to the standard so that it could slide up and down as well as turn in any direction in the plane of the standard. Thus the gadder could drill in any direction, even at the base of the block to be freed.

Invention of the quarry-bar made possible "broach-channeling", which was of special importance in quarrying hard rocks. By this method a series of parallel holes was drilled for the length of the bar in the ordinary fashion. Then the drill's steel-rotating device was released (some drills were designed with a special release mechanism) and the regular drill steel replaced with one having a broad chisel bit. With it the web between the holes was "broached" or chiseled out and continuous channels cut.

As already stated, for many years blasting was of great importance in breaking primary blocks. At the sandstone quarry mentioned in connection with the rotary drill, for example, it had been noted that the shape of the hole had a pronounced influence upon the direction of the line of break and the powder containers were shaped and tamped in place so as to

⁷⁴ Oliver Bowles, *The Stone Industries* (2d ed.; New York: McGraw-Hill Book Co., Inc., 1939), pp. 149-50.

⁷⁵ Merrill, *op. cit.*, p. 320.

give the effect of an elliptical hole. A similar result sometimes was obtained by drilling two holes close together and chipping out the core between them. This principle does not seem to have been generally known, for it was not until about 1890 that the Knox system of blasting became important. With this method, holes were drilled as usual, and then diametrically opposed grooves about $\frac{1}{4}$ -inch deep and in the direction of the desired fracture plane were cut or reamed by driving a flanged tool into the hole by hand or by using a rock drill with the rotation released. For this work the piston drill was eminently suited. This method was widely used,⁷⁶ particularly in granite and sandstone quarries; not only could the line of fracture be accurately propagated (of great value where jointing or inherent planes of weakness are not pronounced) but also fewer holes were needed to free a given block. Another method (known as the "Githens"), in which an oval hole was formed in one operation, was patented in 1892 and displaced the Knox system to some extent.

Another limited but interesting use of the piston drill was as a "circle cutter" or "ditcher" in producing cylindrical blocks for grindstones. A tripod with a vertical bar set into a hole in the upper surface of the stone was used for support and the drill clamped on a counterweighted radial bar swung with a worm gear. By securing the drill in different positions a wide variety of block diameters could be obtained. The floor break was done by gadding. Bowles states that such a drill would cut as many square feet per day as a channeler and much less time was required to set it up.⁷⁷

Hammer Drill.—Although the superiority of compressed air for certain types of drills had long been recognized, its general adoption did not occur much before 1900 when pneumatic hand tools such as the chipping and riveting hammers became very popular. These hammers were tested in dimension-stone quarries,⁷⁸ using a $\frac{5}{8}$ - or $\frac{3}{4}$ -inch-diameter steel drill in place of the riveting or chipping tool. This steel drill worked so satisfactorily in drilling the shallow 3- to 4-inch plug-and-feather holes that the earliest general acceptance of the hammer-type drill may be said to have been in the quarry industry. Such a drill used very little air and was light enough to be held in one hand, leaving the other free to turn the steel with a wrench. Within a few years, however, it lost its place to the plugger drill, which could bore holes 3 to 4 feet deep and

⁷⁶William L. Saunders, "Dimension Stone Quarrying - The Blasting Process," *Transactions of the American Society of Civil Engineers*, 1891, Vol. XXV (1891), p. 501. In 1885, 2 quarries used this patented system and by 1891 about 300 had adopted it.

⁷⁷Bowles, *op. cit.*, p. 85.

⁷⁸H. L. Sinclair, "The Development of the Air-Hammer Drill," *Engineering and Mining Journal*, Vol. LXXXIII, No. 15 (Apr. 13, 1907), pp. 714-6.

was designed to use hollow steel through which air was passed to blow out the cuttings. The plugger could handle nearly all types of plug-hole drilling; it rapidly displaced hand labor and to some extent the piston drill. Later developments followed the progress of the hammer drill. The jackhammer replaced the plugger, and the various types of drifters (with some modifications) almost entirely replaced the piston drill, even when it was used as a channeling and a gadding machine. Furthermore, the changes in motive power, materials, and accessory apparatus discussed in chapter III were quite as important as in underground mining.

Special Dimension-Stone Quarry Machines

The Channeler⁷⁹.—The most carefully planned and supervised blasting damaged much stone. On the other hand, the labor of cutting channels by hand, except in the softest of rocks, was so great and costly that much effort was expended to devise a machine to perform that task. The track channeler solved the problem. "The first successful machine was built. . . . [by George J. Wardwell of Rutland, Vt.] in 1863, . . . and that original machine has been at work . . . constantly until within a few months (1885). These machines are now in operation in all the important quarries of sandstone, limestone and marble in the country, and it is calculated that over 5,000,000 square feet have been cut by them."⁸⁰

The early channeler was a self-contained unit that ran on tracks on the quarry floor. It consisted of a heavy truck on which were mounted an upright boiler, a horizontal engine, and crank, levers, and springs which actuated the "gangs" or sets of cutters. The machine had either one gang or two placed on opposite sides, each consisting of five steel bars 7 to 14 feet long having transverse or diagonal cutting edges and tightly clamped together to an M-shaped bit. The center bar projected below the two adjacent bars, which in turn were below the outside two. The machine was automatically moved by gears from the engine shaft. To change bits the gangs of cutters were raised or lowered by small hand winches and a chain attached to the upper end of the cutter bars. Channels were about $1\frac{1}{4}$ to 2 inches wide, as long as was desired, and usually 4 to 6 feet deep, although deeper cuts could be made with longer bars. Two men were required for the single-gang and three for the double-gang machine that was claimed to do the work of 40 men.⁸¹

⁷⁹The channeler has been extensively used in other than dimension-stone quarries; for example, in the cutting of smooth canal walls, and for building foundations in rock where ordinary drilling and blasting could not be used (because of the proximity of other structures, etc.).

⁸⁰Merrill, *op. cit.*, p. 321.

⁸¹"Improved Stone Quarrying Machine," *American Journal of Mining*, Vol. I, No. 4 (Apr. 21, 1886), p. 49.

The first machines were very heavy and cumbersome, the frame alone weighing about a ton. They could cut only vertical channels, could not work close to corners, and were useful only on flat surfaces. By 1866, however, the track channeler had been redesigned so that it could cut at an angle of 45° to the horizontal. About the same time the "duplex" machine was evolved; this model had two gangs of cutters on one side, and both worked in the same channel. Although the early channeler had some disadvantages it was so superior to hand channeling or to drilling and blasting that many of these machines were put into operation in the 20 years following their introduction.

About 1885 the first of the now generally used direct-acting track channelers was patented. This was in reality a piston rock drill that worked without rotation; it had a single gang of bits set into a cross-head and attached to the piston rod so that the blow was dealt directly by the steam acting on the piston and not through intervening cams, levers, or springs as in the older Wardwell channeler. The drill was mounted on a wheeled truck and could be inclined forward, backward, or transversely, to cut at any angle, and was particularly useful in making inclined channels or in cutting out corners where the older machine could not work. The boiler could be removed from the truck and steam delivered by hose; when this was done the machine required but little headroom and could work in underground quarries when necessary. It was reported to strike about 250 blows per minute as compared with the 100 to 150 of the ordinary single-gang channeler and to cut about twice as fast.

Another type of channeling machine, the bar-channeler, was introduced into marble quarries in 1888.⁸² This was essentially a variable-stroke, powerful piston drill mounted on a modified quarry-bar. The movement of the drill on the bar was automatic, and the strength of the blow was adjusted by the runner to suit the characteristics of the rock. The drill had a simple rotation release so that after conventional drill steel had been used to start a cut by boring a hole it could be replaced by a gang of cutters. Bits were made with 18- to 24-inch changes as with ordinary drill steel. The bar mounting made it possible to channel in sloping floors and to make horizontal cuts.

Progress in direct-acting channelers paralleled advances in rock-drill construction. The use of such channelers in the construction of the Chicago Drainage Canal about 1894 brought about many improvements; their speed was increased, they were designed for heavy duty (12- to 15-foot

⁸²"The Saunders Bar Channeler," *Engineering and Mining Journal*, Vol. XLVII, No. 15 (Apr. 13, 1889), p. 347.

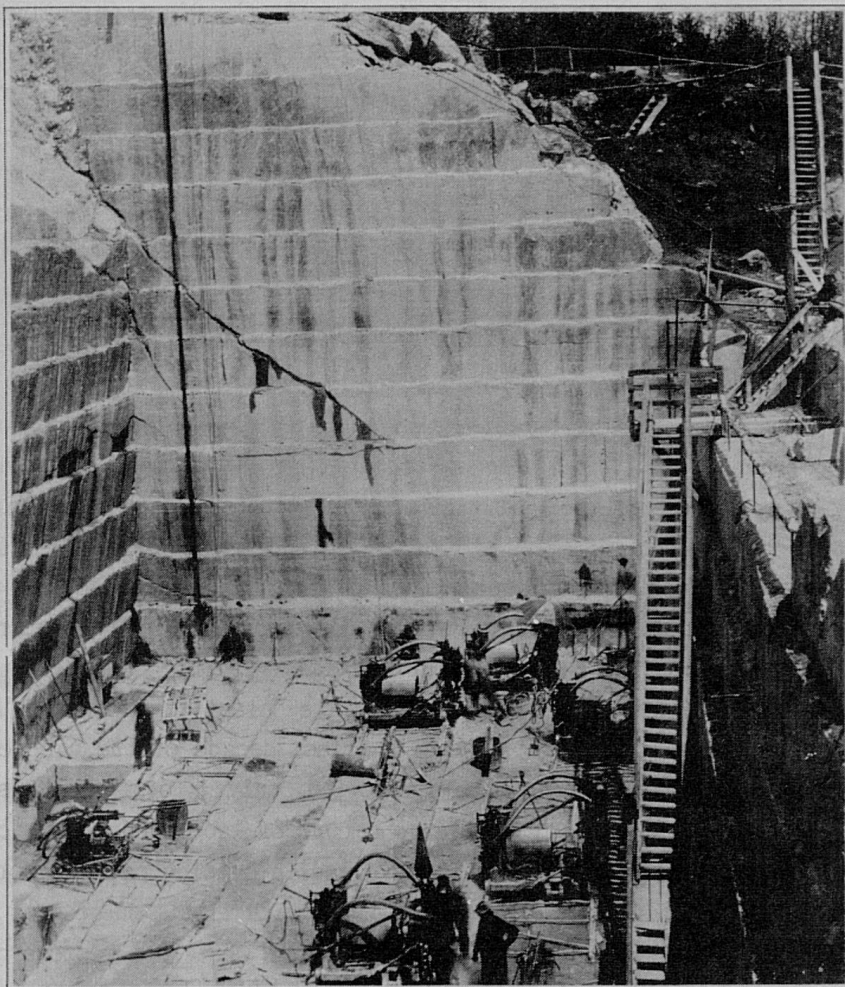


FIGURE 20.— DIRECT-ACTING CHANNELERS

The channeler invented in 1863 was driven by a steam engine acting on levers and springs. The direct-acting steam type came into use about 20 years later. It consisted essentially of a piston-type drill mounted upon a frame so that the drill could be lowered as the channel was deepened. Instead of drill steel, a gang of cutters was clamped in the chuck. The direct-acting electric air channelers shown in the photograph are actuated by compressed air from an integrally mounted, motor-driven compressor. The air is not exhausted but circulates between compressor and channeler.

cuts), and were provided with independent engines which moved the channeler and raised the piston cylinder to change bits. Various types of bits were designed for the different rocks. Although steam was the usual source of power for the early channelers, it has been displaced at many quarries by compressed air supplied from a central compressor or by an electric air-pulsator. Electric power was not adaptable to the direct-acting channeler, but about 1895⁸³ it was applied to the Wardwell type and is still so employed.

⁸³ *Annual Report of the Secretary of the Interior for the Fiscal Year Ended June 30, 1896* (1896), Vol. IV, pt. 3, p. 809.

The channeling machine was of great value to the dimension-stone industry. It reduced the volume of waste rock, which was often more than 60 percent of the marketable production and increased the output per man at least 15 to 30 times over hand methods. The channeler had some disadvantages, particularly in certain types of quarrying; power consumption was high, and the percussive action jarred the rock (or, as quarrymen say, "stunned" it) and set up incipient fractures. This was an especially important problem in slate and sandstone quarries, and attempts to overcome it brought about the recent readoption of the wire saw.

The Wire Saw.—The idea of using a moving wire rope to cut stone dates from 1854, when the patentee claimed ". . . as basis of my invention the employment, as sawing instrument, of one or several wires or metal cords or chains acting in a continuous or alternating rotary motion driven by hand or machine" ⁸⁴ This method was not used until over 25 years later when some practical improvements were made. In 1886 the wire saw was being successfully applied in a Belgian marble quarry ⁸⁵ and about 1900 its use had become quite general on the Continent. The date of the earliest use of this device in the United States has not been ascertained, but it was probably in the last decade of the nineteenth century as the Census Office (1902) reported "only 32 of these saws actually in use." Because of the large amount of labor necessary to put "the saw in position and the waste involved in cutting out the corners in which the pulleys" ⁸⁶ ran, the wire saw met with little success at this early date, except in a few of the larger Middle Western limestone quarries. Renwick, writing of marble quarries in 1909, said that the saw had met with little favor at such operations in the United States because, although channeling was more costly and was economical only where there was a large and continuous output, it would do twice the work of a wire saw and "the various concerns experimenting have reverted to channeling as being the more economical" ⁸⁷ Nevertheless, the wire saw appears to have been successfully used in a Colorado marble quarry in 1913. ⁸⁸ Despite this fact, it was not until after the U. S. Bureau of Mines purchased a wire saw in 1926 in cooperation with quarrymen and set it to work in a Pennsylvania slate quarry ⁸⁹ that this machine became significant in the dimension-stone industry.

⁸⁴W. G. Renwick, *Marble and Marble Working* (London: Crosby Lockwood and Son, 1909), p. 36.

⁸⁵"Quarrying by Wire Cord," *Engineering and Mining Journal*, Vol. XLVII, No. 14 (Apr. 8, 1889), p. 321. Additional details are given in "Mechanical Quarrying and Stone Cutting," *Engineering and Mining Journal*, Vol. XLVII, No. 21 (May 25, 1889), p. 478.

⁸⁶*Special Reports of the Census Office*, "Mines and Quarries: 1902," p. 805.

⁸⁷Renwick, *op. cit.*, pp. 47-50.

⁸⁸Bowles, *op. cit.*, p. 255.

⁸⁹Oliver Bowles, *The Wire Saw in Slate Quarrying* (U. S. Dept. Com., Bur. Mines, Tech. Paper No. 469, 1930), p. 15.

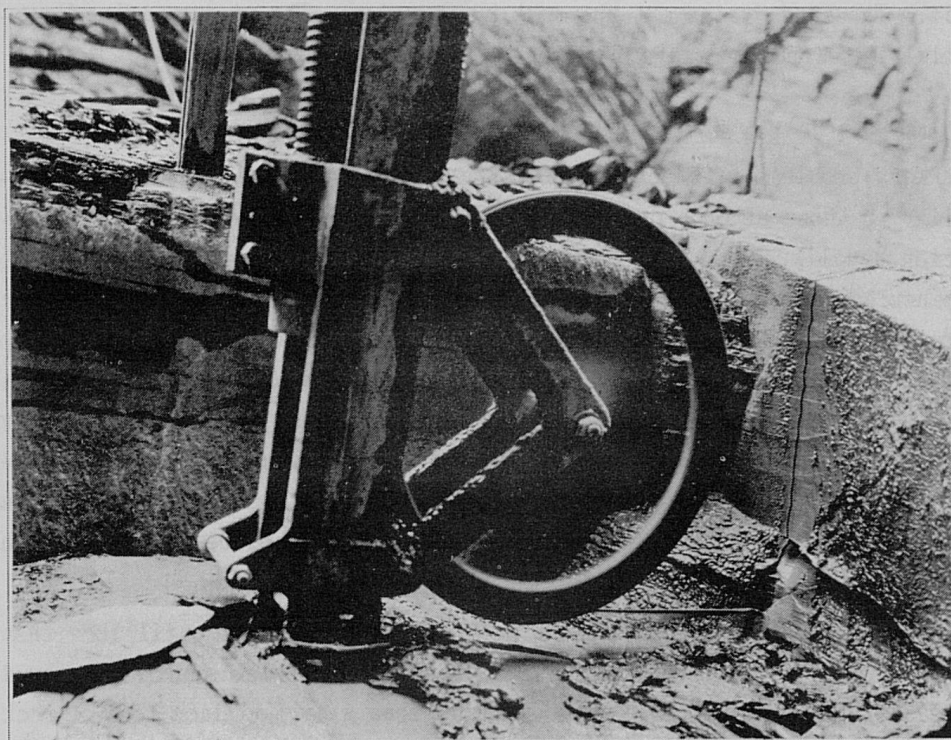


FIGURE 21.— WIRE SAW IN A SLATE QUARRY

When the block of stone to be cut by the wire saw has no free ends where the standards carrying the wire guide pulleys can be erected, holes about 3 feet in diameter are bored with the calyx drill. Steel shot is the customary abrasive in drilling and the drill frame may be inclined up to about 45 degrees. Inclined saw cuts can thus be made, which is a matter of much importance in slate quarrying, for, if possible, cuts are made parallel to the bedding, which is usually inclined to the horizontal, to avoid waste. The picture shows the lower guide sheave of a wire saw as well as the wire as it leaves the cut. The small, rapidly moving steel wire using sand as an abrasive readily cuts the softer rocks. The saw kerf is much narrower and the rock is not "stunned" as with a percussive machine like the channeler; loss of usable stone has been greatly reduced. In slate production, moreover, its cutting rate is often four to five times that of a channeler.

The wire saw consists of a three-stranded endless wire rope usually $\frac{5}{16}$ or $\frac{1}{4}$ inch in diameter and 800 to 2,400 feet in length. The driving unit is generally an electric motor with a grooved pulley. From the driving pulley the rope passes over guide sheaves to the part of the quarry where the cutting is to be done. A tension carriage is placed in the rope circuit to keep the wire taut and to allow for changes in the length of the wire as the cutting proceeds. If there are no open ends in the quarry, holes 20 to 36 inches in diameter and somewhat more than the depth of the desired cut are bored with a shot drill at intervals of 60 to 200 feet, depending on the length of the primary block. Steel standards 14 to 18 feet long are set in the holes and carry on top one or two sheaves that guide the rope to a lower sheave which moves up or down by means of a rope or chain-pull worm gear. The rope travels about a thousand feet per minute while a pulp of sand and water is poured upon

it. The sand grains cut the rock by abrasion. The wire saw is of special importance in slate quarries.

Blasthole Drilling in Open-cut Metal Mines

Many problems of blasthole drilling at general-type quarries are similar to those at open-cut metal mines, although each metal-mining operation usually offers special problems. Unlike the quarryman the metal miner has no broad choice in the selection of a deposit to be worked for relatively few are near enough to the surface and large enough to justify open-cut exploitation. The topography especially may present obstacles to the maintaining of a large and continuous output of ore of relatively constant grade from an ore body limited in extent or overlain by valueless rock. The principal factors determining the type of drill used in such mining are the physical characteristics of the ore and overburden and the method of extraction.

Open-pit mining is an ancient method, but it was not until 1887 that the application of stripping "to solid rock-masses was scarcely dreamed of."⁹⁰ At that time the removal of more than a half million tons of rock to recover about 600,000 tons of iron ore was undertaken.⁹¹ In commenting upon this task R. W. Raymond said, "The successful application of stripping, as a systematic method of exploitation, although it presents no features of startling novelty, entitling it to be ranked among great inventions, is, nevertheless, in my judgment, one of the most important improvements which the art of mining has received during the present generation; and it is, like many other great improvements, a return to the simpler methods of the past, with the perfected means of the present."⁹² The "perfected means" Raymond referred to were the use of exploratory drills (the diamond drill in this particular instance) that permitted close measurement of the quantities of ore and waste to be moved, power drills for drilling blastholes in both overburden and ore, greatly improved explosives, and mechanical methods of handling large quantities of material. The development of efficient surface-drilling equipment and techniques has been an important aspect of technical progress in open-pit metal mining.

Blasthole Drilling in Open-cut Iron Mines.— No great drilling problems beset open-cut iron miners in the early days. Often the ore and

⁹⁰R. W. Raymond in discussion (p. 635) of an article by F. H. McDowell, "Stripping Ore-Deposits," *Transactions, A.I.M.E.*, Vol. XVIII (1890). Italics supplied by the authors.

⁹¹F. H. McDowell, "The Reopening of the Tilly Foster Iron-Mine," *Transactions, A.I.M.E.*, Vol. XVII (1889), pp. 760, 766.

⁹²Raymond, loc. cit.

overburden were so soft they could be dug with picks and shovels. Where blasting was needed, holes were bored with the simple hand tools or by driving down a steel bar with sledge hammers. It was reported that nearly all the ore produced on the Marquette Range in 1870 came from open-cuts worked by "pick-and-shovel, hammer-and-drill", that holes 15 feet deep were common and sometimes reached 22 feet, and that as much as 5,000 tons of ore was broken at a single blast.⁹³ Surface mining usually was undertaken only where the overburden was of moderate depth. It generally consisted of easily excavated glacial-drift soil (often sandy and with few boulders) and thin, soft rock.⁹⁴ Benches were limited to about 15 to 20 feet as the economic depth for hand drilling. The boulders uncovered in the drift were block-holed as a rule by single-jacking. This work was commonly paid for on a footage basis, and the men drilled as much as 12 to 15 feet per day - about three times as much as in hard-rock mines. Under such conditions there was no pressing incentive to mechanize drilling.

The development of the Mesabi Range after 1892 and the expanded use of the power shovel brought about a more intensive form of open-pit mining. Because the early shovels had a limited-action radius there was no immediate need of increasing bench heights. Although the shovel could dig rather hard ore or even the thinner rock layers its loading speed was greatly diminished by such material; it was advantageous to loosen the ore or overburden by blasting before loading without moving it much from its original position. Such blasting was also required during the winter when the ground in Minnesota was frozen as deep as 6 feet. Manual methods continued to be employed for drilling the necessary blastholes. The only development of consequence was the use of "gopher holes", especially when bank heights exceeded 15 feet. They were inclined from 10° to 20° below the horizontal and driven into the bank from the toe of the slope. At first they were just large enough for a man to work in; because of the danger of cave-ins and injury to the workman, however, it became the practice to make these holes about 12 to 14 inches in diameter, using a long-handle shovel as far as possible and then completing them with an earth auger. Such holes were made up to 25 feet in length at nearly the same speed as the vertical jumper holes. This hand drilling was commonly

⁹³Major T. B. Brooks, "The Method and Cost of Mining the Red Specular and Magnetic Ores of the Marquette Iron Region of Lake Superior," *Transactions, A.I.M.E.*, Vol. I, p. 197.

⁹⁴On the Mesabi the ores were soft; early exploration showed that a rock covering over ore was the exception and that the usual glacial-drift cover was not over 50 feet thick. (Cf. Horace V. Winchell, "The Mesabi Iron-Range," *Transactions, A.I.M.E.*, Vol. XXI [1893], p. 685.)

used on the Mesabi as late as 1913-14,⁹⁵ and it has persisted to some extent to the present.⁹⁶

The increasing depth of overburden plus major technical improvements in surface-mining equipment combined to stimulate the greater use of power drilling. The increase in size, mobility, and digging radius of the power shovel greatly expanded the area and particularly the thickness of ore and overburden that could be mined. In the earlier days 35 to 40 feet was thought to be the maximum depth of overburden that could be stripped; but by 1907, 108 feet of overburden had been removed, and in 1909 J. R. Finlay concluded that it would pay, under the least favorable conditions, to remove 2 tons of overburden to 1 ton of ore (in terms of depth a ratio of about 4 : 1) and under the most favorable, where both overburden and ore were soft and uniform, "4 or even 5 to 1"⁹⁷ (or in terms of depth a ratio of at least 8 : 1). By 1911, 147 feet of overburden had been removed, and stripping was reported at sites where the overburden was even deeper. Higher banks required at new operations, rockier nature of overburden that accompanied increased depth, some increase in the hardness of ore, and the need for moving constantly greater bulks both of overburden and ore⁹⁸ made drilling of greater importance and provided incentives for the use of power equipment.

The piston drill was used in Pennsylvania open-cut iron mines as early as 1882,⁹⁹ but machine drilling did not begin seriously to displace hand work in the Lake Superior district until the second decade of this century. In 1911 three piston drills operated by 6 men replaced 30 men

⁹⁵Charles E. van Barneveld, *Iron Mining in Minnesota* (Univ. of Minn. School of Mines Expt. Sta., Bull. No. 1, 1912), pp. 135-7, 149. See also C. M. Haight, "Steam Shovel Operation," *Engineering and Mining Journal*, Vol. 97, No. 7 (Feb. 14, 1914), pp. 359-60.

⁹⁶*Wages and Hours of Labor in Metalliferous Mines, 1924 and 1931* (U. S. Dept. Labor, Bur. Labor Statistics, Bull. No. 573, Jan. 1933), p. 38. Of the 16 open-cut mines studied, 7 reported hand drilling. These operations, however, were not very significant from the standpoint of employment or production.

⁹⁷J. R. Finlay, "Cost of Pig Iron Made From Lake Superior Ores," *Engineering and Mining Journal*, Vol. LXXXVII, No. 15 (Apr. 10, 1909), p. 743. Note that Dwight E. Woodbridge, "Lake Superior Iron Mines in 1907," *Engineering and Mining Journal*, Vol. LXXXV, No. 2 (Jan. 11, 1908), p. 115, said, "the rule of 2 ft. of surface to 1 ft. of ore, radical as that appeared two or three years ago, must give way to 3 or 4 ft. to one."

⁹⁸See Dwight E. Woodbridge, "The Mesabi Iron Ore Range - IV," *Engineering and Mining Journal*, Vol. LXXIX, No. 6 (Feb. 9, 1905), p. 267; Edgar K. Soper, "The Iron Ranges of Minnesota," *Engineering and Mining Journal*, Vol. 91, No. 15 (Apr. 15, 1911), p. 769.

⁹⁹J. P. Lesley and E. V. d'Invilliers, "Report on the Cornwall Iron Ore Mines, Lebanon County," *Annual Report of the Geological Survey of Pennsylvania for 1885* (Harrisburg, Pa.: Board of Commissioners for the Geological Survey, 1886), p. 557. See also E. V. d'Invilliers, "The Cornwall Iron-Ore Mines, Lebanon County, Pa.," *Transactions, A.I.M.E.*, Vol. XIV (1886), pp. 902-3. The ease of breaking soft iron ores is well exemplified. In 1885 the average monthly production was 42,405 tons; about 200 men, mostly "diggers" were employed. There was no hand drilling and only six piston drills were used to drill 12-foot holes. In 1911, with nearly double the output, 13 drills were in use. The ore was somewhat harder but 18- to 24-foot holes were bored. Cf. E. B. Wilson, "The Cornwall, Pa., Magnetite Deposits," *Proceedings of the Lake Superior Mining Institute*, Vol. XVI (1911), pp. 230, 233, 238.

using hand drills that had prepared ground for one steam shovel in a Michigan stripping operation, where rock and hardpan had been encountered.¹⁰⁰ On the Mesabi Range very few power drills were used for blast-hole work before 1913. One large mine where "the hardness of the ore is such that machine drilling is necessary" had only 6 drills¹⁰¹ and a "well-equipped and well-managed stripping job" listed but two.¹⁰²

The shift to machine drilling of blastholes was accentuated by the general wartime labor shortage and the urgent demand for iron ore for war purposes. One observer reported that although a number of mines had machine drills at this time they were not generally more efficient than hand work where no rock was present;¹⁰³ they could, however, drill to greater depths and thus made possible bench heights of 25 to 30 feet. In this period jackhammers also were first used for secondary drilling.¹⁰⁴ Few pits, if any, had central air compressors, and air was supplied from locomotive air pumps or small compressors on the power shovels. At least one attempt was made to use electric air drills of the pulsator type already described (see page 38). In this instance most of the holes drilled exceeded 24 feet in depth, and the average speed in a 5-month test period was over 6 feet per hour after the drills were in place or nearly 7.5 feet per hour while drilling. The output was about twice that of hand drilling.¹⁰⁵

Although there had been isolated instances of churn drilling at iron mines as early as 1907,¹⁰⁶ widespread use of this machine for blasthole drilling at such operations began only about two decades ago. As late as 1914 Kellogg stated that although overburden and ore generally had to be drilled and blasted "no attempt has been made to employ churn drills

¹⁰⁰P. B. McDonald, "Stripping on Portland Pit Iron Mine, Michigan," *Mining and Engineering World*, Vol. XXXV, No. 4 (July 22, 1911), p. 147.

¹⁰¹Van Barneveld, *op. cit.*, p. 165. This mine (the Biwabik) produced an average of nearly 356,000 tons per year from 1910-12 inclusive (*Lake Superior Iron Ores: 1935* [Cleveland, Ohio: The Lake Superior Iron Ore Association, 1935], pp. 225, 228).

¹⁰²Van Barneveld, *op. cit.*, p. 162.

¹⁰³L. D. Davenport, "Steam-Shovel Mining on Mesabi Range - III," *Engineering and Mining Journal*, Vol. 105, No. 13 (Mar. 30, 1918), pp. 581-2. A gang of hand churn drillers were said to drill 50 feet per man-shift, and the piston drill with two men drilled about 90 feet. The indicated hand rate is much higher than averages given in standard handbooks such as Gillette's (*op. cit.*), for example, where the average in stripping was reported about 10 feet per man per 10-hour shift and, in ore, about 24 feet.

¹⁰⁴L. D. Davenport, "Steam-Shovel Mining on the Mesabi Range," *Engineering and Mining Journal*, Vol. 105, No. 9 (Mar. 2, 1918), p. 406.

¹⁰⁵"Record of Temple-Ingersoll Drills on the Mesabi Range," *Engineering and Mining Journal*, Vol. 98, No. 24 (Dec. 12, 1914), pp. 1042-3. The statement is estimated on the basis of costs given in the article.

¹⁰⁶Edwin Higgins, "Stripping Clinton Iron Ore in New York State," *Engineering and Mining Journal*, Vol. LXXXVI, No. 24 (Dec. 12, 1908), p. 1151. E. B. Wilson (*op. cit.*, p. 233) reported that although two well drills in use at Cornwall in 1911 drilled slower than the piston drills they could put down deeper holes. As these holes were larger the tonnage removed was probably as great as that of the piston-drilled holes.

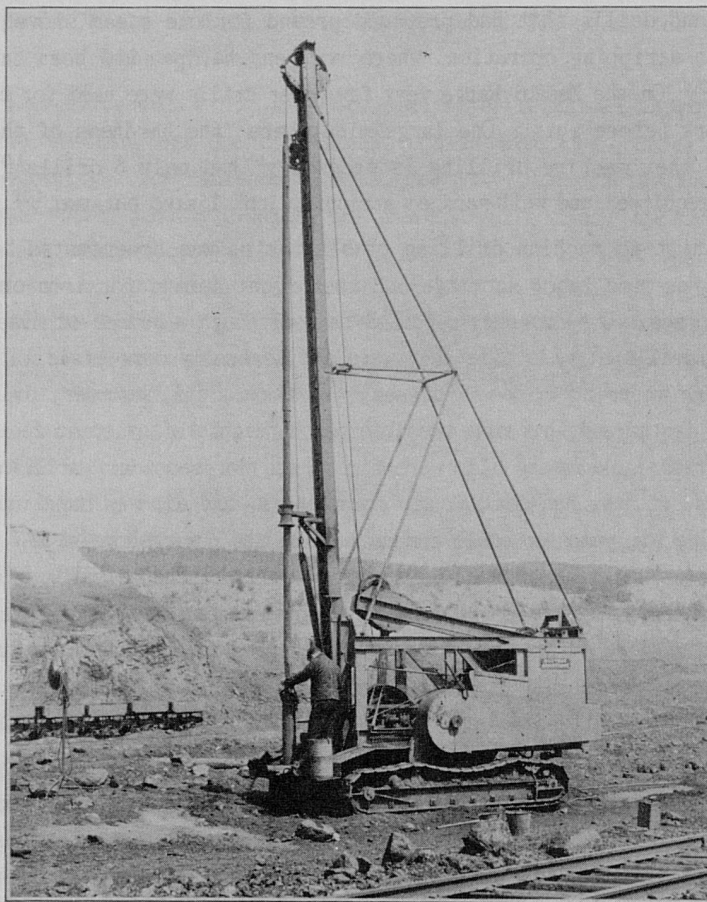


FIGURE 22.— ELECTRIC CHURN DRILL AT AN IRON MINE

This welded, all-steel, caterpillar-mounted blasthole drill is a vast improvement over the machines shown in figure 12 and is used extensively in open-cut mining and quarrying. For a 9-inch hole the tool string, shown at the drill runner's left, weighs about 2,700 pounds or 50 percent more than that for a 6-inch hole. Because of the great weight of the tools and the long, rapid stroke the larger holes are not infrequently drilled more rapidly than the smaller. The machine is operated by one man and can drill 5 to 10 times as fast as a hand driller, or about 130 times as much measured by hole volume.

for blasting purposes and with the relatively low benches carried, they would not seem to be applicable."¹⁰⁷ The introduction of very large and more mobile shovels about the end of the World War period facilitated the adoption of a drill of greater capacity than that of the piston machine then in fairly widespread use.

By 1923 electric churn drills were at work on the eastern Mesabi where there was little glacial drift and a hard rock-capping in which the rate of drilling 20- to 40-foot holes was only 12 to 14 feet in 10 hours.

¹⁰⁷L. O. Kellogg, "Notes on Mesabi Range Mining Practice - I," *Engineering and Mining Journal*, Vol. 97, No. 14 (Apr. 4, 1914), p. 698.

One man was employed to run each drill, with a helper servicing three to five machines.¹⁰⁸

The trend toward higher benches of 40-100 feet and the practice of shooting a large number of holes at one time followed the extensive use of churn drilling. Electric-traction churn drills were used on the Marquette Range by 1928 for holes up to 60 feet deep in very hard ground,¹⁰⁹ and by 1929 it was reported that well drills were used for primary drilling in the majority of Mesabi pits and that the output ranged from 1.5 to 8 feet per hour, depending on the character of the ore or capping.¹¹⁰ The introduction of caterpillar mountings, all-steel rigs, shock absorbers, and other improvements greatly increased the footage that could be drilled in a given working time,¹¹¹ and the trend has continued toward the use of larger, heavier, and more powerful machines.¹¹²

*Blasthole Drilling in Open-cut Copper Mines*¹¹³.—The idea of mass-mining low-grade copper ores¹¹⁴ by open-cut methods at the turn of the

¹⁰⁸W. G. Swart, "Mesabi Iron Company's Reduction Plant," *Proceedings of the Lake Superior Mining Institute*, Vol. XXIII (1923), p. 113.

¹⁰⁹L. S. Chabot, Jr., "Field Blasting at the Volunteer Mine," *Proceedings of the Lake Superior Mining Institute*, Vol. XXVII (1929), pp. 259-61. Cf. also W. R. Meyers, "An Efficient Technique for Drilling and Blasting," *Engineering and Mining Journal*, Vol. 133, No. 1 (Jan. 1932), pp. 30-1.

¹¹⁰F. E. Cash and M. W. von Bernewitz, *Methods, Costs, and Safety in Stripping and Mining Coal, Copper Ore, Iron Ore, Bauxite, and Pebble Phosphate* (U. S. Dept. Com., Bur. Mines, Bull. No. 298, 1929), pp. 201-2.

¹¹¹Max H. Barber, *Progress in the Improvement of Methods and Equipment at Open-Pit Iron Mines on the Lake Superior Iron Ranges* (American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 487, 1932), p. 5.

¹¹²"Blast-Hole Drilling at the Tilden Pit," *Engineering and Mining Journal*, Vol. 138, No. 11 (Nov. 1937), pp. 51-2. In the fall of 1936 one of the latest-type drills that bored 9-inch holes replaced one that made 6-inch holes. In the very hard ground at a Marquette Range mine the larger drill bored 15.6 feet in 8 hours and the 6-inch drill averaged 13.7. The operating cost per foot was 13.3 percent lower for the 9-inch than for the 6-inch drill. The holes were at intervals of 20 feet in rows 30 feet apart for the 9-inch drill and at intervals of 15 feet in rows 22 feet apart for the 6-inch drill. The 9-inch holes were shot without springing (enlarging the hole to hold blasting charge), but the 6-inch ones were sprung.

A similar but somewhat smaller machine used on the Mesabi was said to have drilled 4,544 feet of 6-inch hole in ore and taconite during 1 month and to have averaged over 200 feet per day in 22-foot holes. See "Blast-Hole Drill," *Engineering and Mining Journal*, Vol. 138, No. 9 (Sept. 1937), p. 91.

¹¹³In presenting this summary the authors have made extensive use of publications of the U. S. Bureau of Mines that relate to drilling practices at open-cut copper mines, and especially the following reports: Donald F. MacDonald and Charles Enzian, *Prospecting and Mining of Copper Ore at Santa Rita, New Mexico* (U. S. Dept. Int., Bur. Mines, Bull. No. 107, 1919); E. D. Gardner, *Drilling and Blasting in Open-Cut Copper Mines* (U. S. Dept. Com., Bur. Mines, Bull. No. 273, 1927); F. E. Cash and M. W. von Bernewitz, *op. cit.*; E. D. Gardner, C. H. Johnson, and B. S. Butler, *Copper Mining in North America* (U. S. Dept. Int., Bur. Mines, Bull. No. 405, 1938); A. Soderberg, *Mining Methods and Costs of the Utah Copper Co., Bingham Canyon, Utah* (U. S. Dept. Com., Bur. Mines, Inf. Cir. No. 6234, 1930); E. M. J. Alenius, *Methods and Costs of Stripping and Mining at the United Verde Open-Pit Mine, Jerome, Ariz.* (U. S. Dept. Com., Bur. Mines, Inf. Cir. No. 6248, 1930); H. A. Thorne, *Mining Practice at the Chino Mines, Nevada Consolidated Copper Co., Santa Rita, N. Mex.* (U. S. Dept. Com., Bur. Mines, Inf. Cir. No. 6412, 1931); and G. R. Ingham and A. T. Barr, *Mining Methods and Costs at the New Cornelia Branch of Phelps Dodge Corporation, Ajo, Ariz.* (U. S. Dept. Com., Bur. Mines, Inf. Cir. No. 6666, 1932).

¹¹⁴For a brief description of the shift to mass mining of copper ores see A. V. Corry and O. E. Kiessling, *Mineral Technology and Output per Man Studies: Grade of Ore* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-8, Aug. 1938), pp. 48-50.

century was regarded as visionary. Although open-pit iron mining had been established on a large-scale basis and general-type stone quarries were entering a period of great expansion and technical advancement, there was grave doubt whether the technique of mass mining could be extended to any of the important nonferrous metals. The surface mining of copper presents problems different from those in iron and stone production. By far the greater part of the iron ore, for example, was so soft that heavy shooting was not required; it was composed almost entirely of iron minerals that needed no treatment before smelting, and was overlaid by easily excavated glacial drift. In stone quarries stripping of rock had not yet been undertaken to any extent, and almost the entire quarry output was useful. On the other hand, at the Utah Copper Mine - the first and largest of the open-cast copper properties - the early report of Jackling and Gemmell¹¹⁵ estimated rock-capping of 40 feet with 110 feet of ore having about 2-percent copper content with about three-fourths recoverable.¹¹⁶ In addition, very fine crushing was prerequisite to recovery because copper minerals equivalent to about 30 pounds of recoverable copper were disseminated in 2,000 pounds of ore.¹¹⁷ Both capping and ore were rocks that had to be drilled and blasted before loading. The availability of effective drilling methods and machines was of great importance at this and all other surface copper mines.

Considerations in the selection of the drilling and blasting methods at copper mines were the hardness, toughness (occurrence of planes of weakness, joints, and stratification), thickness, soundness, and abrasiveness of the ore or overburden. These and other characteristics controlled the safe slope of the rock face of the bench which, with its width, determines the over-all slope of the pit.¹¹⁸ In working a given deposit, high and narrow benches with steep slopes would require the removal of a minimum of overburden and the least amount of drilling and blasting. This was illustrated by Soderberg, who cited an instance at

¹¹⁵For an account of the history and development of this mine the reader is referred to a series of articles by T. A. Rickard entitled "The Utah Copper Enterprise" beginning in Vol. 117, No. 14 (Oct. 5, 1918), p. 445 in *Mining and Scientific Press*. This has been summarized and other pertinent data added by A. B. Parsons in *The Porphyry Coppers* (1st ed.; New York: American Institute of Mining and Metallurgical Engineers, 1933).

¹¹⁶Actual recovery was about 63 percent at first and did not reach 70 for some years.

¹¹⁷The ratio of overburden to ore by weight is now roughly 1.1 to 1; the capping has ranged from 40 to 200 feet and averaged about 115 feet. The grade of ore now worked is approximately 1 percent or 20 pounds of copper to the ton, of which over 90 percent is recovered. It has been stated that still-lower-grade material may be mined. Cf. *Twenty-Fourth Annual Report of Kennecott Copper Corporation: 1938*, p. 8. In 1937 the stripping ratio was 1.1 to 1 but in 1938 the ratio was exceptionally high - 1.95 to 1.

¹¹⁸Louis S. Cates, "Factors Affecting Bank Slopes in Steam-Shovel Operations," *Transactions, A.I.M.E.*, Vol. LXXIV (1927), p. 818, and discussion of this article on p. 826. See also Gardner, Johnson, and Butler, *loc. cit.*; Soderberg, *loc. cit.*

the Utah Copper Mine where a change of the over-all slope from 40° to 38° to the horizontal above a certain bench would have added 2 million dollars to the cost.¹¹⁹

Technical progress in blasthole drilling at open-cut copper mines was closely related to the expanding use of surface mining in copper production. The number of copper mines developed by surface methods, however, has never been large. The first was the Utah mine, where stripping commenced in 1906 and ore production in the following year. In 1907 the removal of overburden was begun at the Nevada Consolidated Mine. Steam-shovel work started at Chino in 1910, at United Verde and New Cornelia in 1917, and at Sacramento Hill in 1923.¹²⁰ One of the greatest of the disseminated ore bodies, the clay ore body at Morenci, has been of wide interest during the last 10 years because of the possibilities for surface mining; it was thoroughly diamond-drilled in 1928-30, and stripping preparatory to surface mining was begun in August 1937 with ore production scheduled for 1939.¹²¹

The ground at the Utah, Nevada, and Morenci mines was relatively soft, and at the other surface copper mines it ranged from medium-hard to hard rock. Differences in the character of the rock (capping and ore) at these operations were sufficient to cause wide variations in the drilling and blasting practices; the type of drill used; the number, inclination, and length of holes; the number of holes fired simultaneously; and other features. Thus, the rock characteristics have direct bearing upon the character and amount of drilling done and the labor required. Although there was a wide range in practice at different mines, there was a definite trend toward bank heights of about 50 feet, and black powder was displaced almost entirely by dynamites. At all mines, however, the essential problem was the same - that of uninterruptedly furnishing the shovels with well-fragmented rock at the lowest possible cost and with the greatest safety.

When stripping was first undertaken at a surface copper mine in 1906 all of the drills now used for blasthole work were available except the

¹¹⁹Soderberg, *op. cit.*, pp. 9-10.

¹²⁰The open-cut copper mines were situated in the following mining districts, counties, and States:

Mine	District	County	State
Utah Copper	West Mountain	Salt Lake	Utah
Nevada Consolidated	Robinson	White Pine	Nevada
New Cornelia	Ajo	Pima	Arizona
Chino	Central	Santa Rita	New Mexico
United Verde	Jerome	Yavapai	Arizona
Morenci (Clay)	Copper Mountain	Greenlee	Arizona
Sacramento Hill (Copper Queen)	Warren	Cochise	Arizona

¹²¹Phelps Dodge Corporation, *Annual Report: 1937*, p. 7.

jackhammer. The Jackling report on the Utah prospect stated that the ore "will be quarried" using drills supplied with air from a centrally located electrically driven compressor.¹²² Heavy tripod-mounted piston drills have been used from the beginning.¹²³ With a few exceptions and unlike all other copper pits, vertical down-holes have been seldom employed. The piston drill, customarily using a $3\frac{3}{4}$ -inch starting bit, bores toe holes about 22 feet long and inclined so as to bottom about 5 feet below bench level. If the bank does not break nearly horizontally to the crest, "bank" holes are then drilled about 12 to 20 feet into the face, with the machine set at the top of the pile of rock broken in starting the toe hole. For many years bank heights averaged about 70 feet, and a row of bank holes placed about halfway up the slope with occasional down bench holes was required for satisfactory breaking. This method was most suitable on the usual narrow benches because the broken rock would be held close to the face and the loading tracks kept free.



FIGURE 23.— TOE-HOLE DRILLING AT AN OPEN-CUT COPPER MINE

This wet hammer-type drifter is in use at a southwestern surface copper mine. It was said to drill 50 percent faster than the piston drill.

Before surface mining was undertaken the entire ore production at the Utah property had been won from underground workings by a caving method of mining.¹²⁴ This had fractured the cap rock so badly that piston

¹²²Rickard, *op. cit.*, Vol. 117, Nos. 14, 18 (Oct. 5 and Nov. 2, 1918), pp. 484, 590.

¹²³At first the ordinary $3\frac{1}{2}$ -inch piston drills were used underground and in the pit but were succeeded by heavier and more powerful $3\frac{1}{2}$ -inch auxiliary valve drills.

¹²⁴For a brief description of this method see: Y. S. Leong and Others, *Technology, Employment, and Output per Man in Copper Mining* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-12, in press).

drilling was very difficult in certain areas; for a time the coyote-hole blasting was used which, though quite common in quarry work, has seldom been used in either copper or iron open-cut mines. It is of interest that this method was employed in an extremely high bank. The tunnels were 30 to 40 feet deep, with crosscuts 25 to 30 feet long, and were driven into a bank variously reported to have been 220 to 240 feet high. Up to about 60,000 tons were broken at one time.¹²⁵ The tunnels probably were driven with the "chippie" drills, the light $2\frac{1}{4}$ -inch piston machines in principal use in the underground mine.¹²⁶ According to DeKalb, it had been hoped to apply this method to a 310-foot bank,¹²⁷ but the rock was fragmented so coarsely that a great deal of secondary blasting was necessary. Both block-holing with piston drills and "dobe"¹²⁸ shots were made but caused much shovel delay. Moreover, there had been rock slides that covered the shovels so that the high bank was apparently never successfully worked.

At the Boston Consolidated Mine, which adjoined the Utah mine and was incorporated with it in 1910, churn drills were in use for blasthole work by 1907.¹²⁹ Practice here differed from that at Utah as the aim was to work 50-foot benches, although there was some variation in the height of the bench owing to surface irregularities. One deep blasthole of 120 feet was tried, but the results were not so satisfactory as with the lower benches.¹³⁰ The churn drills continued in use at least up to 1918, when Rickard reported that two were working at the top of the cut where the bench height and width were such that their use was economical.¹³¹ They were also used to put down 30- to 80-foot holes in the higher banks, with both coyote holes and toe and bank piston-drill holes.¹³²

The use of the well drill was the exception, however, and the Utah Copper Mine represents one of the few operations at which the piston drill is used for blastholes.¹³³ Numerous trials made with hammer drills

¹²⁵Courtenay DeKalb, "The Utah Copper Mine," *Mining and Scientific Press*, Vol. XCVIII, No. 15 (Apr. 10, 1909), pp. 520-1.

¹²⁶"The Utah Copper Company's Mine and Mills," *Engineering and Mining Journal*, Vol. LXXXII, No. 10 (Sept. 8, 1906), p. 435.

¹²⁷DeKalb, *op. cit.*, p. 520.

¹²⁸A corruption of "adobe" or clay used for mudcapping.

¹²⁹James W. Abbott, "Mining at Bingham, Utah," *Mining and Scientific Press*, Vol. XCIV, No. 19 (May 11, 1907), p. 597.

¹³⁰Courtenay DeKalb, "Boston Consolidated, Bingham, Utah," *Mining and Scientific Press*, Vol. XCVIII, No. 16 (Apr. 17, 1909), p. 554.

¹³¹Rickard, *op. cit.*, Vol. 117, No. 16 (Oct. 19, 1918), p. 524.

¹³²Robert Marsh, Jr., *Steam Shovel Mining* (1st ed.; New York: McGraw-Hill Book Co., Inc., 1920), pp. 140-1, 158-9.

¹³³The general practice is to use piston drills for toe holes; recently, however, large electric churn drills have been used for special purposes. Nine-inch holes were drilled with these drills to a depth of 58 feet (or 8 feet deeper than the bench height); because the ground caved, casing was used to protect the holes. The holes were chambered before loading. (Information courteously furnished by D. D. Moffatt, Vice President and General Manager, Utah Copper Co.)

have proved unsatisfactory. The ground "ravels" or caves easily, as was demonstrated in deep prospecting churn-drill holes where, in order to finish at $4\frac{1}{2}$ or 6 inches, a starting bit 26 inches in diameter was used. As a result over-all drill speeds were very low. The piston drill is more effective than the hammer drill in withdrawing the steel in caving ground, and it is unnecessary to maintain the long water lines which are required for hammer drills and may become troublesome in cold weather. Usually two piston drills, each having a runner and two helpers, worked with each shovel. The drill crews also loaded and fired all holes and blasted down any large boulders that remained partly suspended on the face. The little secondary breaking needed was customarily done by "dobeying" which, although wasteful of powder, was cheapest in the long run. Since the same type and size of piston drill has been used almost throughout the life of the Utah mine, increased productivity in drilling and blasting must be largely attributed to improvements in explosives and to more effective planning and technical direction.

At Nevada Consolidated and Morenci open pits churn drills are used exclusively for primary blasthole drilling. The choice of drill was not difficult for the Nevada mine. Before stripping was begun in August 1907, more than 100 prospect holes had been bored with well drills. These holes were all much deeper than the 50-foot bench decided upon and, as no great difficulties were met in the prospect work, the churn drill was adopted for blasthole drilling. The steam churn drills originally used did not stand up well under the severe service and were remodeled and strengthened at the mine shops. With these changes the drill speed averaged 60 feet in $10\frac{1}{2}$ hours' working time.¹³⁴ Though traction drills, they were self-propelled for only short moves; for moving to another bench they were lifted by a locomotive crane onto a flatcar and hauled to the new position. In this manner much road making was spared and little time lost. In 1934 the old steam machines were replaced by caterpillar-mounted, electrically driven churn drills which nearly doubled the drilling speed and halved labor requirements. Six-inch holes about 55 feet long are drilled from about 10 feet behind the crest of the slope to about 5 feet below grade. Usually they are sprung one to three times, as a heavy burden is placed on the holes and large explosive charges are needed. As the rock is relatively soft and drills and breaks well, little secondary breaking is required. Occasionally some block-holing is done with a hand hammer drill.

¹³⁴"Blast-Hole Drilling in Open-Pit Copper Mining," *Mining and Scientific Press*, Vol. 107, No. 17 (Oct. 25, 1913), p. 645.

The ground also drills and breaks well at Morenci.¹³⁵ Heavy jackhammers (sinkers) suspended from pipe tripods with block and tackle are used for work incidental to the lay-out of benches. For deeper holes caterpillar-mounted electric churn drills with a 9-inch bit and a heavy tool string are used. Fifty feet was adopted as the standard bench height and the churn-drill holes are sunk 8 to 10 feet deeper. The reported speed is the same as at Nevada but the holes are one-half larger in diameter and are shot without springing - a definite advantage over small-diameter holes. The hammer-drill holes, however, are sprung. Light jackhammers are used for block-holing when necessary.

Chino may also be included in the relatively soft-ground group, even though some of it is hard and tough; but the rock has a marked tendency to be blocky, so that secondary drilling is very important. Churn drilling used for prospecting the ore deposit for nearly 2 years before stripping was begun in 1910 indicating the practicability of using these drills for blasthole work. They were not used alone, however, for without toe holes many hard ribs were left on the benches, fragmentation was poor, and the shovels could not perform satisfactorily.

The first churn drills used at Chino were steam-driven. Later, compressed air was used in a few of them but by 1916 nearly all the blasthole machines were of the traction type and were driven by gasoline engines. Benches were about 30 feet high at first but a change to 50 feet reduced shovel delays and decreased the cost per ton of drilling and blasting. The drilling practice generally followed combined toe holes about 22 feet deep with vertical churn-drill holes started from about 10 feet behind the crest of the slope and carried a few feet below grade. Heavy piston drills mounted on standard tripods were first used for the toe holes and continued to find some employment as late as 1927 in "ravelly" ground.¹³⁶ Tripod-mounted hammer drills introduced about 1922 worked much faster than the piston machines in firm ground and at about the same speed in fractured ground. Soon sturdier hammer machines with a more powerful rotation were substituted and by 1931 had entirely replaced the piston drill.

Coyote-hole blasting was undertaken in 1914 in a bank about 100 feet high where it was too hazardous to drill and chamber toe holes. Three small tunnels that totaled 352 feet in length, including crosscuts, were driven by hand and machine. Over 50,000 pounds of explosives were fired

¹³⁵Walter C. Lawson, "Preliminary Stripping of the Morenci Open Pit, Arizona," *Mining Technology*, Vol. 2, No. 5 (Sept. 1938), A.I.M.E. Tech. Pub. No. 980, p. 13.

¹³⁶H. A. Thorne, "Mining Methods at the Chino Copper Mines," *Mining Congress Journal*, Vol. 13, No. 10 (Oct. 1927), pp. 783-4.

in one blast and it was estimated that nearly 119,000 cubic yards (about 240,000 tons) were broken.¹³⁷

The close relation of ground-breaking techniques to other phases of pit operation was well exemplified at Chino. Primary blasting, for example, left many large boulders and from 5 to 15 percent of the material broken had to be blasted again to be easily handled by the 3- and $\frac{1}{32}$ -yard shovels and to provide pieces smaller than 12 inches for rapid unloading at the mill. In 1914, after a primary crusher that would take pieces 48 by 60 inches was put into operation it was estimated that the cost of secondary breaking was reduced 80 to 90 percent¹³⁸ and "the cost of the primary crushing and of loading the railroad cars from the bins was half the cost of bringing the material down to proper size by bulldozing and blockholing . . . a number of men were released and delays eliminated"¹³⁹ Though a still larger crusher (84 by 66 inches) was put into operation in 1917, drilling for secondary breaking remains a serious problem for "the footage drilled in breaking boulders is about double that drilled for primary blasts."¹⁴⁰

The New Cornelia deposit has great lateral extent and is about 425 feet thick. There was capping only at one end but it has been necessary to remove waste about the margin of the deposit in order to mine all the ore. In the last few years the waste-ore ratio increased greatly and was 1.32 to 1 in 1937.¹⁴¹ The ore is the hardest of all the open-cut copper mines and breaks into large boulders. Because of the hardness of the rock the churn drill was not considered suitable, although it had been employed in the removal of three low hills. When the face height exceeded 45 feet, coyote holes were found economical.

It was soon shown that the air drill was more satisfactory than the churn drill for holes up to about 30 feet deep and such banks were chosen as soon as it became possible to lay out permanent benches. A 25-foot bench height has been found most economical and is used in opening new levels.¹⁴²

On regular benches up to about 35 feet in height heavy tripod-mounted, compressed-air piston drills were employed until 1923, when tests were made with hammer machines. These were drifter-type drills removed from

¹³⁷R. I. Kirchman, "Gopher Blasting," *The Colorado School of Mines Magazine*, Vol. IV, No. 5 (May 1914), pp. 103-8. This is quoted in part in MacDonald and Enzian, *op. cit.*, pp. 59-62.

¹³⁸MacDonald and Enzian, *op. cit.*, p. 57.

¹³⁹Thorne, *Mining Practice at the Chino Mines, Nevada Consolidated Copper Co., Santa Rita, N. Mex.*, p. 16.

¹⁴⁰Gardner, Johnson, and Butler, *op. cit.*, p. 131.

¹⁴¹Phelps Dodge Corporation, *op. cit.*, p. 6.

¹⁴²Ingham and Barr, *op. cit.*, p. 10.

the guide shell and equipped with a special back-head, spring handle, and air blowers. A special support was also evolved; instead of being carried on a standard tripod the drills were suspended by block and tackle from a tripod made of pipe. With this rig the drilling speed was nearly four times that of the piston machine which was replaced.¹⁴³ Such a comparison, however, favors the hammer drill¹⁴⁴ which used hollow steel with a starting bit $2\frac{3}{4}$ to $2\frac{1}{2}$ inches in diameter¹⁴⁵ compared with the $3\frac{1}{2}$ -inch solid-steel bit of the piston machine.¹⁴⁶ Recently, derrick-mounted drifters have replaced the tripod-suspended drill, and a further increase of about 10 percent in drilling speed is reported.

Drilling practice at Ajo differs especially from that at other open-cut copper mines in that many holes in rows are shot at one time. This procedure obtains better fragmentation and leaves fewer hard ribs between contiguous blasts. Vertical holes are drilled to 2 feet below grade and about 10 to 20 feet apart, depending on the hardness of the rock. Toe holes are sometimes used where the bank slope is low. After being sprung, groups of up to 100 holes are loaded and blasted, breaking areas 90 to 100 feet wide by 200 to 300 feet long. Two drill crews of two men each per shovel are generally required. Secondary breaking is done by block-holing and usually requires two additional men per shovel, one to handle the drill and another to prepare places for the drill set-up.

The success attained with the latest type of electric churn drill in hard rock, such as that at the Tilden iron mine and in quarry work, led the Ajo management to experiment with this machine. In 1935 such a drill was purchased and in the following year it was said that "improved drilling and breaking results were achieved by the use of churn drills." In 1937, additional churn drills were installed, together with drill-sharpening and other equipment, and have been important in attaining increased drilling productivity.¹⁴⁷

Open-cast mining at the United Verde and the Copper Queen Mines was auxiliary to regular underground work. At the latter, shovel mining ceased in 1929 and at the former, ordinary pit operation was to be concluded in 1939.¹⁴⁸ They presented some difficult mining problems because

¹⁴³*Ibid.*, p. 11.

¹⁴⁴See p. 117.

¹⁴⁵Gardner, *op. cit.*, p. 28; G. R. Ingham, "The Mining Operations of the New Cornelia Copper Co.," *Mining Congress Journal*, Vol. 14, No. 8 (Aug. 1928), p. 625.

¹⁴⁶A. W. Allen, "The Ajo Enterprise of the New Cornelia Copper Co. - IV," *Engineering and Mining Journal-Press*, Vol. 114, No. 5 (July 29, 1922), p. 184.

¹⁴⁷Phelps Dodge Corporation, *Annual Report: 1935*, p. 6; same, 1936, p. 5; and same, 1937, p. 6.

¹⁴⁸The ore remaining has been or will be obtained by glory-holing, necessitating drilling and blasting. It is probable that such drilling will be entirely accomplished with hammer machines.

of the relatively great ratio of waste to ore, the small area of the deposits, and the irregular occurrence of ore within the mass to be excavated. At both mines the ground has been generally hard, and it broke in large fragments.

At Sacramento Hill (the Copper Queen open-cast operation) steam and electric churn drills had been used in prospecting between 1914 and 1916; stripping was begun in 1917 and continued until 1921. Above the pit entrance level, benches were spaced at 60-foot intervals. They were prepared by working upward, using horizontal piston-drill holes about 20 feet deep. A part of the face above the upper bench was as high as 130 feet, and to break it churn-drill holes 40 to 85 feet deep were used in conjunction with the horizontal piston-machine holes. In one section where the face of the hill sloped away from the shovel and there was danger of rock being shot onto buildings below, cuts a few feet deep were made, using piston drills for flat holes and jackhammers for down-holes.

The 60-foot benches proved to be too high to be broken effectively by blasts in churn-drill holes alone and toe holes about 20 to 25 feet deep were used with churn-drill holes about 42 feet deep; these were sprung several times. A series of toe holes was first shot, loose rock removed, and the bank holes blasted. This method caused the shovels to lose much time, and churn-drill holes about 27 to 30 feet deep were used in combination with the piston-drill toe holes to open two lower benches at 45-foot intervals. Even this was found uneconomical, and about 1921-22 all future work was planned for a 30-foot-bench height; churn drills were to be used exclusively on these benches, but toe holes were occasionally required. The reduction in bank height and the increased use of the churn drill greatly improved drilling and blasting efficiency. It was reported that the shovels could load more cars before each forward move on the 30-foot bench than on the 60-foot,¹⁴⁹ and that the proportion of explosive used for secondary blasting was reduced from 10.2 to 4.3 percent.¹⁵⁰

For early stripping heavy, gasoline-engine churn drills were used for blasthole work. Output per churn-drill shift increased by more than 150 percent from 1917 to 1921 (from 12.5 to 31.2 feet) and in 1921 was about 15 percent higher than the average piston-drill speed in all kinds of ground.¹⁵¹ The increase was attributable in part to changes in the rock

¹⁴⁹H. M. Ziesemer and George Mleyr, "Steam-Shovel Operation at Bisbee, Arizona," *Transactions, A.I.M.E.*, Vol. LXVIII (1923), p. 263.

¹⁵⁰Gerald Sherman, "Steam Shovel Operations at Sacramento Hill," *Arizona Mining Journal*, Vol. VII, No. 13 (Dec. 1, 1923), p. 23.

¹⁵¹Ziesemer and Mleyr, *op. cit.*, pp. 262, 260. About 4 years later when drilling was almost entirely in ore the average piston- and churn-drill speeds were further increased about 20 to 25 percent. Cf. Gardner, *op. cit.*, pp. 30-1.

characteristics as the workings were extended. On the upper benches the capping was drilled with great difficulty and generally was harder than the ore. Other factors were the reduced length of hole, corresponding to the lower bench height, and the increased skill of the personnel. About 1924-25, experiments with drifter-type hammer drills indicated that they were about 50 percent faster than the piston drill,¹⁵² and they soon displaced the latter.

The United Verde operation is of particular interest because of the reason for the adoption of surface mining and special problems it presented. The ore body consisted of highly inclined lenses of massive sulphides that were readily ignited; fires had started in 1893 and became a very serious problem. Underground mining was carried on in the fire zone (until about 1918) using a pressure system of ventilation. Costs of operation, however, increased about 150 percent and the fires had spread almost to the 1,000-foot level in spite of all efforts to control or extinguish them. The smelter and a great part of the mine surface plant, moreover, were endangered by subsidence intensified by the fire. It was then decided to recover the temporarily abandoned ore above the 1,000-foot level by open-cutting. The waste-to-ore ratio was estimated at nearly 7 to 1, but the pit depth attained has been greater than was planned; the final ratio will be about 2.5 to 1.

The pit entrance level corresponded with the 160-foot mine level above which was a hill of barren rock about 500 feet high. A large part of the hill had to be cut away to make it possible to get the ore below the 160-foot level. The first bench was about 110 feet high and those above it about 50 feet except for the top bench that ranged from a few feet to 140. Steam churn drills were used to good advantage in the relatively soft and weathered rock of the uppercut but in the fresh, dense, underlying rock which had many slip planes and broke into large boulders their speed dropped nearly 80 percent.¹⁵³ It had been planned to use 3¼-inch piston drills for long holes in inaccessible places, and jackhammers for short holes but after churn drilling was abandoned in 1924 two-man Leyner drifters suspended from a pipe tripod were used for vertical holes, and medium-weight one-man jackhammers for toe holes. On the usual 50-foot benches the down-holes were about 30 feet deep and the toe holes about 20, and were chambered before shooting. This method gave much better fragmentation than churn drilling, but about 20 percent of the explosives required were used for secondary breaking. At the 160-foot level and above it two other breaking methods were also employed.

¹⁵²Gardner, *op. cit.*, pp. 28, 30.

¹⁵³Alenius, *op. cit.*, p. 8.

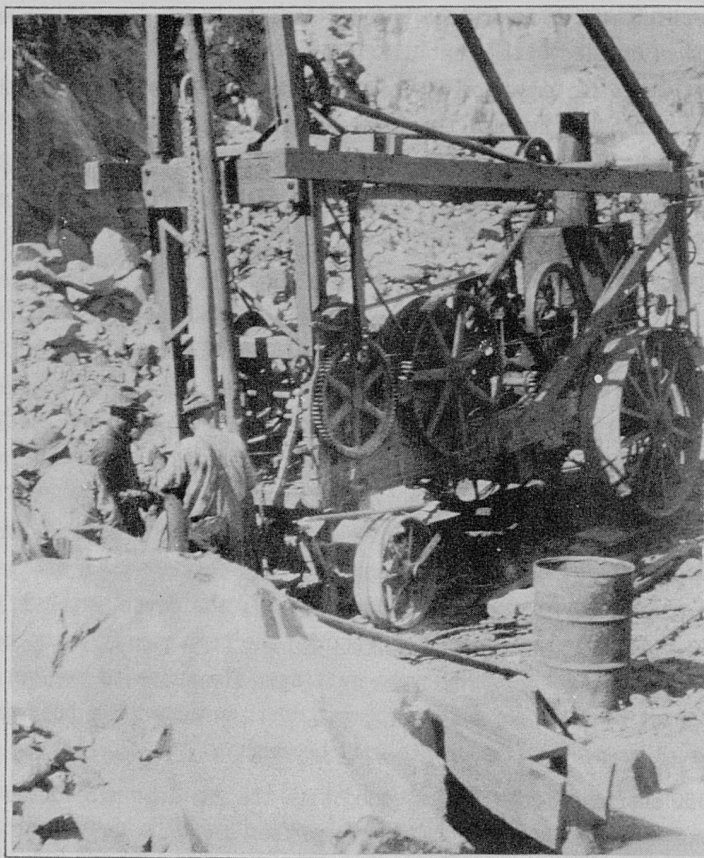


FIGURE 24.— A STEAM-DRIVEN TRACTION CHURN DRILL SAMPLING ORE
AT AN OPEN-CUT COPPER MINE

Churn drills are widely used in sampling disseminated or low-grade "porphyry" copper ores as well as for blasthole drilling. An older wooden-derrick drill at an open-cut copper mine is pictured above. The upright steam boiler stands at the rear of the drill. The bailer (or sand pump), which has just discharged a load of cuttings into the trough seen in the foreground, is again being lowered into the hole. The tool string is standing at the right of the bailer.

Where ground and bank slope permitted, steam churn drills put down 6- to 8-inch holes to a depth 10 to 12 feet below bank height. The other scheme was that of coyote-hole blasting and was employed in the highest bank ever used in any American metal mine. This bench, which was 315 to 320 feet high, was a merging of those immediately above the 160-foot level. Six coyote-hole blasts were set off and broke about 1.8 million tons of rock, the largest breaking a half million tons.

Hot ground was first encountered at the 160-foot level, and rock temperatures as high as 240° F. were reported. In the lower pit a maximum ground temperature of 780° F. was recorded. Generally the holes were cooled to 120° F. or below with water or water and sand before loading

and shooting. Obviously drilling and blasting efficiency was low compared with that of other mines with normal rock conditions. No attempt was made to chamber the hotter holes and special blasting methods were employed.

Below the 160-foot level the excavation was principally in ore. Although the ore was not as hard as the rock on the upper benches, the occurrence of waste masses intermixed with several grades and varieties of ore led to the adoption of benches of 25 to 33 feet. When ore extraction from this section was begun about 1927, traction churn drills operated by electric power were introduced. This resulted in saving the labor of one man per drill compared with the steam machine, and an increase in footage drilled per drill-shift.

Tripod-mounted hammer drills and jackhammers have been used in drilling for bank trimming and for places inaccessible to the churn drill. The churn drill is preferred, however, especially where heat and gas are factors, and the cost of breaking ground with it is reported to be about 16 percent lower than with air drills. Closely spaced, lightly loaded jackhammer holes supplant churn-drill holes near the outer limits of the pit to minimize fracturing the walls. Wagon-mounted drifters also have been used recently, with a reported gain in drilling speed. Secondary breaking is accomplished exclusively by block-holing with jackhammers.

It is noteworthy that the outstanding developments in drill design had all taken place before the open-cut copper mines came into production. These mines presented a wide range of rock characteristics, however, and required specially developed drilling practices to best meet local conditions. The character of these practices, in turn, was greatly affected by mechanization and technical improvement in other mining processes, particularly loading, hauling, and crushing. With reference to drilling equipment itself there were shifts from one type of machine or model to another and toward heavier, more powerful, and mobile drills, accompanied by gains of 200 to 300 percent in footage drilled per man-shift. At Nevada, for example, four electric churn drills replaced one small and eight large steam drills. The steam drills used about two and a half man-shifts per machine-shift but the electric drills required only one man, with occasional aid from a helper. At New Cornelia the shift from piston to hammer drill nearly quadrupled the drilling speed, and the change to the derrick-mounted hammer machine resulted in a further increase of 10 percent, accompanied by even greater proportionate increases in drilling productivity. Similar gains due to improvement of blasthole-drilling practice have been noted for other surface copper mines.

IMPORTANCE OF VARIETY OF DRILLS

Discussion of the introduction and development of the principal types of power rock-perforating and cutting machines in this and the preceding chapter¹⁵⁴ indicates that the individual machines have rather limited and specialized uses and that the mining engineer selects whatever equipment is most effective and economical for specific purposes. The extent of current application of major types of power drills and cutters is briefly summarized in table 5.

Table 5.- CURRENT USE OF MAJOR TYPES OF POWER DRILLS AND CUTTERS

Type of drill or cutter	Prospect drilling		Blasthole drilling		Dimension-stone quarrying
	Underground	Surface	Underground	Surface mining and general quarrying	
Piston drill	(a)	(b)	Virtually obsolete	Seldom	Seldom
Hammer drill					
Drifter	Seldom	(b)	Almost universal	Extensive	Extensive
Stoper	(b)	(a)	Almost universal	(a)	(a)
Jackhammer	(a)	(a)	Almost universal	Extensive	Extensive
Auger ^c					
Rotary	(b)	(a)	Decreasing	Seldom	(a)
Jackhammer	(b)	(a)	Extensive use in soft ground	Seldom	(a)
Rotary drill					
Diamond	Extensive	Extensive	Seldom	(a)	(a)
Shot-calyx	Seldom	Seldom	(a)	(a)	Seldom
Hydraulic ^c	(a)	Seldom	(a)	(a)	(a)
Churn or well drill	Seldom	Extensive	(a)	Extensive	(a)
Quarry machine					
Channeler	(a)	(a)	(a)	(a)	Extensive
Wire saw	(a)	(a)	(a)	(a)	Increasing

^aUse of the equipment for the purpose indicated would be exceptional.

^bQuite frequently samples are taken from blasthole cuttings obtained with these drills to check primary sampling or to determine current (ore) grade.

^cIt should be noted that the information summarized in this table does not include coal mining and oil- and gas-well development.

Some of the drills now in use have been adapted to other purposes than those for which they were primarily designed. The diamond drill, for example, is now used almost entirely for prospect drilling, although it was originally intended for blasthole and dimension-stone quarry work. For more than a quarter century no new type of drill has been developed,

¹⁵⁴In addition to the machines described in these chapters, there were other types of equipment that were never widely used and were replaced by more effective devices. The coal pick or puncher was used to some extent in salt and iron mines, for example, and a modified form, the "radialaxe", was employed in marble quarrying and in Tennessee blue-rock phosphate operations. The coal pick generally resembled a piston drill but there was no rotation of the steel or bit. The piston rod was 3 or more feet long so that deep cuts could be made; the puncher was usually supported by a pair of low wheels and made the undercut by swinging from side to side. The "radialaxe" machine was essentially a heavy, moderately long-stroke piston drill mounted on a column and could be swung in a vertical or horizontal arc by a worm gear.

and technical progress has consisted mainly of improvements in existing machines.

In contrast with operations more than 60 years ago on the Comstock lode, where the piston drill was the only machine available for underground work, no one type of drill is employed today to meet the needs of all operating conditions. The development of an increasing array of machines of varying abilities and capacities placed a more flexible drilling procedure in the hands of the mine technologist and opened the way to new efficiencies. This factor was probably just as important to over-all drilling progress as the increases in effectiveness and efficiency of the individual types of drilling machines noted in preceding sections.

CHAPTER V

PROGRESS IN OUTPUT PER MAN IN ROCK DRILLING

As noted in chapters III and IV, major technical advances and the development of special types enormously improved the rock drill. The result was greater effectiveness which was reflected in rising output per machine- or driller-shift. Quantitative appraisal of changing output per man in rock drilling, however, presents difficult problems.

DIFFICULTIES OF MEASURING OUTPUT

Tonnage broken per machine- or driller-shift is the main objective of drilling in actual mining but leaves much to be desired as an indicator of changing productivity. Such figures exclude consideration of prospect drilling and the remarkable progress made in machines used largely for that purpose. Statistical data on tonnage broken, moreover, are not generally available on a basis that permits desired comparisons. Much of the material moved in a quarry or mine, either underground or surface, may be waste; although the records of ore or stone moved are reasonably accurate, records of the tonnage of waste broken are frequently not available or are subject to considerable error. Furthermore, the ratios of waste to ore are not constant and the drilling requirements and degree of fragmentation of ore and waste generally differ. As a result reliable estimates of total tonnage broken generally cannot be made from ore-tonnage data.

Tonnage broken reflects progress in the quality and use of explosives and the blasting practice followed as well as the prevailing state of drilling technology. The blasting practice is in turn influenced by the mining method employed - especially whether surface or underground,¹ the amount of fragmentation needed,² and the structure of the rock or

¹Working conditions are often experienced underground that are not met with on the surface. The walls or roof of a stope may be weak, for example, and heavy charges of explosives may not be used, thus making necessary more than the ordinary amount of drilling per ton. Wide variations in hardness of the ground are also not uncommon. This reacts not only on quantity and strength of explosive required but also upon the number of holes used in breaking a given quantity of ground. At an iron mine, for instance, 15 holes comprised a regular drift round in average ground and 80 sticks of 40-percent dynamite a normal loading. In ground that is hard and more difficult to break, 22 holes and 168 sticks of 60-percent dynamite were necessary to break a round.

²In mechanized surface mining the size of the power-shovel dipper or primary crusher may be such that fragments as large as 4 or more feet in diameter may be handled. Thus, in comparison with operations where small fragments must be obtained, relatively little drilling per ton is required. On the other hand, in many underground mines there are constricted ore-passes that usually have at the top, as a safety measure, a bar grating with openings not much over a foot in width; mine cars also may be so small that large pieces cannot be loaded. Thus a relatively large footage must be drilled per ton broken and the driller's tonnage output is correspondingly low. That the use to which the product is put also affects tonnage is illustrated in cement manufacture where there is no objection to large amounts of fines in the broken limestone; for lime manufacture, however, the lumpy rock generally required demands greater pains in drilling and blasting.

ore - which includes consideration of the homogeneity, stratification, presence or absence of joints and fractures, and other structural characteristics. The amount of fragmentation needed is governed by the maximum size that can be conveniently loaded and by the use to which the product is put. Where wage payments are made on the basis of footage drilled there may be also a tendency to gain footage at the expense of tonnage. The temperature and humidity of the workings also affect the tonnage output per driller-shift. These and other factors that vary widely from operation to operation and at different periods in the life of the same mine suggest the use of some other measure than tonnage broken as an indicator of changes in productivity in rock drilling.

Although it has many of the disadvantages of tonnage broken, footage drilled per driller- or machine-shift is a better yardstick of changing unit output. It permits inclusion of progress made in prospect drilling, is not heavily weighted by changes in explosives and in blasting practice, and does not require extensive supplementary data on tonnage.

FACTORS AFFECTING FOOTAGE DRILLED

These advantages are partly offset by the fact that the number of feet drilled per driller-shift depends on many important and variable elements that must be understood before even crude measures of drilling progress can be properly interpreted. Some of the more significant of these factors are outlined briefly in the following paragraphs and include consideration of rock or ore characteristics related to drill penetration; effective drilling time per shift; depth, inclination, and diameter of hole; removal of cuttings; shape and quality of drill bits; air pressure; and skill of driller and management.

Rock or Ore Characteristics

The resistance offered by a rock to penetration by a drill is important in records of drill performance. The principal physical characteristics of rock which affect its resistance to drilling are hardness, toughness, abrasiveness, friability, plasticity, sludging character, and the presence or absence of bedding planes, joints, and fracture planes. Of these, hardness and toughness are most significant.

Most rocks and ores are mineral aggregates in which the minerals themselves show a considerable hardness range. Rocks of the same general classification also vary in content of the predominant minerals. The effect of such variation was well illustrated by Dale. Although structural and ornamental granites are commonly thought to be of roughly equal hardness, in 1907 Dale reported that granites from different European

localities tested for losses in abrasion showed a hardness range of about 110 percent.³ In the same year Lord reported a toughness range of from 1 to 3 and a hardness range of from 1 to about $2\frac{1}{3}$ for about 30 rocks commonly found in mining and quarrying.⁴ Lord determined the hardness by grinding with a standard abrasive agent, and the toughness, or the ability to withstand fracture by impact, by dropping a weight on the specimen until it failed. Although the values so obtained can hardly be directly applied in comparing drilling speeds they do indicate wide variations in the hardness and toughness of different kinds of rocks.

Table 6.- VARIATIONS IN HARDNESS OF MATERIAL RELATED TO DRILLING SPEEDS AT THE SOUDAN MINE, MINNESOTA, 1938^a

Item	Ore ^b	Jasper ^c	"Rock" ^d
Average penetration per bit, in inches ^e	2.249	1.766	22.130
Range of penetration per bit, in inches	1.01-8.68 ^f	1.16-3.22	13.5-45.6
Relative hardness based on average bit penetration	9.8	12.5	1
Drillingspeed, operating time, in inches per minute ^g	0.388	0.383	1.901
Range in drilling speed per minute, operating time	0.154-1.0	0.21-0.747	1.51-2.45
Feet drilled	30,046	3,718	30,536
Number of bits used	160,439	25,826	16,559

^aCompiled from W. P. Wolff, "The Soudan - a Hard Rock Mine," *Compressed Air Magazine*, Vol. 43, No. 10 (Oct. 1938), pp. 5717-8. Data cover operations from January to April, inclusive. The estimates of hardness were based on the suggestion made about 50 years ago that rock hardness could be measured by the rate of penetration of a drill. Cf. J. Francis Williams, "The Igneous Rocks of Arkansas," *Annual Report of the Geological Survey of Arkansas for 1890* (Little Rock, Ark.: 1891), II, 41.

^bHard, blue-black hematite.

^cLean iron ore; very hard metamorphosed sediment, largely iron oxide and silica with iron content of 10 to 50 percent.

^d"Average rock" that is locally called "greenstone" and that comprises metamorphic rocks, principally quartz sericite schist, sericite and chlorite schists.

^eDetachable bits only. At the start the bits are 2 inches in diameter and are ground and retempered when dulled. Each bit is used about eight times and is discarded when the diameter becomes $1\frac{1}{8}$ inches. One-man, 3- and $3\frac{1}{2}$ -inch drifters are used, some with automatic feed.

^fThe range is wider than for jasper or rock and the variation is often much greater than shown. In one case cited, 103 bits were required for a 36-inch hole, or an average penetration per bit of only 0.349 inch. Hardness varies among holes and within one hole.

^gOperating time is "all the elapsed time from the instant a drill is set up ready to run until it is ready to be taken down after the completion of drilling from a given position. It includes all ordinary delays."

³T. Nelson Dale, *The Granites of Maine* (U. S. Dept. Int., Geol. Survey, Bull. No. 313, 1907), pp. 64-5.

⁴Edwin C. E. Lord, *Examination and Classification of Rocks for Road Building* (U. S. Dept. Agr., Office of Public Roads, Bull. No. 31, 1907), table 2, opposite p. 14. Later methods of testing the physical characteristics of rocks and the results of about 8,000 determinations made up to the end of 1927 are given by D. O. Wolff, *The Results of Physical Tests of Road-Building Rock* (U. S. Dept. Agr., Misc. Pub. No. 76, 1930).

Drilling speeds have been reported as high as 240 feet in 8 hours for a one-man jackhammer in limestone, a comparatively soft rock with characteristics that usually favor rapid drilling. At the other extreme is the hard ore and jasper of the Soudan iron mine near Tower, Minn. Table 6 shows not only the extraordinary hardness⁵ of these materials and the resulting slow drilling speed but also the great range of drilling speeds found in one mine.

Effective Drilling Time per Shift

Reports on drilling speed are given most frequently in terms of feet per machine- or man-shift, and the length of the shift has varied. Although the 8-hour shift now is common practice 10-hour or longer shifts persisted at underground mines in some localities up to about the time of the World War; at surface operations the shift frequently was longer. Even where the "8-hour day" was worked it was somewhat elastic. At some operations it meant 8 hours actually spent at the working face and at others "8 hours from collar to collar",⁶ a difference of probably 10 to 15 percent in available working time in many instances. In making long-range comparisons of performance per shift, changes in the length of the working day must be taken into consideration.

The amount of time actually spent in drilling within the regular shift is also variable. Even when the miner or driller is assigned to a drilling task much of his time is spent in performing work of a preparatory nature, some of which is necessary to insure his safety. Once at the working face he must "bar down" any loose rock and perhaps place some temporary timber. Setting up his machine is a negligible matter with jackhammer or stoper, but for a drifter he must block securely in place a bar or column on which to set the drill, although in surface workings and in the Mississippi Valley zinc-lead mines tripod mountings are generally used. The next step is to connect air and water hoses to pipe lines and the drill. This preliminary work may require considerable time. With a steel in the chuck, drilling may begin, but within a few minutes the machine must be stopped to change to a longer steel or to a sharp bit, or the steel may have stuck or broken. It may take some time to change steel, especially if it is long; not only does the drill have to be brought back in its carriage but clamps also may have to be

⁵W. P. Wolff, "The Soudan - a Hard Rock Mine," *Compressed Air Magazine*, Vol. 43, No. 10 (Oct. 1938), p. 5718, states that "Brinnell tests have shown specimens of the ore to be actually harder than the steel that was used to drill it. It would seem that the steel survives only because it is tough, while the ore is relatively brittle."

⁶A common phrase used to mean that 8 hours elapse from the time the miner passes the mouth of the shaft or drift on his way into the mine to the time he passes the same place on his way out.

slackened so that the drill may be swung aside to let the steel or rod pass it. With the older-type piston drill, changing steel took much more time than for hammer drills since the steel was clamped in the chuck with a U-bolt on which two nuts had to be loosened and then tightened with a heavy wrench. When a hole has been completed the drill must be shifted to a new position and sometimes a second set-up may be necessary to complete a group of holes. After drilling has been finished the drill and its auxiliaries have to be taken down and moved back from the face. "Tearing down" takes ordinarily about half as long as "setting up." Customarily the driller also loads and fires the holes; this operation may take 30 minutes to an hour depending primarily on the number of holes.

There are many other reasons why the time actually spent in drilling varies during the shift. Some of the most common are shortage of drill steel, machine break-downs, and insufficient air pressure.

Furthermore, there are factors that act adversely upon the physical ability of the drill runner to perform work. These include high temperatures and humidities and other atmospheric conditions.⁷ With increased depth, mines tend to become hotter and more humid. Conditions particularly unfavorable to physical exertion were common on the Comstock lode. Although mechanical ventilation was begun in 1868, in the late seventies temperatures on lower levels were very high. In the hottest workings of the California and Consolidated Virginia Mines during the summer of 1878 the average daily consumption of ice for every miner was 95 pounds. It was also stated that "if power-drills had not been in general use the work of exploration would probably have come to a close. To penetrate hard rock while breathing such an atmosphere would have taxed human endurance too greatly; even to cut out the decomposed feldspar with light steel picks was a painful labor." In some stopes of mines mentioned above "four miners could scarcely do the ordinary work of one man in a moderately cool drift; yet no mines were more carefully ventilated than these."⁸ Thirty-five years later Higgins reported that he found many cases on the Comstock where miners were working only one-fifth to one-sixth of their time, though they received a full day's pay, and that frequent observations in Lake Superior iron mines, where conditions were

⁷R. R. Sayers and Sara J. Davenport, *Review of Literature on the Physiological Effects of Abnormal Temperatures and Humidities* (Reprint No. 1150 from *Public Health Reports*; U. S. Treasury Dept., Public Health Service, 1927), p. 56. "The upper limit in atmospheric conditions at which work can be performed efficiently corresponds to a dry-bulb temperature of 100° and a relative humidity of 30 per cent, or 90° or 95° F. in still saturated air, even when stripped to the waist. The optimum temperature at rest is around 66° F.; and with hard work the optimum temperature is 59.5° An air current of less than normal body temperature reduces discomfort but if warmer affords no benefit and may be disadvantageous."

⁸Elliot Lord, *Comstock Mining and Miners* (U. S. Dept. Int., Geol. Survey Monograph No. IV, 1883), p. 394.

much less severe, showed that with wet-bulb temperatures of 80° to 90° (relative humidity 90 to 100 percent) the average miner worked only one-third to one-half his shift.⁹ Abnormal temperatures and humidities may also be found in surface work because of seasonal climatic changes, but the effects of exposure generally are less severe. Underground atmospheric conditions change but little with the season, except in shallow mines.

Various estimates of net drilling time underground range from about 30 to 60 percent of the shift length. Illustrations of time losses from all sources and the low percentage of time actually drilling in development work were reported by Mitke.¹⁰ Elsing in summarizing several investigations states that, with drifter drills in an 8-hour shift, 4 to 5 hours are used in drilling but that the drill actually is running often only 40 to 90 minutes of this 4 or 5 hours.¹¹ In surface work actual drilling generally occupies a larger proportion of working time than underground. The time lost for all reasons in heavy jackhammer surface drilling in highway construction in four groups of rocks ranged from 36.1 to 62 percent, and the weighted general average was 45.6 percent.¹² Summarizing available data for piston drills in surface work, Gillette stated that "drills . . . are actually striking or cutting rock only 40 to 70% of the time, the average under most conditions being about 55%."¹³ He concluded that the higher figure was seldom reached and 40 percent could be taken as a typical average.

Depth, Inclination, and Diameter of Hole

Depth, inclination, and diameter of the hole are factors that also affect drill performance. In underground work most machine-drill holes are 6 to 10 feet in length. When such holes are drilled with the modern wet hammer drills the net effect of length of hole upon footage per driller-shift generally is small. In general, however, drilling speed usually decreases with increasing depth and reduces footage drilled per shift. Offsetting factors are a decrease in hole diameter with increased depth and less lost time in moving the drill from hole to hole. In some instances, as where longer holes are used in stoping, the offsetting

⁹Edwin Higgins, "Ventilation in the Iron Mines of the Lake Superior District," *Proceedings of the Lake Superior Mining Institute*, Vol. XIX (1914), pp. 172, 159.

¹⁰Charles A. Mitke, "Standardization of Mining Methods," *Engineering and Mining Journal*, Vol. 106, No. 28 (Dec. 28, 1918), pp. 1108-90.

¹¹Morris J. Elsing, "Cost of Drifting," *Engineering and Mining Journal*, Vol. 133, No. 1 (Jan. 1932), p. 13.

¹²Andrew P. Anderson, "Some Studies of Drilling and Blasting in Highway Grading," *Public Roads*, Vol. 12, No. 12 (Feb. 1932), table 2, p. 298.

¹³Halbert P. Gillette, *Handbook of Rock Excavation* (rev. ed.; New York: McGraw-Hill Book Co., Inc., 1918), p. 219.

factors have more than overcome the difficulties of greater depth and there has been an increase in footage per driller-shift.

Although handicaps that accompany greater depth of hole in present-day drilling may be largely offset by modern equipment this was not the case when boring was done by hand or with the piston machine. In surface work by hand on the Marquette Range, for example, the cost per foot of 15-22-foot blastholes was nearly double that of 15-foot holes (or the drilling efficiency was halved), and the drilling speed for smaller and much shallower block-holes (averaging about 1 foot) was about two and one-half times that in holes up to 15 feet.¹⁴ In piston drilling the greater weight of long steels and the increased friction between the steel and the wall of the hole acted to decrease speed with depth. To offset this, machines with large-cylinder diameters were employed for deep-hole work.

The influence of the slope of the hole on the footage drilled per time unit is also best illustrated by hand and piston drilling. Experiments showed that nearly vertical down-holes were hand-bored at slightly more than twice the rate of horizontal holes; for holes inclined upward the rate was lower than for horizontal holes.¹⁵ The energy of a vertical downward piston-drill blow is estimated to be about 14 percent more than that of a horizontal blow.¹⁶ Uppers¹⁷ from which cuttings fell by gravity were drilled much more rapidly than down-holes with piston drills, but with a wet hammer drill the inclination of the hole made little apparent difference.¹⁸ It was Young's view that uppers were generally drilled more rapidly than down-holes.¹⁹ With the development of different modern wet hammer drills for specific tasks, however, it is difficult to segregate the effect of hole inclination. Although unmounted jackhammers have been used for relatively horizontal holes, it has been observed that the footage per shift is appreciably less than when used in down-hole work. This is so even when the jackhammers are supported for horizontal drilling. In general, hammer drills of the same piston diameter drilled horizontal holes at a lower rate than uppers or down-holes.

¹⁴T. B. Brooks, "Iron Bearing Rocks (Economic)," *Geological Survey of Michigan, Upper Peninsula: 1869-1873* (New York: Julius Bien, 1873), vol. I, pt. I, pp. 284-5.

¹⁵Gillette, *op. cit.*, p. 23.

¹⁶Richard T. Dana and W. L. Saunders, *Rock Drilling* (1st ed., New York: John Wiley & Sons, 1911), p. 38.

¹⁷Holes that are inclined more than 20° above the horizontal usually are called "uppers." At a 20° inclination dry cuttings will not run out but the reciprocating motion of the piston drill will keep the hole fairly clean.

¹⁸Gillette, *op. cit.*, pp. 170-1.

¹⁹George J. Young, *Elements of Mining* (3d ed.; New York: McGraw-Hill Book Co., Inc., 1932), p. 108.

The net effect of hole diameter on footage drilled has not yet been fully determined. Dana and Saunders reported that drill-performance tests with piston drills on the Witwatersrand more than 30 years ago indicated the importance of bit size in drilling speed.²⁰ The gain from a decrease in bit size also was noted in tests conducted by the Bureau of Mines in 1921. Using 1-inch steel with $1\frac{3}{4}$ -inch starting bits in one series of tests with drifter-type hammer drills "the drilling speed as compared to previous results with $1\frac{1}{4}$ in. steel [presumably having a $2\frac{1}{2}$ -inch starting bit] was increased about 90 percent."²¹ More recent studies also show that drill gage is a major factor affecting footage obtained.²²

Removal of Cuttings

Drilling efficiency with hand and piston drills was reduced by the continued comminution of fragments already broken from the hole bottom, within the period between hole cleanings. The regular or continuous removal of cuttings became of greater importance, moreover, with the adoption of machines that cut so much faster than hand work. The effect of this factor on drilling speed was early recognized and in 1878 Saunders patented his water-jet system for subaqueous drilling and later reported that "jets will increase the output from 30 to 100%" and cited a number of instances to prove the point.²³

The designers of hammer drills used hollow steel that permitted the passage of compressed air or a combination of water and air to eject cuttings. This resulted in a marked improvement in drilling rates, and the use of such drills is now almost universal in all underground work.

Air Pressure

The early piston drill used pressures about half the present ones and its lower drilling speed was partly due to this fact. Experiments have shown the importance of optimum air pressure to drilling progress. A series of tests made with stopers, for example, showed a very close relation between air pressure and foot-pounds per blow.²⁴ The number of

²⁰Dana and Saunders, *op. cit.*, p. 40.

²¹C. R. Forbes, *Rock Drilling Tests in the Tri-State Mining District* (U. S. Dept. Int., Bur. Mines, Report of Investigations 2297, mimeo., Nov. 1921), p. 3.

²²McHenry Mosier and Wing C. Agnew, *Mount Weather Testing Adit Progress Report 1* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3439, mimeo., Feb. 1939), pp. 8-9; McHenry Mosier and Wing C. Agnew, *Bit Gage v. Drilling Speed* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3447, mimeo., May 1939), pp. 2-3.

²³Dana and Saunders, *op. cit.*, pp. 23-4, 31, 62. In soft rock and subaqueous drilling the speed increase was very much higher.

²⁴Robert H. Bedford and William Hague, "Rock-Drill Testing at the North Star," *Mining and Scientific Press*, Vol. 107, No. 5 (Aug. 2, 1913), p. 180. With a 32-percent pressure drop the foot-pounds per blow dropped 31 percent. The [Con.]

blows per minute declined and the footage drilled dropped sharply when the air pressure was reduced below the optimum. For jackhammer work, both hand-held and mounted, Forbes and Barton showed that speed and air pressure are closely related for several bit types.²⁵

The modern hammer drill is most efficient over a pressure range of about 85 to 95 pounds per square inch but will be quite effective from about 70 to 100 pounds. The efficiency drops rapidly, however, when the air pressure falls below 70 pounds. Tests have been made at 125 to 200 pounds and much higher drilling rates have been attained, but the additional wear and breakage of machines and steel and the added cost of high-pressure air more than offset the gain in speed.²⁶

Shape and Quality of Drill Bits

Aside from the size of the bit previously discussed, the shape and quality have a marked effect upon drilling speed. Many shapes have been devised and the greater number discarded. The bit used most widely is the 4-point cross bit illustrated on page 44. Other types, such as the Z and Carr afford higher drilling rates under certain conditions.²⁷ Where gage loss is great - for example, in the Tri-State district - bits that have good reaming qualities are preferable. Limited tests conducted by the U. S. Bureau of Mines indicated that a full-reaming bit advanced about 20 percent faster than a standard bit of the same manufacture and of closely identical gages, and the gage loss was about one-third.²⁸

There has been some improvement in the bit steel and perhaps greater gains have been due to advances in forging and heat-treating and the development of the mechanical sharpener. It was claimed that machine-sharpened bits could drill 25 to 100 percent more than hand-dressed

²⁴[Con.] results of 1,500 tests made at the United Verde Mine about 1921 are reported by H. W. Seamon, "Relation of Air Pressure to Drilling Speeds of Hammer Drills" and discussion of this article, *Transactions of the American Institute of Mining and Metallurgical Engineers*, Vol. LXVI (1922), pp. 743-57. A condensed summary of part of Seamon's tabular data follows, covering all drills tested. Performance at different air pressures is shown relative to that at 80 pounds.

Item	Test pressures in pounds					
	40	60	80	100	120	130
Blows per minute	76	89	100	111	119	122
Strength of blow	49	75	100	125	151	160
Drilling speeds	31	64	100	140	180	198

²⁵Carroll R. Forbes and Joseph C. Barton, "Comparative Tests of Hammer Drill Bits," *Transactions, A.I.M.E.*, Vol. LVIII (1918), pp. 8, 24.

²⁶Ocha Potter, "Block Testing of Drill Steel and Experiments With High Air Pressure," *Proceedings of the Lake Superior Mining Institute*, Vol. XXVII (1929), pp. 85-7.

²⁷Forbes and Barton, *op. cit.*, p. 24.

²⁸Mosier and Agnew, *Mount Weather Testing Adit Progress Report 1*, p. 7.

bits.²⁹ The use of other devices and controls made the bits more durable. The effect cannot be accurately measured but, like other changes, the net result has been to increase speed not only by cutting more rapidly but also by reducing the time spent in changing steel.

The use of detachable bits not only made possible a notable saving of labor in transporting drill steel³⁰ and a major increase in footage, but also introduced other timesaving factors that add to driller productivity. In drilling in hard ground with the conventional steel where many pieces may be required the miner frequently uses one already partly dulled rather than change to a sharp steel. How this practice retards drilling progress was indicated by Bedford and Hague, who used a sharp set of steel in one hole and then re-used it in a second, testing the results meanwhile. Under the same pressure conditions the number of blows and force per blow were essentially constant for both holes but the drilling speed dropped nearly 30 percent when the dulled steel was used in the second hole.³¹ Further, if the bit does not penetrate the rock most of the blow energy is consumed in rebound absorbed by the machine, and its effectiveness is rapidly reduced by the shocks. Such effects have been frequently noted, and Ross estimated that drill-repair costs may be reduced as much as 20 percent because of the use of the sharper detachable bits.³²

Skill of Driller and Management

The skill of the drill runner is also a factor influencing the footage drilled, although it is not as important as in the early period when the operator also had to service his drill.³³ Until recently some repairs

²⁹T. H. Proske, "Rock Drill Bits," *Mining and Scientific Press*, Vol. 100, No. 10 (Mar. 5, 1910), p. 347.

³⁰W. M. Ross, "How Detachable Bits Reduce Mining Costs," *Compressed Air Magazine*, Vol. 44, No. 4 (Apr. 1939), p. 5862. The author apparently referred to the mine for which speed and hardness data are given in table 6, p. 112. He says that with the conventional steel, often 140 to 170 pieces weighing about 2,800 pounds were needed to drill one 7-foot hole. It is patent that much time and energy would be expended in transporting such a great weight and number of pieces from about 2 to 7 feet long into a stope, for example. With the separable bits, assuming 20 percent fewer bits [and 140 used] the miner would have to carry only about 55 pounds in bits and perhaps two rods, say 6 feet long and weighing 50 pounds, or roughly 105 pounds instead of about 2,800.

Tests made by TVA covering more than 225,000 feet, of which 130,000 feet was with detachable bits, showed the latter drilled about 10 percent faster than the conventionally forged bit. There was also a saving of one blacksmith and helper and one man with distributing team or truck for the detachable over the ordinary bit. Cf. "Cost and Performance Data on Forged and Detachable Bits," *Engineering and Mining Journal*, Vol. 137, No. 1 (Jan. 1936), pp. 24-5.

³¹Bedford and Hague, *op. cit.*, pp. 180-1.

³²Ross, *loc. cit.*

³³Dana and Saunders (*op. cit.*, p. 19) remarked that "the power drill appeals as presenting . . . one of the most *perverse machines to handle*, and one of the most *complex tools ever invented*." Italics in source.

continued to be made at the working face, but this is rarely permitted now. Although the function of the driller has been increasingly confined to drilling and blasting and closely related work individual skill and muscular coordination still aid in obtaining high drill performance. For example, in so simple a function as changing steel, skill and experience are important. This is especially true if the steel becomes stuck, although a skilled operator seldom sticks a steel. One observer reporting on many thousand time studies said the time range for changes was from 12 seconds to over 6 minutes, with an average of 45 seconds per change. In bad ground an inexperienced man often took many times as long as an experienced one to withdraw the steel.³⁴ Another example will illustrate the effect of skill and experience in one form of surface drilling. On the Cuyuna Range the ordinary Mesabi rig was frequently used to drill inclined prospect holes. The drillers were skilled in its use in vertical holes. At first they drilled about 6 to 8 feet per shift in inclined holes and considered the hole-depth limit about 140 to 150 feet. Subsequently holes up to 200 feet were easily made at a speed of 12 to 15 feet per shift over the full depth. This doubling of output was attributed to the increased experience of the men, better knowledge of the ground drilled, and "adaptation of methods" to conditions.³⁵

The skill of management exerts an even larger influence on drill performance than the skill of the miner. It is responsible, for example, for the choice of the mining method and of the drilling devices to be applied for specific tasks both of which are of tremendous importance in the conduct of satisfactory drilling. The wise operator schools the drill runner, standardizes drilling methods, and plans and directs effective utilization of the machineman's time. In fact, within certain limits, the skill and productivity of the driller as well as over-all drilling efficiency are products of management.

CHANGING FOOTAGE PER MAN-SHIFT IN ROCK DRILLING

Recognizing the influence of wide variations in the factors just noted upon footage drilled, it is also advisable to consider the principal differences in mining in developing comparisons and indicating trends. For example, the notable differences between certain types of surface and underground drilling machines and the absence in surface work of spatial restrictions and of the need for most of the preparatory tasks of the

³⁴Anderson, *op. cit.*, pp. 299, 300.

³⁵Percy W. Donovan, "Churn Drill Angle Holes on the Cuyuna," *Engineering and Mining Journal*, Vol. 98, No. 24 (Dec. 13, 1913), p. 1117. By "adaptation of methods" the writer referred to the use of inclined, auxiliary tripod legs to support the casing (drivepipe) at the desired slope. Added experience and skill appear to have been the important factors in increasing the drilling rate.

underground driller make comparison of footage rates in surface and underground drilling of doubtful use. Thus in this discussion comparisons of footage rates in underground drilling and in surface work are presented separately. Surface drilling is further divided into (1) surface drilling at mines and general quarries, and (2) drilling and cutting at dimension-stone quarries. The latter uses relatively precise techniques and practices which differ notably from those of general quarries and open-cast mines which chiefly seek mass fragmentation at low cost.

The discussion of drilling rates at mines and general quarries is differentiated as to prospect drilling and blasthole drilling. Footage rates shown for blasthole drilling are supplemented by a rough comparison of different machines as to the volume of hole drilled, a somewhat better indicator of performance per driller-time unit.

Finally it is important to note that although a large volume of data is available on drilling speeds it is not suitable to the preparation of averages or conventional statistical indicators of trends. It is possible, however, to review the extensive literature on drill speeds and to derive qualitative judgments, supported by examples that avoid extreme conditions, regarding the general trends for different types of drilling equipment. The conclusions presented herein represent judgments arrived at in this way by the authors.

Underground Drilling

Hand Drilling.—Holes were seldom bored over 3 to 4 feet deep by single-jacking with hammer-and-steel and 6 to 8 feet by double-jacking. The amount drilled per driller-shift³⁶ ranged from about 2 to 10 feet, in most instances falling between 3 and 5. It is believed that an approximate over-all average of 4 feet per driller-shift³⁷ was obtained with hammer-and-steel for both single- and double-jacking.

Piston Drilling.—Drilling speeds also varied widely with the two-man piston machine, ranging from a low of 5 to 8 feet per machine-shift at the Soudan iron mine to as much as 80 feet per machine-shift in the medium-hard Mesabi ores. About 1910 when the piston drill had been improved and was meeting competition from hammer drills, a good average machine-shift output was 35 to 40 feet, with a range of about 20 to 60 feet. About this time also there was introduced the lighter one-man piston drill that had a boring rate often nearly as high as its heavier relative. Making allowance for many variable factors it appears that

³⁶Unless otherwise noted a shift is 8 hours; and the footage is that for a full shift including all time losses.

Footnote 37 appears on following page.

roughly 40 feet per drill-shift or 20 feet per man-shift may be taken as representative.³⁸ This is about five times the hand-drilling rate.

Hammer Drilling.—The hammer-type drills, including the drifter, stoper, and jackhammer, rendered the piston machine virtually obsolete by about 1915. Not only were they much faster in drilling but also some models were one-man machines. The drilling speeds of the three classes of hammer drills are not exactly comparable because of differences in the machines and the inclination of the holes most suitable to each. The range is from about 20 feet in very hard ground to 120 or more in good drilling ground. As a rule the stoper has given the greatest footage per man-shift. Eighty feet per man-shift may be taken as an average, about four times that with a piston drill and 20 times that of hand drilling.³⁹

³⁷ This average, of course, is much below the records made in surface hand-drilling contests where the drilling conditions were far more favorable than those in mines. Holes were drilled vertically downward, usually with water, in a homogeneous and generally hard rock. The hammer and drills were of the best and the steel very carefully forged and tempered and with small gage changes. The men, moreover, were outstanding specimens of strength and skill and drilled for 15 minutes straight and stopped. Nevertheless these records are particularly interesting as an indication of the maximum possible rates of advance in hand work and are given as follows:

Year	Place	Driller	Rock	Time (minutes)	Inches drilled
Single-jacking					
1903	Bisbee	Yockey	Gunnison granite	15	26 $\frac{1}{2}$
	Not given	Boulder Dopp	Granite	10	18 $\frac{1}{2}$
Double-jacking					
1888	Butte	Page, O'Neil	Granite	15	18
1901	Spokane	Bradshaw, Freethy	Not given	15	55
1903	El Paso	Tarr brothers	Granite	15	44
1903	Bisbee	Chamberlain, Maka	Gunnison granite	15	46 $\frac{1}{2}$
1903	Bisbee	Ross, Maka	Gunnison granite	15	35 $\frac{1}{2}$
1903	Bisbee	Tarr, Malley	Gunnison granite	15	38 $\frac{1}{2}$
1906	Butte	Bradshaw, McNichols	Granite	15	45 $\frac{1}{2}$
1909	Butte	Pickens, Page	Granite	15	43 $\frac{1}{2}$
1911	Hancock	Kinsella, McLean, McCormack	Vermont granite	15	59 $\frac{1}{2}$

These records, with the exception of the 1909 record on double-jacking, are from Allen S. Park, "Super Hammermen," *Compressed Air Magazine*, Vol. 43, No. 1 (Jan. 1938), pp. 5506-7; the data on the double-jacking contest in Butte in 1909 are from *Engineering and Mining Journal*, Vol. LXXXVIII, No. 8 (Aug. 21, 1909), p. 379.

Page and O'Neil, Ross and Maka, and Tarr and Malley did "straightaway drilling", in which the striking was done by the first named of each pair throughout the entire period without a break. Page and O'Neil drilled dry; the others with water. For the 1911 three-man team McLean and Kinsella did the striking and McCormack turned.

³⁸ The rate of about 3 feet per man-shift obtained with the first drills employed in the Hoosac Tunnel (1866) was about 15 percent less than by hand drilling. In the Musconetcong Tunnel (1873-74) where the rock was said to be harder than in the Hoosac the output was about 8 to 10 feet per man-shift. At that time improved machines were also in use in the Hoosac. During the drilling period - nearly one-half the shift - under good conditions the drills averaged over 6 feet per hour or 3 feet per man-hour. In the Sutro tunnel driven to drain the Comstock lode in the late seventies the heavy Burleigh drill progressed nearly 4 to 7 feet per hour during the drilling period, and the lighter Ingersoll about 4 $\frac{1}{2}$ to nearly 13 $\frac{1}{2}$ feet. The range was from a little over 2 to nearly 21 $\frac{1}{2}$ feet. All machines had a runner and helper.

³⁹ In Michigan copper mines in 1878 a contract stope miner produced a little less than 2 tons in 10 hours' working time and it was said that with hand drills 2 to 2 $\frac{1}{2}$ feet were easily drilled per man-shift (T. Egleston, "Copper Mining on Lake [Con.]

Surface Drilling at Mines and General-Type Quarries

Notable progress has been made in the effectiveness of all types of surface drills, but the effect upon driller output is not of the same order in prospecting as in blasthole drilling. Because of inherent differences in the kind of work done drill performance for each is considered separately.

Prospect Work.— Since the function of the prospecting drill is to procure an adequate and accurate sample of the rock or ore perforated, speed of drilling is of secondary importance. Thus much of the working time is given to the removal of the core or sludge, and actual drilling time per shift is reduced. To prevent contamination of the sample, moreover, casing must frequently be used and the hole started large enough for all the strings of casing required to reach a predetermined depth with a hole of useful size.⁴⁰ Data on drilling speeds are sparser than for blasthole work and the difficulty of making comparisons is greatly enhanced.

Nearly all prospecting from the surface is performed with either rotary or percussive drills and there are but three types important in mining or quarrying. These are the rotary diamond and calyx (including the

³⁹[*Con.*] Superior, "Transactions, A.I.M.E., Vol. VI [1879], p. 290). In 1931 in two Michigan mines 20 to 26 tons were broken per 8-hour, one-man drill-shift and the contract base for drilling at one of them was 35 to 50 feet per shift. The ratio of hand to machine footage was then about 1 to 18 and, allowing for the longer day, the tonnage ratio was roughly 1 to 18 (Chas. F. Jackson and E. D. Gardner, *Stoping Methods and Costs* [U. S. Dept. Int., Bur. Mines, Bull. No. 390, 1936], p. 67).

The steam piston drill was introduced in the Joplin district in the eighties. About 1887 it was said that "... one steam drill, with two men handling it, has done the work of ten men [hand workers] ..." (Jno. N. Wilson, *Lead and Zinc Ore of Southwest Mo. Mines: Authenticated Statistics* [Carthage, Mo.: Jasper County Democrat], p. 12).

Comparing results obtained in Michigan in 1909 with piston drills and in 1929 with hammer drills, Ocha Potter (*op. cit.*, p. 84) said that "the efficiency [of stope miners], measured in tons per man per shift had increased over 200 per cent" and that "their [drift miners'] increased efficiency is 410 per cent."

Benjamin F. Tillson, "The Testing and Application of Hammer Drills," *Transactions, A.I.M.E.*, Vol. LI (1918), pp. 256-9 gives the following data from stoping practice at the mines of the New Jersey Zinc Co., Franklin Furnace, N. J. In hand work with bit sizes graduated from $1\frac{1}{2}$ to $1\frac{1}{4}$ inches 8 feet in three holes was a good day's work (10 hours) for two men. With the piston drill and bits from $2\frac{1}{2}$ to $1\frac{1}{2}$ inches in diameter 20 to 40 feet was common though sometimes 80 to 90 were drilled. With one-man hammer drills using bits $1\frac{1}{2}$ to $1\frac{1}{4}$ inches in diameter 80 to 100 feet were good averages. In drifting and raising comparable results were noted. With the reciprocating drill 18.4 man-hours were required per foot of drift and only 5.3 with hammer drills (1913). In raising with the $2\frac{1}{2}$ -inch piston drill it took 28.5 man-hours per foot (1908). In the same year the hammer drill was put to use and the time dropped to 13.3 man-hours. With the development of the stoper came further great reductions in time; in 1910 the man-hours per foot were 7.8, and in 1912, only 4.8.

In South Africa in 1912 it was shown that with the $2\frac{1}{2}$ - and $3\frac{1}{4}$ -inch piston drills the tonnage output was respectively 9.7 and 10.8 times that of "hammer boys." ("Machine Drilling at the Robinson Deep," *Engineering and Mining Journal*, Vol. 94, No. 11 [Sept. 14, 1912], p. 498.) A recent report said "a modern mechanical rock-drill requires only one man for its operation and will put in ... what is equivalent to the labours of from 30 to 45 men. A direct comparison is offered by Rhodesian mines, where both hand and machine methods are in use. A Kaffir 'boy' with a single-hand hammer can pound a $2\frac{1}{2}$ -ft. hole in quartz in a shift. The same workman will drill 30 holes, each 4 ft. to 5 ft. deep, with a jackhammer." ("Rock Drill Efficiencies and Reduced Drilling Costs," *The South African Mining and Engineering Journal*, Vol. XLIX, pt. II, No. 2384 [Oct. 8, 1938], p. 168.)

⁴⁰At the Utah Copper Mine a churn-drill hole 1,489 feet deep was started with a 23-inch-diameter bit in order to bottom at about 8 inches. The average speed was only 3.23 feet per day.

shot) drills and the percussive churn drill, each of which has a special sphere of use in prospect drilling.

The Diamond Drill.— The early diamond drill was a crude machine but was said to have been successful in drilling a hole about 130 feet deep in the Michigan iron-mining area about 1869. In other tests, however, the greatest depth attained was only 96 feet, the drill did not perform well, and bits were lost in two holes. An observer remarked further that since it was a steam machine the drill had to be used near a town and could not be taken into the "woods."⁴¹ The advance per drill-shift with the early diamond drill was undoubtedly low and its usefulness very limited. Within a few years, however, it was being used to drill holes 400 to 1,100 or more feet and speeds of about 1 to 2 feet per drill-hour were reported.

The introduction of a swivel head that could be swung out of the way when the rods were hoisted or lowered, the inclusion of a hoist integrated with the machine, the adoption of the double-tube core barrel, and the application of the hydraulic feed further raised drilling rates. There also was a pronounced improvement in the quality of the drill rods and accessories as well as minor changes in bits, and the development of a highly skilled class of drill runners. Such improvements have continued to the present.

For the usual type of holes the standard crew consisted of a runner and helper, and used the part-time services of a bit setter.⁴² More recently the use of factory-set bits has partly displaced the bit setter. For short-hole work both underground and surface mobile one-man diamond drills are now extensively employed.

Significant progress has also been made in increasing the depth drilled. Holes over 5,000 feet deep are not uncommon and have exceeded 10,000 feet. For such work the drill crew is large and over-all speeds low, since much of the working time is spent in hoisting and lowering the rods.⁴³ Here, however, the economic value of a sample obtained either in advance of expensive mine development or from depths not as yet reached in the exploitation of ore deposits counterbalances the low footage advance per shift.

The Calyx and Shot Drills.— The calyx machine has not been widely applied principally because it is most useful in soft rocks and unconsolidated strata. The shot drill will penetrate harder rocks than the

⁴¹Brooks, *op. cit.*, p. 204.

⁴²Occasionally in early prospect work three men were employed at the drill. Cf. Louis A. Riley, "Costs and Results of Geological Explorations With the Diamond Drill in the Anthracite Regions of Pennsylvania," *Transactions, A.I.M.E.*, Vol. V, p. 304.

⁴³In South Africa, at a vertical depth of 8,000 feet, the round-trip time was 11 hours.

regular calyx, but its effectiveness is low in such workings.⁴⁴ For about 10 to 15 years after it was introduced the shot drill attained popularity as a substitute for the diamond drill, primarily because the cost of carbons had risen so greatly. In general it has not been widely employed but its recent use for boring large-diameter holes for purposes other than exploration or blasting is of considerable interest.

The shot drill, used underground as early as 1910 to bore 20-inch holes about 50 feet deep for ventilation and for ore chutes,⁴⁵ is not well-suited to routine work below ground because it required much headroom and a good deal of time was needed for erection and dismantling. Nevertheless it has been advantageously employed under the extreme temperature and humidity conditions found in new, low-level development of some deep mines, as in Butte. Between 1936 and 1938, six 36-inch holes averaging about 106 feet in depth were drilled between the 3,600- and 4,100-foot levels of one mine to provide a primary ventilation circuit.⁴⁶ In medium-hard rock where conditions were said to be "average" the net speed while actually drilling was close to 5 inches per man-hour or about 10 inches per machine-hour; the over-all speed for the entire drilling period, however, was about 1 inch per man-hour. Hoisting and lowering the bit, pumping, and core removal (largely hand mucking) took more than twice as long as drilling; a large portion of time was also spent in cementing caving walls.

The application of the shot drill in investigating rock conditions at dam sites by TVA represents a use that is more closely akin to prospecting. At Norris Dam about 1934, 651 feet of 36-inch holes were bored in limestones to an average depth of about 34 feet; at the proposed sites of four other dams on the Tennessee River 30- to 40-inch holes were sunk to depths of about 70 feet. In the soft rocks a speed up to 3 feet per hour was attained but in hard rocks it dropped to a few inches per hour. The average speeds were 6 to 9 feet per drill-shift. Under similar conditions the 2-inch core drill also used bored 30 to 50 feet.⁴⁷ Although speed of advance was much slower than with the small core drill, the

⁴⁴In 1900 the shot drill was tried in the Southeastern Missouri lead district; about 1904-6 at the Ray copper mine in Arizona; in Minnesota iron mines and in the Tri-State zinc areas in 1911 and 1915. Although encouraging results were reported to have been obtained the churn or diamond drills continued to be preferred in all the districts named.

⁴⁵"Use of the Terry Core Drill in Mine Operations," *Engineering and Mining Journal*, Vol. 89, No. 23 (June 4, 1910), p. 1156.

⁴⁶Michael P. Tierney, "The Calyx Core Drill," *Mining Congress Journal*, Vol. 24, No. 11 (Nov. 1938), pp. 14-9.

⁴⁷"Safeguarding Norris Dam Foundations," *Compressed Air Magazine*, Vol. 39, No. 8 (Aug. 1934), pp. 4501-5. See also Barton M. Jones, "Core Drilling for Visual Examination of Foundation Material," *Transactions of the Third World Power Conference* (1936) (Washington, D. C.: 1938), I, 225-8 and Berlen C. Moneymaker and Portland P. Fox, "Large-Diameter Core Drill for Geologic Exploration," *Mining Technology*, Vol. 2, No. 6 (Nov. 1938), A.I.M.E. Tech. Pub. No. 1000, pp. 3-12.

advantage of being able to directly inspect the foundation-supporting strata in place far outweighed considerations of speed.

A development that may have a great influence upon the future opening of mines is the shaft-size shot drill described on pages 65-6. Although such drills are not used for prospecting, data on their performance can be given advantageously at this point. In 1935-36 a 5-foot hole to be used as an operating shaft was sunk to a depth of 1,125 feet at a California gold mine⁴⁸ and in 1938 a 5½-foot ventilation shaft was bored about 1,200 feet for an iron mine at Ely, Minn. At both shafts the operating crew of the large borer consisted of two men but additional labor is required when hoisting the apparatus or removing core, so that about eight man-shifts were employed per 24-hour day. In California the record for a continuous run was 21 feet in 3 days or 2.3 feet per machine-shift and the best day's run was 10 feet. Before the Minnesota job was undertaken the machine was rebuilt and powered with a 100-horsepower motor in place of the earlier 40-horsepower motor; weight and peripheral speed were increased, and a separate core lifter added. With a nucleus of skilled men from California operating the modified drill a 208-foot advance was made in one uninterrupted 21-day run,⁴⁹ or about 3.3 feet per drill-shift. In California the work and machine were of an experimental nature and the higher speed and larger diameter achieved in Minnesota was a sizable increase in man-shift output. The advantages of a smooth-walled circular opening over the common rough rectangular one, the ability to sink the shaft at least 1,200 feet without interruption for cutting intermediate stations, and the greater safety of drilling were additional considerations in a comparison with conventional shaft-sinking.

The Churn Drill.— Since the first decade of the present century, the churn drill has been widely used as an alternative to the diamond drill for certain types of work. The diamond drill provides but a small core and core recovery may be so little that the principal reliance must be placed upon sludge; since the hole is small and a continuous current of water is required, the collection of a good sample and the correlation of core and sludge are rather difficult. In ground that stands reasonably well and is not too hard the churn drill is very satisfactory for sampling and delineating ore bodies. It works by percussion, and samples are in the form of sludge only. The sample obtained by the usual churn

⁴⁸J. B. Newsom and C. F. Jackson, *Shaft Sinking With a Shot Drill, Idaho Maryland Mine, Grass Valley, Calif.* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 8923, mimeo., Oct. 1936).

⁴⁹B. S. Richards, "Sinking a Ventilation Bore Hole in Minnesota," *Mining Congress Journal*, Vol. 24, No. 10 (Oct. 1938), pp. 28-31. The best month's record in California was 147.5 feet; in Minnesota during July 1938, 240 feet were sunk.

drill is about six times that of the largest and roughly 25 times that of the average diamond-drill hole. Collecting the sample is also somewhat simpler as no more water is used than is needed for effective drilling.

The early extensive use of a power churn drill for prospecting and exploration accompanied the opening of the Mesabi iron range. The type used was an adaptation of the jetting outfit developed about 1884 for water-well boring in unconsolidated deposits.⁵⁰ It was quite satisfactory in soft and loose overburden and ore but unsuitable for hard rock. A diamond drill was then added, and the composite outfit became known as the Mesabi rig. When it was first used the rate of progress was about 6 feet per drill-shift, or even slower than hand work in shallow test pits.⁵¹ There was virtually no change in the outfit itself during the period of its widest use,⁵² and the higher drilling speeds recorded were due largely to increased crew skill. Van Barneveld reported that a good average speed was 8 to 10 feet per drill-shift (combined churn and diamond drilling) including moving and all delays. This was about 3 feet per man-shift, with a range of 1 to 7.⁵³

Another form of churn drill known as the self-cleaning rod type was also used, and about 1914 a modification was introduced which employed larger rods and an annular saw-tooth bit that permitted the recovery of larger fragments than the ordinary drill. It was of special value in sampling the Western Mesabi wash ores and, as less work was expended in crushing the sample so that it might pass through the hollow rods, drilling speed was somewhat increased. The introduction of the standard churn drill in the Lake Superior region in 1912 also acted to increase drill speed per man-shift, since only two men were required instead of three as with the Mesabi outfit.⁵⁴

Churn drills have also been used in prospecting for ores other than iron. About 1898 they were employed in the Joplin (Mo.) zinc-lead district; in 1900 they were tried as a substitute for the diamond drill

⁵⁰Isaiah Bowman, *Well-Drilling Methods* (U. S. Dept. Int., Geological Survey, Water-Supply Paper No. 257, 1911), p. 26.

⁵¹Cf. J. Parke Channing, "Lake Superior Iron Ore," *Mineral Industry: 1894* (New York: The Scientific Publishing Co., 1895), III, p. 402.

⁵²In 1903 there were over 250 such outfits on the Mesabi; roughly 60 percent of the work was done with the churn drill and 40 percent with the diamond drill. The drill crews averaged three men; additional labor was required for sampling, surveying, and other work. In 1911 there were about 400 outfits at work in the Lake Superior district. The drilling usually was done by contractors.

⁵³Charles E. van Barneveld, *Iron Mining in Minnesota* (Univ. of Minn., School of Mines Expt. Sta., Bull. No. 1, 1912), p. 33. Kirby Thomas, "Test Drilling on the Mesabi Iron Range," *Engineering and Mining Journal*, Vol. LXXV, No. 24 (June 13, 1903), p. 896, said that the churn drill would make 10 to 20 feet per day and the diamond drill would drill 5 feet in hard rock.

⁵⁴The standard churn drill was introduced on the Cuyuna Range in 1913. When first used it was claimed to have drilled 140 feet in 48 hours or more than three times the speed of the Mesabi churn as reported by van Barneveld.

in the southeastern Missouri lead area and were used in alluvial-gold prospecting in California; about 1904 they were used for holes 500 to 600 feet deep at a South Carolina gold mine.

Churn drilling is the best method of sampling placer ground by drilling. The use of the drill for this purpose over an extended period has been accompanied by a 50-percent reduction in drilling labor, since many of the machines used only one man. Cutting speeds have also increased and it appears that there has been an over-all advance of about 150 percent in driller output in alluvial prospecting.

The use of churn-drill sampling as the principal basis of estimating the extent and assay value of an ore deposit was commenced in 1908 at Ray Consolidated Copper Co. mine⁵⁵ and the satisfactory results obtained led to an expansion of prospect churn drilling in the western disseminated copper-ore deposits. The average speed for two steam traction drills over a 10-month period in 1912 at Chino was 1.03 feet per hour of total time. Starting bits generally were 8 inches and the holes were about 500 feet deep.⁵⁶ The progress made in two deep holes sunk by steam and gasoline drills in 1930 was reported by H. A. Thorne. The holes were started with 13-inch bits and carried to depths of 945 and 965 feet. The time spent in casing was the same for both holes, and it may be assumed that drilling conditions were essentially alike. The speed of the gasoline-driven drill, excluding moving and casing time, was nearly 38 percent higher than that of the older steam-driven drill. The drilling rate was nearly 1 foot per hour, almost that attained in 1912, despite the fact that the later holes were much larger and nearly twice as deep as the earlier ones.⁵⁷

Important increases in footage attained per driller-shift have been noted in prospect drilling with churn drills in the Wisconsin and Tri-State zinc fields. On the whole, as the holes were smaller and shallower than in copper prospecting and the ground was more easily penetrated, the usual speeds were higher. In 1906 in Wisconsin about 20 feet per day were churn drilled with a $3\frac{1}{2}$ -inch bit in hard rock.⁵⁸ The gasoline-driven

⁵⁵ Edwin Higgins, "Copper Deposits of Globe-Kelvin District - III," *Engineering and Mining Journal*, Vol. 89, No. 17 (Apr. 23, 1910), pp. 870-4. At Utah and Nevada copper mines some prospect work was done with churn drills in 1908-7.

⁵⁶ Donald F. MacDonald and Charles Enzian, *Prospecting and Mining of Copper Ore at Santa Rita, New Mexico* (U. S. Dept. Int., Bur. Mines, Bull. No. 107, 1916), pp. 10, 14.

⁵⁷ H. A. Thorne, *Mining Practice at the Chino Mines, Nevada Consolidated Copper Co., Santa Rita, N. Mex.* (U. S. Dept. Com., Bur. Mines Inf. Cir. No. 6412, mimeo., 1931), pp. 6-8. It is suggested by Thorne that the earlier holes were sunk by "spudding" (drilling with the tool string disconnected from the walking beam), and the deep ones using the walking beam. Spudding usually results in much faster drilling.

⁵⁸ W. F. Boericke and T. H. Garnett, "The Wisconsin Zinc District," *Transactions, A.I.M.E.*, Vol. LXIII (1920), p. 226.

drill was introduced about 1913, and it was reported that a fair daily average for it or the steam drill was about 24 feet. Although the steam drill was still considered sturdier and more reliable it required two men for operation; the gasoline drill needed only one man, although a helper was generally present to assist in removing sludge and to dress bits. About 1919, with $4\frac{1}{4}$ -inch bits speeds of 35 to 40 feet per day were common. This gain of roughly 100 percent in speed per machine-shift was attributed to the use of more powerful drills with longer and heavier tool strings.

About 1900, most prospect holes in the Tri-State zinc-lead mining district were put down with traction steam churn drills. The standard bit was $5\frac{5}{8}$ inches, though holes occasionally were started at 8 inches to allow for a short piece of casing. Reported drill speeds were as low as 1 foot per hour in hard, tough chert and ranged up to 3 feet in ordinary soft limestones. An average performance was between 100 and 200 feet for six 10-hour days,⁵⁹ or about 2.5 feet per hour. The current drilling rate with modern machines that use wire instead of manila rope is about 4 feet per hour with $6\frac{1}{4}$ -inch bits,⁶⁰ an indicated rise in machine output of about 60 percent. Average depth of hole has just about doubled; in 1900, most holes were 150 to 250 feet deep and are now often up to 400.

In prospect churn drilling there has been an increase in footage per driller-shift from about 35 to 100 percent or more for different types of operations. This conclusion probably errs on the conservative side, for it has been assumed that the drill crew (samplers excluded) consisted of two men throughout the period under review. Tool dressing is now often done with mechanical sharpeners at a central shop, some drills are run by one man, and the much higher mobility of the modern truck- or caterpillar-mounted drill has greatly shortened the time used in moving.⁶¹ Although over-all data are lacking, the generalization seems justified that output per driller in churn-drill prospecting has increased approximately 75 percent in the past 35 years.

Blasthole Drilling.—The machines used for blasthole work are of such widely different character and capacities that footage alone does not seem an adequate indicator of changing output per man. As the work performed in drilling varies directly with the volume of hole produced the

⁵⁹Harold A. Titcomb, "Cost of Prospecting by Drilling in Joplin District," *Engineering and Mining Journal*, Vol. LXIX, No. 14 (Apr. 7, 1900), p. 405.

⁶⁰C. W. Nicolson, "Recent Improvements in the Mining Practice of the Tri-State District," *Mineral Technology*, Vol. 2, No. 3 (May 1938), A.I.M.E. Tech. Pub. No. 905, p. 3.

⁶¹Titcomb (*loc. cit.*) stated that to move a nontraction drill a quarter mile and set it up took $2\frac{1}{2}$ to 5 hours with the aid of four to six horses. Under like topographic conditions such a move with a modern machine would be a matter of minutes and would be accomplished without extra help.

hole volume made per driller-time unit may be said to reflect more precisely the driller's capacity to produce.⁶² In addition to data on footage drilled, therefore, the various drills used for blastholes are compared on the basis of volume of hole achieved per driller-shift.

Hand Drilling.— Footage drilled per man-shift with hammer-and-steel was usually higher on the surface than underground largely because on the surface most holes were drilled downward, working conditions were better by daylight, and the effective shift was longer. Average advances in surface work were also faster to some extent because of the large amount of drilling in the softer rocks such as limestone; there is, however, the offsetting factor of depth of hole, which generally was greater on the surface than underground. The speed varied roughly from $1\frac{1}{2}$ to 20 feet per man-shift. The least progress was made in deep holes with a large bit in hard rock and the greatest progress in the small and shallow block-holes in soft rock. It is believed that 5 feet per man-shift was average performance for hand drilling on the surface.

Piston Drilling.— On the surface the usual holes drilled by the piston drill were two to three times the depth of those common underground. This tended to increase speed because a larger part of the shift was spent in drilling and less in moving and setting up the machine. Counterbalancing factors were larger hole diameter and slower advance with increased depth, so that under like conditions piston drilling on the surface was but little faster than underground. On the other hand the piston drill was used much more widely in crushed-stone quarrying, where about three-quarters of the production was limestone and where drilling progress was greater than in open-cut metal mines; estimated average speed should be correspondingly weighted. Some typical speeds ranged from about $1\frac{1}{4}$ feet per hour in hardcapping at United Verde and in some trap-rock quarries, to 10 feet and over per hour in limestone and other soft rocks. A rough average would be slightly more than 6 feet per hour or about 50 feet per drill-shift and 25 feet per man-shift.

Thus, with the piston machine a driller averaged about five times the footage with hammer-and-steel. But, as shown in table 7, the machine holes were about twice the diameter of those hand drilled and the volume of hole excavated per man was about 20 times as great. Judged by this

⁶²Although the theoretical relationship of hole volume and tonnage broken may not hold exactly, in good practice the deviation would not be great and the volume of hole bored per drilling-shift may be assumed to represent approximately the driller's productivity. Thoenen, in summarizing drilling data from some trap-rock quarries, pointed out that the tonnage broken per cubic foot of hole for 2-inch and 6.7-inch holes was nearly the same. Cf. J. R. Thoenen, *Study of Quarry Costs: Trap Rock, Sandstone, Granite* (U. S. Dept. Com., Bur. Mines, Inf. Cir. No. 6291, mimeo., June 1930), p. 10.

standard the machine driller's productivity in surface work was therefore about 20 times that of the manual worker.

Hammer Drilling.— The jackhammer achieves a wide range of speeds not only because of differing characteristics of rocks penetrated but also because it is used for both primary and secondary drilling and often produces 50 to 100 percent more footage in the latter. As is true of other drills it usually accomplishes more in surface work than underground, and 100 feet per shift may be taken for an average. For ordinary blastholes that not infrequently are 20 or more feet deep an average diameter would be about $1\frac{1}{2}$ inches. Output per driller-shift measured in hole volume would be about 45 times that of the hand driller (see table 7).

The drifter is used widely in open-cut work and the greater part of its drilling is in toe holes or approximately horizontal holes about the same diameter as the usual piston-drill hole but somewhat deeper. The speed of drilling ranges from about 2 to 4 feet per drill-hour in hard, dense trap rocks difficult to drill, to about 20 feet in limestones. An average speed is estimated to be about 100 feet per drill-shift or 50 feet per man-shift. This is about double the productivity of piston drilling⁶³ and about 40 times that of hand work.

The modern derrick-mounted drifter is by far the speediest of all drills and can readily drill to about three times the depth of the usual piston-drill holes and to about twice the ordinary depth of drifter-drill holes. Because of greater depth range the holes are somewhat larger and are taken to be about 50 percent greater in cross section than those of the piston drill. These machines are now usually served by one man, though quite often one helper may be assigned to two drills; one and one-half men per drill is considered the average labor requirement. A speed of 25 feet⁶⁴ per drill-hour is taken to be the average performance. One man with a derrick-mounted drifter would accomplish about as much measured by volume as 167 hand drillers or more than eight times as much as with a piston drill.

Churn Drilling.— Unlike the drills previously discussed the churn drill bores only vertical down-holes. The holes are as a rule much larger and deeper than those of other machines and the cutting rate is therefore

⁶³Cases have been noted where the ratio was nearly 4 to 1 while in others little difference in speeds was reported. The figure given above appears representative but probably is conservative.

⁶⁴Remarkable speeds have been reported. One man with a caterpillar-mounted rig averaged 59.6 feet per hour in soft sandstone and shale and had previously drilled 73 10-foot holes in 10 hours. Later with higher air pressure he succeeded in drilling up to 900 feet in 10 hours. The contractor stated that it would have taken five to six jackhammers to do the same amount of work. See "Tractor Mounted Drill Speeds Reservoir Excavation," *Compressed Air Magazine*, Vol. 39, No. 7 (July 1934), p. 4484.

slower. The usual churn-drill bits are 4 to 8 inches in diameter, with $5\frac{5}{8}$ to $6\frac{1}{2}$ inches the most common. Recently the 9-inch size has attained some popularity for blastholes shot without chambering, and the powerful machines that use such bits with very heavy tool strings have shown drilling speeds as high as those reached under favorable conditions with smaller bits.⁶⁵ Some of the later models are operated by one man, and with the variations in rock characteristics and the above differences in practice, drilling speeds range from a few inches to 12 feet or more per man-hour. An average speed is between 4 and 5 feet per drill-hour or about 36 feet per machine-shift. With an assumed average 6-inch hole diameter and a two-man drill the output per driller-shift measured in hole volume would be about 130 times that with the hand drill, about $6\frac{1}{2}$ times that with the piston, and $3\frac{1}{4}$ times that with the drifter.⁶⁶

Table 7.- RELATIVE OUTPUT PER DRILLER-SHIFT
IN BLASTHOLE DRILLING IN OPEN-CUT WORKINGS
AS MEASURED BY VOLUME OF HOLE

Type of drill	Assumed average hole diameter (inches)	Relative cross- sectional area	Assumed average advance per drill- shift (feet)	Relative volume of hole (2)x(3)	Men per drill	Relative output per driller-shift	
						In volume of hole (4)÷(5)	In terms of hand drilling
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Hand	1	1	5	5	1	5	1
Piston	2	4	50	200	2	100	20
Drifter	2	4	100	400	2	200	40
Jackhammer	$1\frac{1}{2}$	2.25	100	225	1	225	45
Churn	6	36	36	1,296	2	648	130
Derrick-mounted drifter	$2\frac{1}{2}$	6.25	200	1,250	$1\frac{1}{2}$	833	167

Summary of Surface Blasthole Drilling Rates.—As already noted the comparison of unit output for widely different types of blasthole drills used in surface work presents a difficult problem. It has been assumed, however, that a rough measure of driller output with different equipment used in surface work is the volume of hole bored per driller-shift. The

⁶⁵For example, at the Nevada Consolidated Copper Co. Mine a 6-inch electric drill advanced 84 feet in 8 hours and at the new open-cut of the Phelps Dodge Corp. at Morenci, Ariz., 100 feet of 9-inch hole were drilled in the same time.

⁶⁶At the time the heavy hammer and churn drills were successfully replacing the piston drill in quarries it was said that "the churn drill has the advantage of doing the work of four or five tripods [piston] or hammer drills with no greater labor than is required for a single tripod." Cf. Oliver Bowles, *Labor Saving at Limestone Quarries* (U. S. Dept. Int., Bur. Mines, Tech. Paper No. 203, 1919), p. 14.

accompanying table presents a comparison prepared on this basis and summarizes the tremendous increase in output per man that power drilling has made possible.

Drilling and Cutting at Dimension-Stone Quarries

The methods employed in quarrying dimension stone involve the cutting of a channel on one or more sides of a block or the use of many rather closely spaced drill holes, wedging, light shooting, or a combination of these methods. To effect separation of the blocks, drills (except the churn), and special machines - the various channelers and the wire saw - are used, and several types are found in most quarries. The volume of drilling or cutting labor required per unit of product is often many times higher than in open-cast mines and general quarries.

The unit of product in dimension-stone quarrying is usually a cubic foot of marketable stone but it is affected by so many variable factors that it has not been thought useful as a measure of drilling and cutting progress. The amount of drilling required per cubic foot of marketable stone varies notably among different kinds of rocks, with the size of block lifted from the quarry or handled in the dressing plant, and particularly with the amount of secondary breaking required. The ratio of usable stone to total material broken is relatively low and fluctuates widely. Bowles says: "It is estimated that not more than 40 per cent of the rock stripped and blocked out in a [limestone] quarry is recovered in usable form", and in the Barre Vermont granites waste "constitutes 80 to 85 per cent of gross production."⁶⁷ For these and other reasons changing output per man in drilling at dimension-stone quarries will be measured in terms of footage drilled, and for the track channeler and wire saw in terms of square feet of groove or cut.

Hand and Ordinary Power Drills.- On the basis of data available it appears that the relative productivity of hand and machine drilling in dimension-stone quarrying was about that of underground mining. In granite quarrying, for instance, about 3.5 feet by hand per man-shift in moderately deep holes was a good day's work. The tripod-mounted piston drill probably averaged about 35 to 40 feet, or $17\frac{1}{2}$ to 20 feet per man-shift, roughly five times that of the hand driller.⁶⁸ At the Ohio quarry for which data were given in table 4 the cost per foot of drilling indicates that productivity with the air piston drill was at least three

⁶⁷ Oliver Bowles, *The Stone Industries* (2d ed.; New York: McGraw-Hill Book Co., Inc., 1939), pp. 64, 155.

⁶⁸ Measured by cubic feet of stone produced, the rate of the productivity in granite quarrying due to the general use of the piston drill was roughly between two and three and one-half times that of hand work. Cf. *Thirteenth Annual Report of the Commissioner of Labor, 1898 (1899)*, II, 1580-5.

times and probably about four times that of hand work, assuming labor accounts for nearly all the cost of hand drilling and probably not over 70 percent of the cost of machine drilling.

In the plug-and-feather holes drilling rates were very much higher than for moderately deep holes. Gillette estimated that in splitting granite a good workman could hand drill about 20 feet of $\frac{5}{8}$ - $\times$ $2\frac{1}{2}$ -inch hole in 8 hours.⁶⁹ With the nonrotating plug drill three to four times as much footage was bored. The jackhammer has been used in drilling "foot-holes" 1 to 2 feet long, as well as relatively deep holes. Much dry drilling has been done with this machine, and the speeds are somewhat lower than with wet drilling, ranging from about 75 feet per shift in granite up to about 250 feet in some limestones. The average footage with the jackhammer was about 20 times that with hammer-and-steel.⁷⁰

The quarry-bar largely displaced the tripod mounting and effected thereby a considerable advance in drilling, for within the bar length - generally about 10 to 12 feet - the drill could be shifted to a new position in a minute or less compared with a minimum of 5 minutes for the tripod mounting.⁷¹ In short-hole work such a saving would easily double the over-all drilling rate. With the quarry-bar it also became possible to cut channels in the hard rocks like granite by broaching. Although this was a slow process it could hardly be accomplished by hand. It was reported that 15 to 20 square feet per shift could be channeled in granite; with the ordinary spacing of holes and a 6-foot channel, this would have required over 50 feet of hole and about as many linear feet of broaching. All in all the piston bar-channeler performed at least double the work that was done with the tripod-mounted piston drill, and about 8 to 10 times that of the hand driller.

The gadder too was an important labor-saving device. It was used principally to bore horizontal holes in vertical or inclined rows and had at least the same efficiency relative to hand work as the tripod-mounted drill.

The drifter drill has generally superseded the piston machine in its various applications. Its drilling speed is double that of the two-man piston machine and as it is now ordinarily a one-man drill, the runner

⁶⁹Gillette, *op. cit.*, p. 544.

⁷⁰In an Alabama marble quarry in 1915 jackhammers averaged 103-113 feet per 10-hour drill-shift. For holes of about the same dimensions 6 feet per man-shift would have been a good day's work by hand. The jackhammer was therefore about 18 times as efficient as the manual driller. Above data from Oliver Bowles, *The Technology of Marble Quarrying* (U. S. Dept. Int., Bur. Mines, Bull. No. 106, 1916), p. 74.

⁷¹Gillette (*op. cit.*, p. 163) estimated not less than 7 minutes under good conditions.

would have a productivity equal to that of about 20 hand workers. The automatic air-feed drifter which cuts even faster than the hand-crank-fed hammer machine is now employed in some quarries.

Channeling Machine.—The power track-channeler that came into use a few years before the piston rock drill represented a major labor-saving improvement. Before 1890 a single-gang machine of the earlier type with two men was said to cut 40 to 80 square feet per day in marble or limestone, and the double-gang machine with three men twice as much. In 1891 Merrill reported that "a good workman by the old hand process would formerly cut from 5 to 10 feet; that is, a groove 1 foot deep and from 5 to 10 feet long per day."⁷² The hand-channeling rates quoted by Merrill appear high when compared with hand-drilling speed. They were probably based on a 12-hour day then not uncommon. In 1884 F. W. Sperr⁷³ reported 3 square feet as an ordinary day's work in Vermont marble. For comparative purposes 5 square feet per man-day has been taken as average. It should be noted that with hand work only shallow grooves were cut but with the machines cuts 12 feet deep could be made. With the earlier single-gang gravity-type channeler average output per man was about six times that of hand work; for the double-gang machine it was roughly eight times that of hand labor.⁷⁴

The direct-acting type of channeler that became important about 1885 had a capacity about double that of the earlier machine.⁷⁵ This two-man steam machine cut in marble 6 to 15 square feet per hour and averaged about 8.5. In moderately hard limestones, the rate was much faster.⁷⁶ The modern electric and electric air-channelers average about 10 square feet per hour and are usually run by one man although considerable extra labor is needed for moving. Generalizing where conditions vary widely,

⁷²George P. Merrill, *Stones for Building and Decoration* (New York: John Wiley & Sons, 1891), p. 338.

⁷³*Tenth Census of the United States: 1880*, Vol. X, "Special Reports on Petroleum, Coke, and Building Stones" (U. S. Dept. Int., Census Office, 1884), "Building Stones of the United States," p. 36.

⁷⁴These seem to be conservative estimates for it was claimed that an early, double-gang Wardwell channeler which could cut up to 8 feet deep could do the work of 40 men. See "Improved Stone Quarrying Machine," *American Journal of Mining*, Vol. I, No. 4 (Apr. 21, 1866), p. 49. In 1889 it was claimed that the three-man, double-gang machine would channel 75 to 150 square feet in marble and 150 to 400 in limestone and sandstone, "which is equivalent to the work of fifty men" and that its use had reduced the cost of block stone by nearly one-half. See "The Wardwell Stone Channeling and Quarrying Machine," *Engineering and Mining Journal*, Vol. XLVII, No. 22 (June 1, 1889), p. 500.

⁷⁵Merrill, *op. cit.*, pp. 337-9.

⁷⁶On the Chicago Drainage Canal (1893), 12- to 15-foot cuts were made in irregular hard and sometimes flinty limestones. An average speed of 121 square feet per 10-hour day and a maximum of 300 square feet were attained. Cf. "Chicago Main Drainage Channel - XV," *Engineering News and American Railway Journal*, Vol. XXXIV, No. 9 (Aug. 29, 1895), pp. 133-4. In soft limestone at a Middle Western quarry records of 400 square feet in 5 hours and 750 square feet in 10 hours in cuts 6 to 12 feet deep have been reported. See Samuel Calvin, "The Cedar Valley Quarry," *Engineering and Mining Journal*, Vol. LXI, No. 23 (June 6, 1896), p. 544.

it is believed that the productivity per man-shift with the direct-acting channeler has been not less than double that of the early machine described in the preceding paragraph.

Wire Saw.—Where suitable the wire saw has proved many times more productive than the channeler and its use has increased notably in the past decade and a half. For many years the removal of the primary blocks was entirely a hand operation involving much drilling and light shooting, with consequent enormous waste. Both the bar- and track-type channelers were great improvements, but the "stunning" effect of the percussive cutting caused excessive waste. That source of loss has been eliminated by the wire saw and a further gain made in that the kerf is little more than one-quarter inch compared with about 2 inches for the channeler.⁷⁷

The first tests of the wire saw in slate quarrying were made under unfavorable conditions and the saw cut less than 10 square feet per hour. After some experience the rate rose to 12.8 square feet with a maximum of 20. In "hard-vein" slate too hard for channeling, 11.4 square feet per hour was reached. By the end of 1928, when 27 saws were in use, the average hourly rate was 20 to 25 square feet, with a maximum of 34.⁷⁸ Bowles cited cases where the output of the wire saw was about four to five times that of the channeler; and since fewer men were required to run the saw and do the necessary shot-drill hole boring the productivity was about six times that with the channeler. At one quarry the rate of cutting with a saw was reported to be about 25 square feet per hour and that of the channeler about 4 square feet. The channeler, however, was a two-man machine, and a blacksmith and helper were constantly employed to sharpen bits for six channelers. Two men handled two wire saws and did the necessary core drilling and no blacksmithing was required. Thus the output per man with the wire saw was more than 12 times that with a channeler.⁷⁹

The pronounced success of the wire saw in slate quarries led to applications in the Indiana limestone region. Tests made in 1931 showed that the use of the wire saw reduced losses which had been over 30 percent to about 20 percent, a reduction of about one-third. Of about 1.5 million cubic feet of limestone quarried by channeling only 1 million were salable; that is, the direct and indirect losses attributable to channeling and wedging amounted to 30.5 percent and use of the wire saw would cut

⁷⁷Bowles (*The Stone Industries*, p. 280) says that "various operators estimate a saving of 30 to 50 per cent."

⁷⁸Oliver Bowles, *The Wire Saw in Slate Quarrying* (U. S. Dept. Com., Bur. Mines, Tech. Paper No. 469, 1930), pp. 15-8.

⁷⁹Oliver Bowles, "The Wire Saw as a Tool for Cutting Slate and Building Stone," *Transactions, A.I.M.E.*, Vol. 129 (1939), pp. 56-8.

the loss to 20 percent. Based on 1930 production it was equivalent to a saving of \$720,000 to the Indiana limestone producers.⁸⁰

Although the wire saw is being applied in marble and sandstone quarrying, little information regarding performance is available. In a few instances reported, the sawing rate in marble was about 3 to 10 square feet per hour or roughly that of channeling. It is believed that the future trend will be toward wider acceptance of the wire saw and that higher output per man would follow this development.

The character of the data for dimension-stone quarrying permits only the broadest generalizations concerning the effect of a changing drilling- and cutting-machine technology upon output per man-shift. As already noted, the power drill, which is employed in one form or another in nearly all quarries, had an effect comparable to that in underground mining. Comparisons of hand and machine channeling are difficult to make since the same work could hardly be performed by hand, but the output of channeled surface per man can be roughly estimated to be 15 times as great with the direct-acting machine as by hand. Under suitable conditions the wire saw was several times as productive as the channeler.

⁸⁰J. B. Newsom, "Quarry Waste in the Indiana Limestone District," *Transactions, A.I.M.E.*, Vol. 102 (1932), p. 115.

CHAPTER VI

ROCK-DRILLING PROGRESS AND EMPLOYMENT IN MINING

The adoption of and subsequent improvements in drilling machines and techniques have been among the most important of the various types of technological change in mining, and have been a major factor in the increased production of minerals at relatively lower cost and in the increased productivity of mine labor.

In the latter half of the nineteenth century numerous efforts were made by individual inventors and technicians to develop mechanical substitutes for the arduous work of hand rock drilling which at all types of mines and quarries consumed an enormous amount of labor time and bulked large in the operating costs. Beginning with the introduction of the piston drill about 1865, various new mechanical devices gave promise of reducing the costs of breaking rock. However, the transition from hand to mechanical drilling was a slow process. The success of early machines was limited not only by the prevailing general level of machine technology but also by a host of special problems inherent in underground work and in the wide variety of resource conditions encountered in the extraction of different minerals, at different operations, or even within a single mine or quarry.

GENERAL CHARACTER OF TECHNOLOGICAL ADVANCE IN ROCK DRILLING

The first important step in mechanization was the invention of the piston drill and its adoption for underground work, but 20 years passed before it came into wide use. General acceptance of other early machines, such as the diamond and churn drills for surface mining and prospecting, also required long periods of time. But once the early machines had been improved on the basis of experimentation and the advantages of mechanization had been recognized, later power drills were more quickly taken up and the use of drilling machines spread to all parts of the mineral industry.

For over a quarter century the piston drill was the only drill used underground, but it did not fully meet the requirements of mine work. The invention of the drifter hammer drill, which replaced the piston drill, was an important forward step. It separated the hammer from the piston and allowed higher operating speeds and faster drilling. The stoper, specially designed for up-hole work, and the jackhammer were also developed. The jackhammer proved to be the most flexible and adaptable of

all drills for down-hole work, and its use spread to all branches of mining and from underground workings to open-cut metal mines and quarries. Other types of drills also began to be used: the diamond drill for prospecting and for gadding and channeling in dimension-stone quarries, the track- and bar-channelers and the wire saw also in dimension-stone quarries, and the calyx drill for exploratory work and shaft-sinking.

The first mechanical drills were powered by steam, but compressed air was available early and was generally utilized to run the drills. There has been a constant tendency toward the use of higher air pressures as the compressors were improved in design and capacity and sources of power loss sought out and eliminated. The auger, the churn and calyx drills, the track-channelers, and wire saw were adapted to motivation by electricity, but compressed air remains much the most important source of power for drilling or cutting and often is used even where other operations have been electrified.

All the machines have advanced in design and construction. Valves, feed and rotation mechanisms have been improved, cast-iron has been replaced by steel as a material for the manufacture of drills, and alloys have been developed for use in the moving parts. Better methods of heat-treating, hardening, and tempering steel have been evolved, usable hollow steels have been developed, advances have been made in sharpening, designs and shapes of bits have been improved, and the detachable bit has resulted in considerable saving of both labor time and drill steel. Drills have been made lighter and easier to operate, and improved rigs, mountings, and traction devices have made the drills easier to set up and to move from one place to another. All these changes have resulted in greater drilling efficiency and with it greater productivity of drilling labor.

The advance of drilling technology has been conditioned by and in turn has influenced developments in the other major mining operations such as blasting, loading, and transporting ore. For example, in open-cut mining the increased depth to which holes can practicably be drilled has made possible the adoption of greater bench heights with consequent larger individual blasts and less frequent interruptions of loading operations, while increased capacity of loading and hauling equipment has made possible the handling of larger rock fragments so that fewer drill holes are needed to shatter a given volume of overburden or ore. Thus changing technology on other operations has served to increase the productivity of drilling labor, and progress in drilling techniques has contributed both directly and indirectly to the rising productivity of mine labor in general.

VOLUME OF EMPLOYMENT

The effect of technological progress in rock drilling upon the volume of employment in mineral exploitation also cannot be readily disassociated from the effects of other closely related factors, and the trend of employment in mining¹ is a net result of many economic, technological, and resource variables. The extent to which drilling progress may have been important in determining the course of the trend can be judged only roughly and qualitatively. In view of the increased productivity and the examples of large labor saving reported in previous chapters as accompanying the improvement of drilling techniques, this statement may appear surprising at first glance. It was indicated, for example, that some power drills could perform more than 150 times as much work as the manual worker and that machines commonly and widely used could perform 20 to 40 times as much. Thus it would appear that, with a constant volume of production and all other things remaining equal, the displacement of labor would have been of high order. The facts are, however, that production multiplied at a phenomenal rate, that other very important changes in mining methods and techniques took place, and that part of the reduction in labor requirements achieved by technical progress - including that in drilling - was offset by increasing physical difficulties resulting from the peculiar depletive character of mining. These factors overshadowed the effect of drilling progress upon employment during the larger part of the past half century.

It is noteworthy that almost all the major types of mechanical rock drills were invented and adopted before the World War (see tables 1 and 2) and had been in use for a considerable period before over-all employment in mining started to decline. From 1880 to 1909, when the basic changes in rock drilling were made and major labor saving was achieved, mine production expanded at such a remarkable rate that there was a net gain in employment.² From 1909 to 1919, the date of the next census, there was only a small net change in over-all employment at mines and quarries. Notable increases in production from 1919 to 1929 were accompanied by declining employment, particularly in metal mining where the drilling techniques discussed herein were of special importance. From 1929 to

¹Generalization regarding broad changes in employment is based on over-all data available only for the decennial census periods; partial information available from other sources on an annual basis indicates that employment at mines and quarries reached a peak in 1917 during the height of wartime demand. For a summary table of decennial employment in mining see O. E. Kiessling and Others, *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-10, July 1939), p. 316.

²F. G. Tryon, T. T. Read, and Others, *Technology and the Mineral Industries* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-1, Apr. 1937), chart 2, facing p. 4.

1935 this tendency was even more pronounced and has been important both for metals and industrial nonmetals.³ Although the data collected by the Censuses of Mines and Quarries on various occupations present many difficulties from a statistical viewpoint, they do provide broad landmarks to show that the number of men employed underground either in drilling or in occupations closely related to drilling reached a peak about 1909 for iron and the principal nonferrous metals and that the trend thereafter has been generally downward.⁴

Although labor saving achieved by continued advances in rock drilling doubtless has been a factor in the general downward trend of mine employment since 1919, its influence in this respect has been relatively small in comparison with other forces. Notable among these have been the pronounced shift to open-cast mining, wherever this method could be economically employed, and the rapid expansion of mechanical loading.⁵ Discussion of such major developments is beyond the scope of this report, but it is appropriate to note that surface mining permitted major economies in unit labor requirements both in drilling and over-all mining and that mechanical loading generally achieved significant labor savings over hand methods.

The foregoing generalizations have been made with reference to drilling in actual mining and do not include prospect drilling. Because data are lacking, broad conclusions are not possible as to the effect of technical progress in this field upon employment opportunities. Except for a few short periods, however, total employment for prospect drilling has never been great. Here too technical progress appreciably decreased man-hour requirements per foot of hole, but this was offset in part, if not entirely, by the larger volume of prospect drilling that could be done because of lower costs or that was made necessary by large-scale operations. The economic significance of the art of subsurface exploratory boring lies largely in the knowledge it furnishes of potential additions to our mineral wealth rather than in the volume of employment it provides.

³Kiessling and Others, *op. cit.*, p. 316.

⁴The occupational classification considered in this generalization includes men reported as "miners, drillers, and their helpers" by the Censuses of Mines and Quarries. See *Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, Bur. Census, 1905), pp. 426, 463, 504-5, 584; *Thirteenth Census of the United States: 1910*, Vol. XI, "Mines and Quarries: 1909" (U. S. Dept. Com., Bur. Census, 1913), p. 29; and *Fourteenth Census of the United States: 1920*, Vol. XI, "Mines and Quarries: 1919" (U. S. Dept. Com., Bur. Census, 1922), p. 34. This comparison, of course, does not take into account the shift to open-cut and caving methods of mining that affected the number of underground workers after 1909. The nonferrous metals as included here are copper, lead, and zinc.

⁵L. N. Plein, F. E. Berquist, and F. G. Tryon, *Mechanization Trends in Metal and Nonmetal Mining as Indicated by Sales of Underground Loading Equipment* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-3, June 1937), pp. 5-13.

The depletive character of the mining industry complicates analysis of the role of a specific technical advance such as the mechanization of drilling in changing employment opportunities. For this reason a relatively short-time view of changing employment may suggest different conclusions than would a view in terms of a long-time typical depletive cycle.⁶ In numerous particular instances technological advances in drilling have displaced mine labor or have permitted expansion of output that otherwise would have been produced with a larger drilling labor force. However, both at individual operations and over entire branches of mining part of the gains of technology has been absorbed by growing natural handicaps, such as increased depth, rock pressures, and heat and humidity. Along with the declining grade of ore they presented formidable obstacles that had to be overcome before net gains in unit output could be achieved. The need for surmounting such growing physical difficulties accompanies a developing mineral industry. Today, for example, approximately one-half of the Nation's copper production comes from deposits that were known in 1900 but were then considered valueless because of their low metal content.⁷

The forces of depletion present a perennial challenge to the mineral technologist, for in general over any extended period successively larger volumes of work must be performed to obtain a unit of product. This can be done only by lowering costs (unless prices of the products are to be notably increased); rock-drilling progress has been part of the large-scale mining and handling techniques that have been developed for this purpose and have provided increased abundance in mineral supplies at generally lower prices⁸ in spite of the difficulties noted. These techniques both "created" employment by rejuvenating mineral enterprises or industries that would otherwise have declined or ceased entirely and "reduced" employment because of the lower unit labor requirements. Over the relatively short span of the past two decades the forces curtailing required manpower because of over-all technical progress in mining have outweighed those making for employment expansion.

CHANGING OCCUPATIONS AND SKILLS

In addition to its influence on the volume of employment rock-drilling progress altered the relative importance of certain occupations and of

⁶D. F. Hewett, "Cycles of Mineral Production: Youth, Maturity, and Old Age," *Mineral Economics: Lectures Under the Auspices of the Brookings Institution* (1st ed.; New York: McGraw-Hill Book Co., Inc., 1932), pp. 62-90.

⁷A. V. Corry and O. E. Kiessling, *Mineral Technology and Output per Man Studies: Grade of Ore* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-8, Aug. 1938), p. 84.

⁸Tryon, Read, and Others, *loc. cit.*

certain types of skills required in mining. It reduced the proportion of the mine labor force engaged entirely or in part in drilling and greatly changed the character of the drilling job itself.

Relative Decline of Drilling Labor

The change in the proportion of the mine labor force engaged in drilling is illustrated by Michigan and Montana copper mines. In his study of Michigan copper mining made as of 1876, Professor Egleston showed that about two-thirds of the underground workers at a large mine were engaged in "mining."⁹ This may be broadly assumed as the approximate proportion of underground men engaged in drilling and blasting in the days of hand work at Michigan copper mines and as also representative of the proportion so employed under similar conditions at other underground hard-rock mines. For those unfamiliar with American mining history it should be noted that persons working as "miners" in 1876 spent the major portion of their time in hand drilling and that the number of power rock drills in use in the Michigan area was negligible. These conclusions appear conservative when compared with data on occupations reported by the Census of 1880, which showed that more than 75 percent of the underground workers at Michigan copper mines were engaged in drilling and blasting.¹⁰ By 1931, however, workers engaged primarily in drilling and blasting comprised about one-third of the underground workers in Michigan copper mines.¹¹

Copper mining in Montana affords another example of the shift in types of jobs. When the production began to rise rapidly at the Butte mines in the last decade of the nineteenth century the piston drill was already in wide use. By 1902, 710 of the 900 power drills employed at the country's copper mines were in use in Montana.¹² In the same year, 4,522 of the 5,196 underground workers were reported as "miners and helpers."¹³ To

⁹T. Egleston, "Copper Mining on Lake Superior," *Transactions of the American Institute of Mining Engineers*, Vol. VI (1879), pp. 275-312.

¹⁰The Census of 1880 reported 2,076 miners out of 2,832 men and boys underground at Michigan copper mines, or nearly 79 percent of the underground workers in the miner category (*Tenth Census of the United States: 1880*, Vol. XV, "Report on the Mining Industries" [U. S. Dept. Int., Census Office, 1886], p. 798). This proportion is believed to be high because the census doubtless classified as miners the underground workers engaged in development work, and these men did a relatively large amount of mucking, tramping, and timbering in addition to hand drilling. On the other hand, the use of the piston drill had expanded between 1876 and 1880 but hand drilling was still used for most work.

¹¹For data utilized by the authors in this determination see *Wages and Hours of Labor in Metalliferous Mines, 1924 and 1931* (U. S. Dept. Labor, Bur. Labor Statistics, Bull. No. 573, Jan. 1933), pp. 19-35.

¹²Excluding Michigan, Nevada, Virginia, and Wisconsin, see *Special Reports of the Census Office, "Mines and Quarries: 1902,"* table 12, p. 477. Almost all the copper production of Montana has come from the Butte or Summit Valley district, and Montana contributed 28 percent of the country's copper production (Corry and Klessling, *op. cit.*, p. 39).

¹³*Special Reports of the Census Office, "Mines and Quarries: 1902,"* p. 505.

a larger extent than in Michigan, however, "miners" in Montana performed other tasks than drilling, especially as a large amount of timbering was required by the square-set stoping method of mining employed.¹⁴ Nevertheless, the 710 drills reported provide a good criterion of the number of men chargeable to drilling. Since two men were employed on each drill and two shifts per day were the rule and assuming that each drill was serviceable and worked throughout the day, it appears that approximately 2,840 drillers and helpers were on the pay roll. This figure probably overstates somewhat driller employment in regular mining, but special work (such as shaft-sinking) was occasionally done on a three-shift basis and a certain amount of additional drilling was done by hand. Recognizing the inadequacies of the data, drillers and their helpers may be taken to have comprised somewhat more than 50 percent of the men working underground at Butte in 1902. In 1931, drillers, helpers, and drill-tool packers comprised about 32 percent of the underground wage earners in Montana.¹⁵

It should be noted that declining employment in drilling is not necessarily an accompaniment of a reduction in the proportion of the underground labor force engaged in drilling. Although the proportion of men that performed drilling at the working face has dropped notably, the workers so engaged have drilled progressively greater footages and have broken successively larger tonnages with the aid of greatly improved power rock drills. The rising volume of material handled has required notable expansion of loading, haulage, hoisting, and milling facilities.

Changing Skills

How drill mechanization changed the character of the driller's job can be illustrated by noting briefly essential features of manual drilling methods and of machine drilling.

Drilling by the hand methods described in chapter II was a hard and tedious task. Considerable skill was required, moreover, to achieve effective results. It was necessary that the driller have enough knowledge of rock characteristics and fractures to be able to space and point the holes so as to obtain the maximum tonnage with a minimum of drilling. The individual worker exercised a wide range of judgment to take advantage of every possible natural aid. In addition the driller had to know something about explosives and how to load and fire holes, for he

¹⁴For a detailed description of various mining methods employed in exploiting copper deposits, see Y. S. Leong and Others, *Technology, Employment, and Output per Man in Copper Mining* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-12, in press).

¹⁵*Wages and Hours of Labor in Metalliferous Mines, 1924 and 1931*, pp. 19-35.

was usually charged for the powder used. Likewise, he was frequently charged for steel sharpening and steel breakage and so became adept at judging the proper hardness and shape of bit best suited to the rock. The skill and physical strength required in hand drilling varied with the type of drill used and with the nature of the rock being drilled.

Hand churn drilling particularly was exhausting work. By far the greater part of the day was occupied by simple physical effort - raising and dropping or thrusting down a heavy steel bar. For this work the driller needed much strength and resistance to fatigue but relatively little skill.

Physical strength was also the chief prerequisite for drilling with the hand auger. Its use in the softer rocks and the mechanical advantage of a crank considerably increased the driller's capacity for work,¹⁶ but he had to lean heavily against the drill while he turned it with one hand. Other types with both double and single cranks afforded support for the drill and some had a feed bar that forced the bit ahead. Some skill was of course necessary in placing the holes to best advantage, but the rocks usually bored were not only softer but more homogeneous than those ordinarily found in hard-rock mining, and skill was not so important as in drilling hard rock.

Manual hammer drilling was almost the sole method employed for perforating hard rock in the early days of metal mining and in most of the dimension-stone quarrying. The use of the hammer-and-steel demanded physical strength, coordination, endurance, and a high degree of skill. Hard rock connotes slow drilling, moreover, and the driller had to husband his strength to last out the shift. Sheer physical force was not enough because each blow had to be struck with the proper amount of force - lightly when starting a hole and harder when it was collared. The blows were also adjusted to the nature of the rock. The steel had to be turned just the proper amount to prevent the formation of a shoulder and to keep the hole round and true, while the bit had to be held solidly at rest on the rock face just at the moment of hammer impact. This was especially difficult in drilling an upper. To break the greatest quantity of ground the hole was pointed to start a fracture along inherent planes of weakness or along predetermined lines. The experienced driller was expected

¹⁶W. R. Hulbert, "Methods of Hand-Drilling," *Mining and Scientific Press*, Vol. XCII, No. 19 (May 12, 1906), p. 310 cites Rankine as authority for the statement that a man using a hammer could develop about 480,000 foot-pounds per day; by turning a crank, as on a winch or windlass, he could develop about 1,296,000 foot-pounds. A medium-sized power drill strikes a blow of about 50 foot-pounds. Drilling 3 hours per shift, such a drill would develop about 18 million foot-pounds. In other words, in 4 to 5 minutes the power drill could do as much work as one hammerman in a day.



FIGURE 25.- A WESTERN HAND-DRILLING CONTEST

The hand driller had to have great skill and strength. Such a contest as that shown above was a fine exhibition of muscular coordination, machine-like precision of movement, and extraordinary teamwork.

The two-man team is double-jack drilling the block of rock shown below the platform. The kneeling partner has just placed a fresh steel in the hole and the dulled steel - approximately 3 feet long - which he has just thrown out may be seen still in the air just above his head. This change of steel was made without any alteration of the striker's rhythm.

to be able to drill in any direction and from various postures; the better drillers were able to work ambidextrously. The necessary skill, rhythm, and muscular coordination were developed only after long training. These characteristics were well-exemplified by participants in the hand-drilling contests that were once the high spots of miners' holiday celebrations. During such feats the steel was changed frequently without interrupting the striking, as described in the following passage:

Changing steel every minute is a man's job. To throw a long piece of steel from the hole and to place the next and longer one in it while the hammerman is raising his hammer requires strength, skill, coolness, and extremely fast action, especially when the striker is swinging at the rate of as many as 85 or 90 blows per minute. Yet the hammerman does not break his rhythm and if one were not looking, it would be impossible by timing the blows to tell when the change is made. The used steel flashes into the air, and the one replacing it is smacked to the bottom of the hole a split second before the hammer descends on it.¹⁷

¹⁷Allen S. Parks, "Super Hammermen," *Compressed Air Magazine*, Vol. 43, No. 1 (Jan. 1938), p. 5504.

The early machines did lighten the operator's labor and relieve the tedium of his task, but brawn was still essential because the drills and mountings were extremely heavy and awkward to handle. At the same time the driller had to learn new skills. He had a powerful machine to control and had to judge the cutting efficiency by the sound of the blow and the exhaust and by the feel of his hand on the feed-screw crank. He had to devise minor arrangements - such as the use of small pieces of scrap iron in the hole - to keep the drill from fitchering. The cumbersomeness of the drill often made it impossible to place the holes in the most efficient position. Thus, somewhat standardized "rounds" were drilled in which the holes were bored with a general regularity of spacing and inclination best suited to the machine at hand and with less reference to rock characteristics than in hand drilling. The driller also became something of a mechanic. The early drills particularly were structurally weak, and the operator was called upon to make many repairs, frequently with whatever materials and tools were at hand.

With machines like the churn and diamond drills, some sensory perceptions had to be modified or developed. The shift from the spring-pole to the power churn drill did not require a major adjustment, for the driller had already learned to drill "on the spring of the rope." With the speedier power machine, however, he had to sense changes more quickly, and with the substitution of steel for manila ropes and the corresponding difference in elasticity the senses had to be more alert. The rate of advance or speed of rotation with the diamond drill was governed by noting the pressure on the rods, by the sound of the engine or pump exhaust, and by the feel of the drill rods as they turned in his hand. There were many problems in deep-hole drilling that required special knowledge and skills; rope or rods broke, bits stuck, and holes deviated from the desired direction. Ingenious devices and techniques were designed to recover tools, to survey the holes, and to control direction. Thus the deep-hole driller became a highly skilled specialist.

With the development of better drills and cutting tools, structural weaknesses were notably reduced and weight decreased. At present the drill runner seldom is permitted to make any repairs, and he need see only that the air and water lines are free and clean and that the machine is lubricated. Physical labor also is reduced by the use of automatic-feed drifters and self-supporting automatic-rotation stopers. In some work, such as drifting and crosscutting, machines may be mounted on drill carriages so that setting up and tearing down the drill is unnecessary. The pointing and loading of holes are often prescribed, and at some mines

a period of intensive instruction with close supervision under operating conditions is required before even experienced men are put to work breaking ground. The modern drill runner is a specialist skilled in getting the maximum footage. He must be alert and have quick reaction time and sufficient intelligence to understand and obey orders. He need not have the physical strength and endurance of his hand-drilling prototype and is generally younger.

HEALTH AND SAFETY

Of the various occupations in mines, that of miners whose principal functions are drilling and blasting is probably the most exposed to the accident and health hazards characteristic of mining. These fall into three general classes: accidents that cause physical injury or death, working conditions that adversely affect physical well-being, and occupational diseases.



FIGURE 26.— DRILLING IN CRAMPED QUARTERS WITH A WET STOPER
The hazards of rock drilling are increased when work is done in restricted space and under difficult conditions.

Accidents are an ever-present possibility for the miner. As a rule he is the first to enter the working place, which he has to make safe for himself and others by barring down loose rock or by placing supports to hold up threatening blocks too large and tightly wedged to be readily and safely moved or to restrain ground that might cave if left unsupported. He has to set up the drilling machine and to handle the needed steel and

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tools. When the requisite number of holes are drilled he tears down the drill and moves it with the water and air hoses, tools, and steel away from the working face. He then loads the holes with high explosives and fires them. From a nearby point of safety the miner counts the shots so that he can report a "missed hole" to the miner on the following shift who might otherwise drill into the explosive and be killed or seriously injured. These tasks are performed by artificial light, usually in cramped quarters, with the worker's ability to sense dangers reduced by the noise of the sharp exhaust of the drill and the clank of steel on rock.

The operation of the machine, the handling of machine equipment, and the inability of the driller to perceive dangers due to noise increased risks for the machine driller but they have been generally offset by greater vigilance and protection against them. Extensive statistical series on injuries and fatalities are not available for individual occupations, but for the 5 years 1931-35 there were about $2\frac{1}{2}$ fatalities and approximately 150 nonfatal accidents per thousand 300-day workers in metal and nonmetallic mineral mines in contrast with about $3\frac{1}{2}$ fatalities and approximately 240 nonfatal accidents on the same comparative basis for the half decade 1916-20.¹⁸ Over the same period the injury and fatality rate in quarries and related activities also showed notable decline.¹⁹

Up to the time the rock drill came into widespread use, high temperatures²⁰ and humidities were found only in exceptional mines because men could not efficiently perform hard physical labor under such conditions.²¹ The power rock drill, however, made work economically possible where drilling could not have been done by hand, but mining with power equipment where temperatures and humidities were excessive went on for a considerable period without adequate provision for ventilation.²²

¹⁸W. W. Adams and M. E. Kolhos, *Metal-Mine Accidents in the United States During the Calendar Year 1936* (U. S. Dept. Int., Bur. Mines, Bull. No. 422, 1939), p. 52.

¹⁹William W. Adams and Virginia E. Wrenn, *Quarry Accidents in the United States During the Calendar Year 1936* (U. S. Dept. Int., Bur. Mines, Bull. No. 416, 1938), p. 61.

²⁰Rock temperatures ordinarily increase about 1° F. for each 70 to 100 feet below the surface.

²¹The Comstock lode was an exception and relatively rich ores were mined by hand under conditions of excessive temperatures and humidities; these were due to the infiltration of large quantities of very hot underground waters rather than to increased depth. John A. Church reported that during 1878 at least eight deaths in Comstock mines were due to heat exhaustion following exposure to high temperatures and to scalding. He also believed that many fatal and nonfatal accidents were indirectly caused by weakness brought about by exposure to high temperatures and humidities. See John A. Church, "Accidents in the Comstock Mines and Their Relation to Deep Mining," *Transactions, A.I.M.E.*, Vol. VIII (1880), pp. 85, 87-90 and John A. Church, "The Heat of the Comstock Mines," *Transactions, A.I.M.E.*, Vol. VII (1879), pp. 45-76.

²²The power drill itself was an aid to ventilation in that the exhaust air noticeably reduced the working temperature in the vicinity of the drill. Effective ventilation, however, required additional facilities.

In a study made of Butte as late as 1916-18, Harrington concluded that "a 30 per cent loss of efficiency, due to defective mine ventilation, among men working underground is probably a conservative estimate" ²³ There is no formula for translating "efficiency" into human values but there are strong indications that continued exposure to high temperatures and humidities may shorten the useful life of the worker. Reporting on studies made in coal mines of the Saar and Upper Silesia, Dr. R. R. Sayers of the U. S. Public Health Service and Sara J. Davenport said that "it was found that, while subjective and objective sicknesses could not be determined and the capacity for work was not lowered, the total incapacity of the workers in coal mines, where the humidity is greater than in other mines, begins at 45 years of age, nine years earlier than with other miners." ²⁴

More serious than the risk of accident or of poor health because of high temperatures and humidities is the danger that the driller might contract pneumoconiosis. This general term is used here to denote the respiratory diseases caused by deposits of dusts in the lungs and which are common among miners. Some typical manifestations are silicosis, caused by siliceous particles, and asbestosis caused by breathing in fine asbestos particles.

These occupational diseases of the miner were not a product of machine mining. The prevalence of such diseases among miners has been recognized for centuries; and references are frequently found in the literature on mining to "miners' cough", "miners' asthma", "miners' phthisis", and "miners' consumption." Agricola in his *De Re Metallica*, published in 1556, said "the miners are sometimes killed by the pestilential air which they breathe; sometimes their lungs rot away." ²⁵ Numerous instances indicate that pulmonary diseases due to rock dust were common in the United States in the days of hand mining. An example of the occurrence of silicosis among quarrymen about 1880, when hand methods of drilling were the rule, was noted by the Census Report for that year as follows: "The work

²³Daniel Harrington, *Underground Ventilation at Butte* (U. S. Dept. Int., Bur. Mines, Bull. No. 204, 1923), p. 117.

²⁴R. R. Sayers and Sara J. Davenport, *Review of Literature on the Physiological Effects of Abnormal Temperatures and Humidities* (Reprint No. 1150 from *Public Health Reports*; U. S. Treasury Dept., Public Health Service, 1927), p. 16.

²⁵Agricola also states, "Some mines are so dry that they are entirely devoid of water, and this dryness causes the workmen even greater harm, for the dust which is stirred and beaten up by digging penetrates into the windpipe and lungs, and produces difficulty in breathing, and the disease which the Greeks call asthma. If the dust has corrosive qualities, it eats away the lungs, and implants consumption in the body; hence in the mines of the Carpathian Mountains women are found who have married seven husbands, all of whom this terrible consumption has carried off to a premature death." Georgius Agricola, *De Re Metallica* (translated from first Latin edition, 1556, by Herbert Clark Hoover and Lou Henry Hoover [London: *The Mining Magazine*, 1912]), pp. 6, 214.

of channeling with picks and shovels is very injurious to the health of the workmen on account of the sand-dust inhaled into the lungs."²⁶

Although respiratory diseases were reasonably common among miners before the advent of mechanical drilling, the use of drilling machines, at least up to about 1915 - and in some areas thereafter - greatly increased the prevalence and seriousness of those diseases. The early piston and hammer drills drilled many times faster than the hand worker and made larger holes that were the source of a larger volume of fine dust and cuttings. There frequently was little air movement close to the working face and dust concentrations remained high in the working places. Although some drilling was done with water to settle the dust even when the piston drills were used, there were instances where water could not be used or was not easily available; the early mines were first piped for compressed air and later for water. In some instances, also, the mixture of water and cuttings dropped on the driller and he frequently preferred to "drill dry and eat the dust." Rules requiring wet drilling were generally disregarded and infractions were conveniently overlooked as long as the tonnage output was satisfactory. The hammer drill bored more rapidly than the piston drill and increased the dust hazard when dry drilling was practiced, but this was offset largely by the more rigorous enforcement of wet-drilling regulations. Even where wet drilling was the practice, however, the driller frequently started the holes dry and often drilled without water for a few inches.

It was not until the second decade of the present century that authentic information was available regarding the high incidence of silicosis among miners. Examination of 720 miners in 1915 in the Joplin (Mo.) zinc-lead mining district, where most of the drilling was in highly siliceous rock, indicated that 46 percent had silicosis and tuberculosis and 5 percent had tuberculosis. Forty-two percent of 1,018 miners examined in Butte in 1921 showed definite signs of lung impairment due to dust; examination of 303 gold miners in Nevada in the same year disclosed that 80 percent had silicosis.²⁷ It is estimated that roughly one-fifth to over a third of the miners in typical hard-rock mining camps 20 years ago were afflicted with silicosis.

²⁶Tenth Census of the United States: 1880, Vol. X, "Special Reports on Petroleum, Coke, and Building Stones" (U. S. Dept. Int., Census Office, 1884), "Building Stones of the United States," p. 37. The same report also noted (p. 25) that "the cutting of such stones often subjects the workmen to serious inconvenience on account of a sharp and very fine dust or powder made by the tools, and which is so light as to remain suspended for some time in the air."

²⁷D. Harrington and Sara J. Davenport, *Review of Literature on Effects of Breathing Dusts With Special Reference to Silicosis* (U. S. Dept. Int., Bur. Mines, Bull. No. 400, 1937), p. 23.

Drilling has been only one of the activities responsible for the general dust hazard in mines. Although under certain conditions it has been the most important source of dust; today in well-managed mines where wet-drilling regulations are rigorously enforced, blasting and even hand shoveling may be more important sources. Thus the general problem of dust control extends beyond the drill, although complete wet drilling is the first effective step. The volume of dust due to blasting can be greatly reduced by thorough spraying of muck piles and working places while shooting is going on and by limiting the shooting to the period between shifts. Adequate ventilation is of great importance. The dust content of the air may be kept below a permissible maximum and the number of workers exposed to the greatest concentrations can be controlled to some extent by careful routing of air currents. The principal methods of dust control are not applied easily and add appreciably to the cost of mining, but their effectiveness has been demonstrated in the United States and abroad. The program sponsored by the Miners' Phthisis Medical Bureau in South Africa has been especially effective, and it has been reported that "since 1923 there have been no cases of contracted silicosis - in other words no new Rand miner has been found suffering from silicosis in the last ten years."²⁸ In this country during the past decade silicosis has been included in the list of compensable occupational diseases under the workmen's compensation laws in an increasing number of States and dust-control programs have received increased attention.

No cure is available for silicosis and the miner who contracts it is permanently handicapped. His effectiveness as a worker is reduced, and other aspects of his life are circumscribed. Although there is no accurate measure of this incapacity, it has been reported that "with the development of first-stage silicosis there was a drop in the number of weeks and shifts worked, and with second-stage silicosis there was a marked drop in amount of work performed on each shift."²⁹ Men with third-stage silicosis and with both silicosis and tuberculosis worked intermittently and during a relatively small portion of the year.³⁰ Notwithstanding a decreased physical output capacity, the simple silicotic can and may work and he represents no hazard to his coworkers as long as he does not contract an infectious disease. He should not be exposed

²⁸"Miners' Phthisis," *The South African Mining and Engineering Journal*, Vol. XLV, pt. I, No. 2171 (Mar. 10, 1934), p. 32. The methods of control employed were wet drilling, water spraying, filtration, allowing of adequate time between blasting and return to the working face, air sampling, ventilation, and the wearing of masks. See Harrington and Davenport, *op. cit.*, p. 289.

²⁹Harrington and Davenport, *op. cit.*, p. 46.

³⁰*Ibid.*

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further to dust, however, and the work should not overtax his reduced strength and endurance. In this respect one medical authority has recently suggested "that emphasis should be placed on the control of dust so as to remove the hazard rather than to remove the workman from the occupation."³¹

Lack of data prevents quantitative appraisal of the dust hazard in mining during earlier decades and of the extent to which various mining operations contributed to that hazard. It may be estimated, however, that a quarter century ago as many as a third of the men engaged in hard-rock mining in the United States had silicosis and that machine drilling was perhaps the most important factor contributing to this situation. There is little question that at least through the first 15 years of the present century the power drill increased the dust hazard, with serious results to the workers. The danger has been greatly lessened by the constant effort of safety engineers and by wide cooperation of mine operators in dust-control programs inaugurated by the U. S. Bureau of Mines and the U. S. Public Health Service. Rigorously enforced wet-drilling regulations and other controls have notably reduced dusts attributable to drilling, and in most well-managed mines today such operations as blasting and loading present a more difficult problem in dust control than drilling. Even dust resulting from blasting and loading is now usually controlled in well-managed mines but constant vigilance is required to keep the hazard under control.

OUTLOOK FOR EMPLOYMENT IN DRILLING³²

What course is future technical advance in rock drilling likely to follow? What will be the effect of new improvements in drilling upon employment in mining? Absolute answers to such questions of course cannot be given, but the major considerations and certain important trends may be pointed out. Future employment in drilling will depend on the quantity of drilling that is performed and the rate per man at which it may be accomplished. Both of these factors, however, will be determined by a host of direct and indirect influences, many of which cannot be foreseen with reasonable accuracy. For some branches of mining the hazards of prognosis are heightened by uncertainty regarding the grade and quantity

³¹R. R. Sayers, "Progress in Combating Silicosis," *Mining and Metallurgy*, Vol. 20, No. 389 (May 1939), p. 252.

³²The reader is reminded that this discussion does not include the drilling of oil and gas wells in which increased employment is expected (see Kiessling and Others, *op. cit.*, p. 309); drilling and cutting in coal mines is also covered in a separate report (see Willard E. Hotchkiss, F. G. Tryon, and Others, *Mechanization, Employment, and Output per Man in Bituminous-Coal Mining* [WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-9, Aug. 1939]).

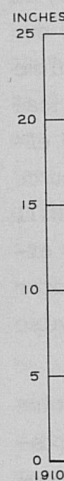
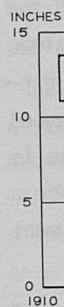
of reserve-ore tonnages. Despite these difficulties, examination of recent tendencies in rock-drilling progress and mineral production offers clues to some probable future trends in driller employment.

Barring a long and costly European war, the short-time prospect - say for the next 10 years - is for a minor reduction in driller employment. The volume of drilling done will depend upon the tonnage broken and this in turn will reflect the level of demand. The reserves that will be mined during the next decade already are largely known and the speed with which they will be exploited varies with the market outlook for different industries. The question of future demand for mineral products is a problem of such large proportions that it could be treated only in a limited manner in the separate commodity studies of this series.³³ In addition to factors influencing demand in the past, new uses for minerals probably will be developed; on the other hand, the substitution of one metal for another, as aluminum for copper, and the increasing volume of scrap material available may notably curtail certain types of mining. Generalizing where conditions vary widely, however, and taking the mineral industries as a group, it seems likely that the trend of demand 10 years hence will show a moderate increase with growth of population, continued expansion of industrialization, and progress toward a higher general standard of living.

The effect on drilling employment of the anticipated increase in the volume of production probably will not be great enough to offset the tendency of a continuing rise in drilling speeds to decrease employment. There are several reasons why the trends indicated in figure 27 are likely to continue upward. Wider use of improved drill steel and detachable bits, additional improvements in both the machine and drill steel, and the replacement of obsolete machines with more efficient models are major considerations leading to this conclusion.

Improvements that have been made in drill steel and in detachable bits have not yet been fully utilized at many operations, and the more widespread application of such developments will result in greater driller productivity. Furthermore, it is probable that such advances will con-

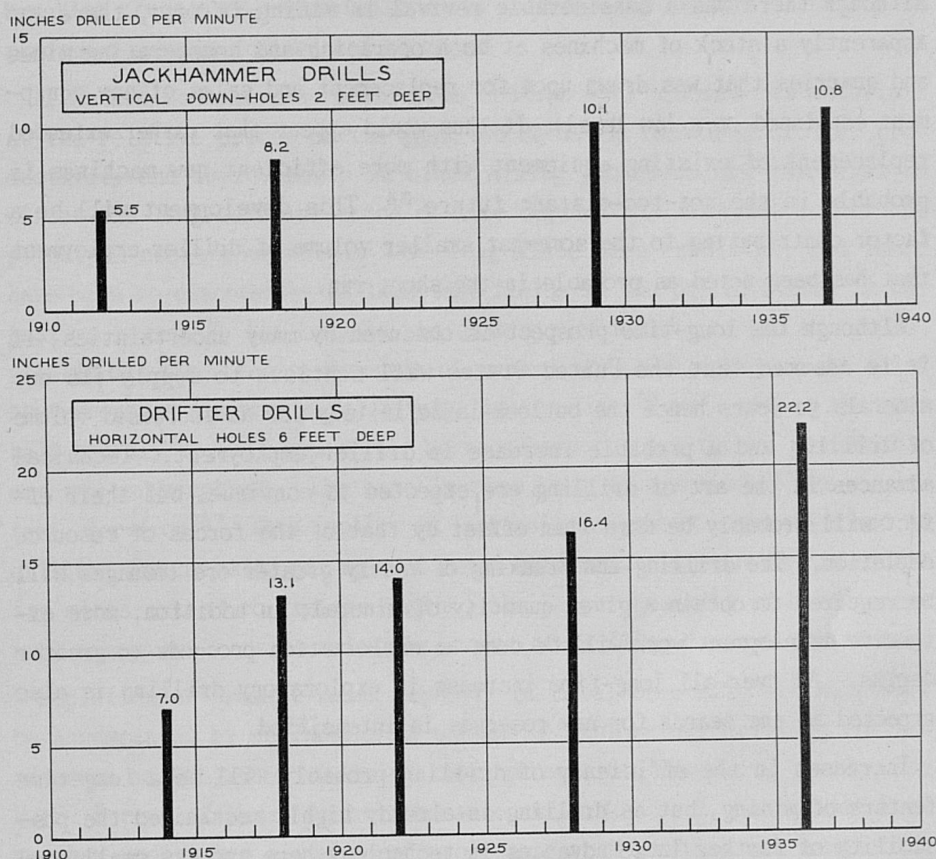
³³The series referred to includes studies on technology, employment, and output per man in various branches of mining conducted by the WPA National Research Project in cooperation with the U. S. Department of the Interior, Bureau of Mines. See: A. Porter Haskell, Jr., and O. E. Kiessling, *Technology, Employment, and Output per Man in Phosphate-Rock Mining, 1880-1937* (Report No. E-7, Nov. 1938); Harry S. Kantor and Geoffrey A. Saeger, *Changes in Technology and Labor Requirements in the Crushed-Stone Industry* (Report No. E-8, Feb. 1939); Willard E. Hotchkiss, F. G. Tryon, and Others, *Mechanization, Employment, and Output per Man in Bituminous-Coal Mining* (Report No. E-9, Aug. 1939); O. E. Kiessling and Others, *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production* (Report No. E-10, July 1939); Y. S. Leong and Others, *Technology, Employment, and Output per Man in Copper Mining* (Report No. E-12, in press); Nicholas Yaworski, O. E. Kiessling, and Others, *Technology, Employment, and Output per Man in Iron Mining* (in preparation); and others, in preparation.



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Figure 27.- UPWARD TREND IN DRILLING SPEEDS INDICATED BY RESULTS ACHIEVED UNDER TEST CONDITIONS



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Penetration rates achieved under test conditions for two of the principal types of one-man hammer drills are shown above as rough indicators of approximate trends. Although useful for this purpose, the data cannot be taken as indicative of average performance in regular mining. They represent the average speed for several holes and the time of drilling is accurately measured. The tests are run under standardized conditions of air pressure, bit gage, and depth and inclination of holes; the drilling is done in a hard granite of relatively constant character with new machines handled by skilled operators. Data are from records furnished by large manufacturers of rock drills.

tinue. This is significant because a bit made of superior material suffers relatively small gage loss, holes can be started with bits of smaller gage, and drilling speed correspondingly increased. Manufacturers will also doubtless continue to take advantage of new special materials and alloys in making the drilling machine more durable and to effect minor improvements.

The useful life of the rock drill is relatively short, and commonly used depreciation rates indicate a life of about 5 years for the hammer-drill group, about 10 years for channelers, and 10 to 15 years for churn

drills. From 1930 to 1935 very little drilling equipment was purchased and at many operations the old machines were repaired and kept in use. Although there was a considerable revival in mining in 1937, there was apparently a stock of machines at both operating and nonoperating mines and quarries that was drawn upon for replacement and sales of new equipment continued on a low level. It thus would appear that rather extended replacement of existing equipment with more efficient new machines is probable in the not-too-distant future.³⁴ This development will be a factor contributing to the somewhat smaller volume of driller employment that has been noted as probable in the short run.

Although the long-time prospect is obscured by many uncertainties, if it is assumed that the United States will continue to supply its own minerals 50 years hence the outlook is definitely for an increased volume of drilling and a probable increase in driller employment. Technical advances in the art of drilling are expected to continue, but their effect will probably be more than offset by that of the forces of resource depletion. The drilling and breaking of vastly greater ore tonnages will be required to obtain a given quantity of mineral; in addition, more extensive development work will be done as exploitation proceeds to greater depths. An over-all long-time increase in exploratory drilling is also expected as the search for new reserves is intensified.

Increases in the efficiency of drilling probably will be a long-time feature of mining, but as drilling is already highly mechanized the possibility of further large advances in technology here appears small compared with 50 years ago. Nevertheless, increased penetrating speeds resulting from factors such as improved utilization of power doubtless will aid in reducing operating costs and holding them at reasonable levels. Also, different machines probably will find broader fields of application. The shaft-size core drill, so far used for vertical holes, may be used for inclined bores or for horizontal openings. It is also possible that some of the quarryman's tools, such as the channeler or wire saw, may be applied for side-channeling in mines. The further development of long-wearing hard or abrasive materials may permit successful use of the powerful hydraulic rotary drill in penetrating rocks much harder than those in which it is customarily used. Changes in drilling and breaking methods are also likely. As greater depths are attained, rock pressures increase and these inherent strains may be increasingly used to break rock. These practices are already known and are used to

³⁴One manufacturer of churn drills informed the authors that his recent models showed gains of 35 to 100 percent in effectiveness, judged both by volume of hole and drilling speed, over the older equipment they replaced.

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a limited extent. Finally, entirely new methods of ore removal, such as by abrasion, may be invented. Such broad changes in drilling and breaking techniques undoubtedly would increase the driller's ability to produce a greater footage and tonnage.

If we are to continue to enjoy an abundance of mineral raw materials at the relative prices of the past two decades, increased driller productivity and improvements in other mining processes are essential to offset the long-time influence of mine depletion. Bonanza ores of the principal nonferrous metals have long since been exhausted, and there have been no discoveries of important fields in the United States in the past 30 years.³⁵ Not only is the quantity of metal per ton of ore declining but also the ore reserves of present workable grade for the chief nonferrous metals have a relatively limited life;³⁶ well within the next half century it will apparently be necessary to turn to ore bodies that are now submarginal. The same is true, but to a somewhat lesser extent, for iron.³⁷ This implies an increasing volume of excavation and of drilling and breaking per unit of metal obtained. In addition, as existing mines extend to greater depths, the larger quantity of development work necessary tends to raise the amount of drilling done per ton of ore.

Depletion of present-known deposits of metal ores also probably will be accompanied by an increasing amount of exploratory drilling for new reserves or for better defining known prospects. Beginning in 1939 the U. S. Bureau of Mines in collaboration with the U. S. Geological Survey has undertaken a number of projects for delimiting and evaluating certain deposits of strategic minerals; private as well as governmental agencies will participate in extensive drilling campaigns in the future. Geophysical prospecting, in which drilling is necessary when the reflection seismograph is used, is expected to be further extended in the exploration of subsurface and deep-lying ore bodies.

The long-time prospect for mine employment in drilling may be summarized as follows: If it is assumed that American industry will continue to be supplied from domestic mines, a much greater volume of ground will have to be drilled and broken in the future to obtain a unit of product because of declining grade of ore; in addition, other increasing physical obstacles, such as greater depth of mines, will require a larger volume of work preparatory to mining proper. Deposits of metal ores workable

³⁵Corry and Kiessling, *op. cit.*, pp. 16-7.

³⁶Kenneth Leith and Donald M. Liddell, *The Mineral Reserves of the United States and Its Capacity for Production* (National Resources Committee, mimeo., Mar. 1936), p. 2.

³⁷Yaworski, Kiessling, and Others, *op. cit.* In general, this aspect of depletion is not pronounced for the industrial nonmetals, but it appears likely that the demand for these materials will increase notably.

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by surface methods - in which drilling is done with large-scale equipment and low unit labor requirements - are known to be limited and any relative increase in underground mining will be accompanied by a larger relative expenditure of labor for drilling. In addition, it appears likely that exploratory drilling will be used even more widely in the future than in the past. Technical advances will, of course, continue, but the margin of possible progress has narrowed because the drilling operation already is highly mechanized. Whether or not these developments produce a net increase or decrease in over-all employment in drilling depends on the demand for minerals. Although the course of future demand cannot be plotted precisely, it will be strongly affected by the growth of population. Another report of this series summarizes evidence which indicates that population will increase for at least the next three decades but at a gradually slackening rate.³⁸ Thus, if our present standard of mineral requirement per capita is maintained, or if it is only moderately increased, the long-time trend of mineral demand will be upward. Countertendencies are greater economies in the use of minerals³⁹ and the substitution of one mineral for another, but in all likelihood they will not change the broad features of the general trend. With more units of mineral needed and with a larger amount of drilling labor required per unit because of such factors as declining ore grade, in spite of expected further adoption of labor-saving technical changes the long-time forces point toward increased employment for drilling in mines and quarries.

³⁸Klessler and Others, *op. cit.*, pp. 299-300.

³⁹For an example of improving economy in mineral utilization see Nicholas Yaworski and Others, *Fuel Efficiency in Cement Manufacture, 1909-1935* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-5, Apr. 1936), pp. 1-2.



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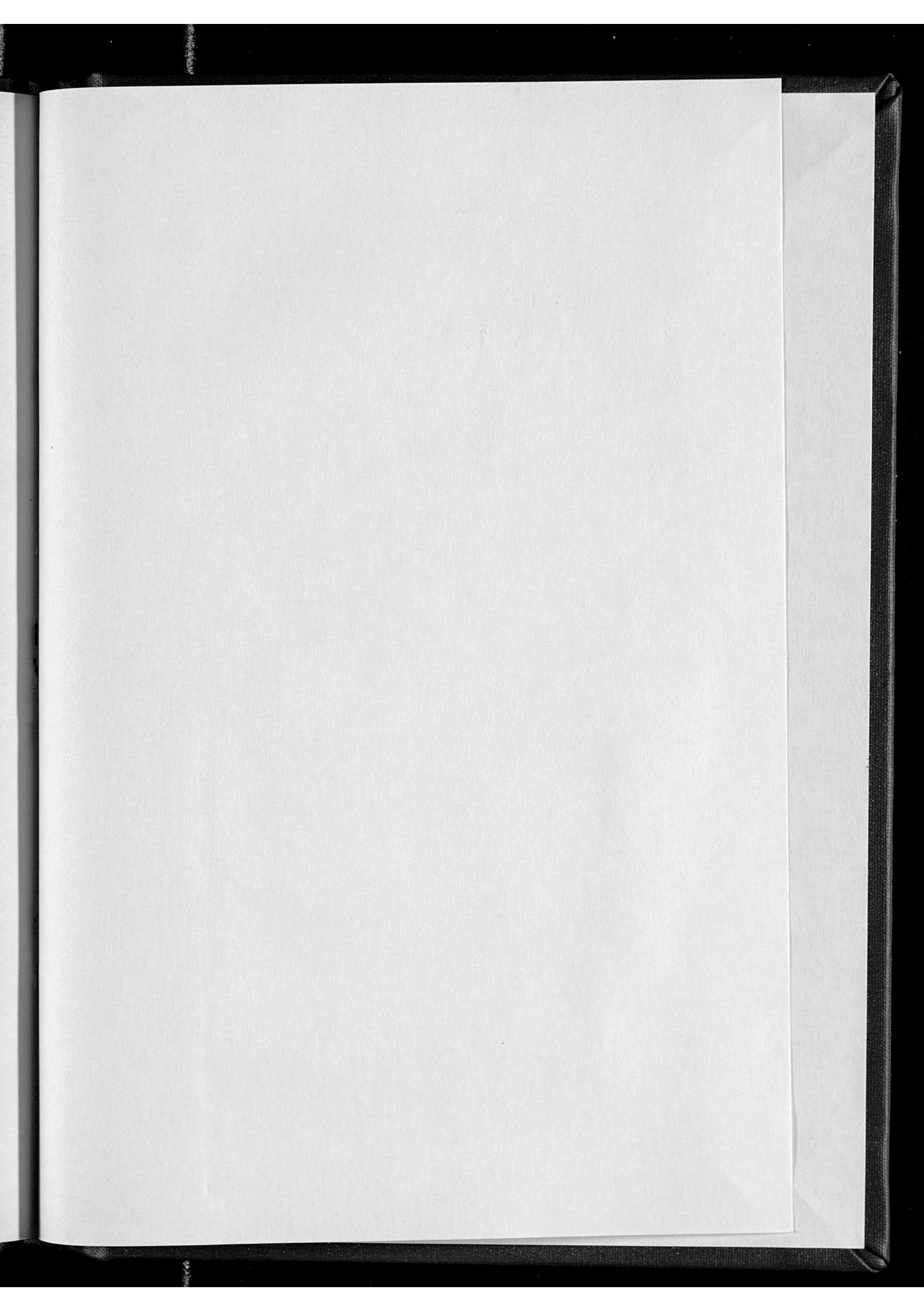
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