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BUREAU OF MINES

SCOTT TURNER, DIRECTOR

**QUARRY PROBLEMS IN THE
LIME INDUSTRY**

BY

OLIVER BOWLES and W. M. MYERS

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QUARRY PROBLEMS IN THE LIME INDUSTRY

By OLIVER BOWLES and W. M. MYERS

INTRODUCTION

Lime is of tremendous importance to modern industries. In agriculture it is regarded as essential to the continued fertility of many important regions, in building it is indispensable, and in the many ramifications of the chemical industries it is so necessary and so widely employed that it has been designated "the king of all the bases." Figure 1 shows a general view of a modern lime plant producing more than 500 tons of lime daily. In 1924 the production of lime was reported from nearly every State in the Union and amounted to more than 4,000,000 tons, valued at nearly \$40,000,000. For a production of that magnitude between 8,000,000 and 9,000,000 tons of limestone are required.

The many problems involved in winning this great quantity of raw material from the natural rock and preparing it for the kilns have in the past received little attention from any governmental agency. Therefore, in compliance with a request from representatives of the National Lime Association in 1922, the Bureau of Mines began a study of problems in limestone quarrying in an effort to advance more economical methods of operation and the utilization of waste material. Field studies were made at many quarries, and the information thus compiled, besides data already at hand from work in other branches of the stone industries, were disseminated to operators in the form of mimeographed Reports of Investigations, eight of which were issued at intervals during 1922, 1923, and 1924. A questionnaire was appended to each report, and quarry operators were invited to contribute additional information obtained as a result of their actual experience and observation. Operators of lime plants have been cordial in their responses and have supplied the bureau with much valuable information. From the data thus obtained, supplemented by later field studies, the revised reports have been combined to form the major part of this bulletin, which is believed fairly to represent present knowledge on the subject of quarrying limestone for lime manufacture.

The purpose of this bulletin is not to describe individual quarries but to describe general methods of operation and give typical

FIGURE 1.—General view of a modern lime plant making more than 500 tons of lime daily

illustrations. The methods employed are discussed critically in an effort to elucidate the best working principles and to assist manufacturers of lime in correcting errors and establishing their industry on the most economical and efficient basis.

The first year's study was conducted from Washington, D. C., but with the establishment of the Non-metallic Minerals experiment station at Rutgers University, New Brunswick, N. J., on July 1, 1923, the work was transferred to that station.

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PART I.—QUARRY OPERATIONS

By OLIVER BOWLES

RAW MATERIAL FOR LIME MANUFACTURE

Limestone is a general term applied to the rock from which lime is manufactured. Strictly speaking, limestone consists, essentially, of calcite (calcium carbonate), which has the chemical composition CaCO_3 . Magnesium may replace the calcium in varying amounts, and when it is present in considerable proportions the rock is designated as a magnesian limestone. If the percentage of magnesium carbonate reaches 45, the rock consists, essentially, of the double carbonate of calcium and magnesium ($\text{CaCO}_3\cdot\text{MgCO}_3$), known as dolomite. Calcite, dolomite, and intermediate forms are commonly included by the lime burner and dealer under the general term "limestone." Impurities, the most common of which are silica, alumina, and iron, occur in varying proportions in limestones, but for the high-grade limes generally produced in this country only small percentages of such impurities are permissible.

PROCESS OF LIME MANUFACTURE

In brief, the process of lime manufacture consists in heating limestone to a temperature at which the carbon dioxide is driven off, leaving the oxide of calcium or the mixed oxides of calcium and magnesium. This process for a high-calcium limestone may be expressed by the chemical equation $\text{CaCO}_3 + \text{heat} = \text{CaO} + \text{CO}_2$. For a high-calcium stone a temperature of about 900°C . is required, and for a dolomite about 550°C .; the magnesian limestones calcine at intermediate temperatures. To promote rapid calcination, much higher temperatures are maintained in the kilns. In converting limestone into lime there is a large loss of weight—100 pounds of pure limestone yield only 56 pounds of finished lime.

In the calcination of limestone the maintenance of proper control of temperature is important. If the temperature is too low, or if the stone is exposed to the heat for too short a time, the finished product will contain cores of uncalcined stone. If too high a tem-

perature is maintained, overburning will result—a condition that makes the product undesirable for many uses.

Although the main product of most lime plants is “quicklime”—either calcium oxide or the combined oxides of calcium and magnesium—within recent years a growing tendency has developed to market the product in hydrated form. When water is added to quicklime, a chemical reaction ensues that is accompanied by the evolution of heat. For high-calcium lime the reaction may be expressed by the equation $\text{CaO} + \text{H}_2\text{O} = \text{Ca}(\text{OH})_2$. According to this equation 56 pounds of lime unite with 18 pounds of water to form 74 pounds of hydrated lime. The essential point in the manufacture of hydrated lime is to hydrate completely without an excess of water. If not enough water is added, some of the lime oxide remains unchanged; an excess of water forms a pasty mass that is difficult to sack and is in poor condition for sale. At least five different types of hydrators are now in use.

A discussion of the processes involved in the manufacture of lime is not included in the scope of this bulletin. Several books¹ are available which cover the subject in considerable detail.

ORIGIN AND CHARACTER OF LIMESTONES

Many beds of limestone have originated from accumulations of the calcareous remains of marine organisms, such as foraminifera, mollusks, coralline algae, and corals. Although the individual shells or skeletons of these organisms may be very small, the vast quantities deposited during countless centuries have in places helped to form limestone beds hundreds or even thousands of feet thick. In some limestones the fossils retain their original forms, but in most deposits these have been largely obliterated. Other extensive beds of limestone have been formed by the deposition of calcium carbonate from solution in the sea. By the pressure of superincumbent beds and by cementation, the limy deposits, however formed, have been consolidated into firm, coherent rock. Later the deposits were elevated above the surface of the sea by earth movements, were eroded by the elements, and thus became accessible for use. Beds that were originally flat-lying have in many places been folded, and in consequence dip at various angles from horizontal to vertical. This inclination of the beds may greatly complicate the process of mining or quarrying.

¹ Eckel, E. C., *Cements, Limes, and Plasters*: 2d ed., New York, 1922, 655 pp. Emley, W. E., *Manufacture of Lime*: U. S. Bureau of Standards Technol. Paper 16, 1913, 130 pp. Heath, A. H., *A Manual of Lime and Cement*: London, 1893, 215 pp. Knibbs, N. V. S., *Lime and Magnesia*: London, 1924, 306 pp. Lazelle, E. W., *Hydrated Lime*: Pittsburgh, Pa., 1915, 95 pp.

Limestones show great variation in such physical properties as degree of crystallization, texture, grain size, grain shape, nature of cementation, brittleness, toughness, or hardness. These properties not only have more or less influence on the method of mining and on mining costs, but they also influence the nature of the finished lime. However, the relation of the physical properties of the stone to the character of the lime produced has not yet been studied thoroughly.

Calcareous rocks are divided into different groups, according to differences in origin, texture, or composition. Marble is limestone that has acquired a crystalline structure, with or without folding of the beds. Marl is a term loosely applied to unconsolidated or partly consolidated masses of lime carbonate, many of which have formed in lake basins. Calcareous tufa and travertine are more or less compact limestones deposited from solution, usually around springs or along stream courses. Oölitic limestone, so named because of its resemblance to fish roe, is made up of small rounded grains of carbonate which show a concentric structure. Chalk is composed of the minute shells of foraminifera loosely cemented together. A siliceous or cherty limestone is one that contains considerable silica, an argillaceous limestone is one containing clay, a carbonaceous or bituminous limestone is one containing carbonaceous matter, and a ferruginous limestone one that contains iron.

DISTRIBUTION OF LIMESTONES SUITABLE FOR MANUFACTURE OF LIME

QUALIFICATIONS

Deposits of both high-calcium and dolomitic limestone are abundant and widely distributed in the United States. The situation of these deposits has been determined by the work of the United States Geological Survey and the geological departments of the individual States in determining the mineral resources of the Nation. This work has shown the broad geographical boundaries of the limestone deposits, their geologic age and many facts concerning their origin, the conditions under which they were formed, and their composition.

Our knowledge of definite localities in which limestone occurs is due mainly to the search of limestone-consuming industries for raw material. The commercial development of any limestone deposit is governed by economic factors, and for this reason only those deposits that are favorably situated with respect to a market and to cheap transportation have commercial possibilities. The greatest activity in the development of limestone deposits has therefore been in localities well served by either water or railroad transportation and surrounded by a large lime-consuming population. The limestone in the Eastern States that is in deposits which can not be

economically exploited at present and the enormous supply in the Western States that has been almost untouched through lack of demand together constitute a reserve that should be adequate for an indefinite period.

Four general fields of utilization may be outlined for commercial limestone: (1) As uncalcined stone (dimension stone, crushed or pulverized stone), (2) as flux or for other metallurgical purposes, (3) in the manufacture of Portland cement, and (4) in the manufacture of lime. For the first of these uses the chemical composition of limestone is of little significance, and its physical properties are of most importance. For fluxing purposes or the manufacture of Portland cement or lime the chemical composition of the stone is all important; its physical properties are secondary.

The official specifications for Portland cement limit the magnesia (MgO) content to 5 per cent. This specification eliminates the dolomitic limestones from this market, as only high-calcium limestones can be used. As clay or shale is added to this type of limestone in the manufacture of cement, the presence of clay as an impurity in the stone is not detrimental but is more of an asset; in consequence, high-calcium limestones containing impurities that render them worthless for the manufacture of lime may be highly desirable for the manufacture of cement.

For the manufacture of lime, high-magnesium as well as high-calcium stone may be used, but it is essential that the stone be composed almost exclusively of the carbonates of calcium and magnesium. The maximum amount of impurity permissible depends on the utilization of the lime. It is doubtful if a limestone containing over 5 per cent of the impurities silica (SiO_2), alumina (Al_2O_3), and iron (Fe_2O_3) could be used as a source of lime. An average of the stone employed by a number of the largest lime manufacturers in the country shows that they commonly use a stone carrying less than 2 per cent of impurities, the total carbonates of calcium and magnesium exceeding 98 per cent.

The chief physical qualification of limestone for lime manufacture is that it be sound and free from fractures, so that it can be quarried with a minimum production of fine material. Some thinly stratified beds that shatter readily and the unconsolidated fossiliferous deposits of the southern coastal plain, although they have a suitable chemical composition, are too friable for use in the shaft kiln. A mere fraction of the limestone deposits of the country possess the chemical and physical properties that make them suitable for the manufacture of lime. In localities where limestones have been actively exploited for years the cheaply quarried stone at or close to the surface has been exhausted and operators have had to go to greater depths and even to resort to underground

mining to obtain adequate stone. Fortunately, the total reserves of limestone suitable for the manufacture of lime are adequate for all expected demands for an indefinite period.

LOCALITIES PRODUCING LIME

In general, the distribution of limestone suitable for the manufacture of lime is indicated by the localities in which lime is being or has been recently produced, although this does not adequately represent the limestone reserve of the country. The constantly expanding demands of modern industry and the growing population of States, in which the production of lime is unimportant at present, will undoubtedly result in the commercial development of limestone deposits that now are untouched.

Rockland, Me., is the most northeastern point in the United States where lime is now being produced. Both dolomite and high-calcium limestone occur in this district. The lime plants are situated at tidewater, and thus enjoy cheap transportation to the New England and New York markets. A belt extending from the Canadian border through western Vermont, Massachusetts, Connecticut, and eastern New York contains both dolomitic and high-calcium limestone. In places, particularly in Vermont, part of the high-calcium limestone has been metamorphosed to marble. The spalls produced in quarrying marble furnish considerable material suitable for the manufacture of lime. Some lime is produced in northern New York, although the bulk of the State's production is from a belt extending across the central part of the State. The production of lime in New Jersey is limited to the northern part of the State. Most of the limestone in that section is high-calcium, although some dolomitic limestone occurs.

Lime is produced in Pennsylvania from localities scattered throughout the entire southern half of the State where both high-calcium and dolomitic limestones are widely distributed. The heavy output of many large plants throughout that district has placed Pennsylvania second in rank among the producing States. Production in the northern half of the State has been limited greatly because the topography is rugged and the region is not as densely settled.

The main limestone belt of eastern Pennsylvania extends southwestward as far as the Birmingham district in Alabama. The belt is of great economic importance in Pennsylvania, and lime is produced from it in Maryland, the Shenandoah Valley of Virginia, eastern Tennessee, northern Georgia, and Alabama. In the latter State the belt furnishes the metallurgical stone for the iron and steel industry centered at Birmingham. In West Virginia a continua-

tion of the narrow limestone belts of western Pennsylvania has been actively exploited, causing West Virginia to rank fourth as a producer. The limestone deposits of the Carolinas have been developed to a small extent for local demands. In general, these deposits are small, impure, and often poorly situated with respect to the markets. In the coastal plain regions marls and soft limestones are abundant but in few places are pure enough for the manufacture of lime. Some of the poorly consolidated stone composed almost exclusively of fossils, although very pure in some localities, is so friable that it can not be satisfactorily calcined in the shaft kiln.

All of the Central States are well supplied with limestone. G. F. Loughlin² has presented a discussion of this area sufficiently brief and concise to warrant quotation:

The broadest and most continuous limestone area in the country extends through parts of all the Central States. Its northern limit in the United States is along Lake Huron, in northern Michigan. From this region it extends in a belt of prevailing magnesian limestone through eastern Wisconsin to northern Illinois, where it divides into an eastern and a western branch. The eastern branch extends from the Chicago district into Indiana and Ohio, both States containing immense quantities of high-calcium and high-magnesium stone of great commercial importance. The belt continues southward through Kentucky and middle Tennessee to northern Alabama but has been relatively unproductive in these States, although some of its beds contain high-calcium stone of excellent quality. Dolomitic limestone occurs near Louisville, Ky.

The west branch of the great dolomitic belt in northern Illinois extends into Iowa and southern Minnesota. In Iowa it is continuous with high-calcium limestone that extends southward into Missouri where it divides into two branches, one following the Mississippi River to Cape Girardeau and connecting across southern Illinois with the deposits in Kentucky, the other extending westward and southwestward into Arkansas and Oklahoma and the southeast corner of Kansas. These two branches nearly surround a great area of dolomitic limestone in the south central part of Missouri and the northern part of Arkansas.

Considerable high-calcium limestone is found in South Dakota, Nebraska, Kansas, Oklahoma, and Texas. Commercial development has been restricted to localities that, in general, are close to the larger cities. In the Rocky Mountain and Pacific Coast States the reserves of both high-calcium and dolomitic limestone are enormous. Commercial development has been limited by the comparatively small population of some of these States, and the present activity in lime production is restricted to areas near centers of population and lime-consuming industries. The most important lime quarries and plants are therefore in the districts near such cities as Denver,

² Loughlin, G. F., "Limestone and lime"; chapter in *Our Mineral Supplies*: U. S. Geol. Survey Bull. 666, 1919, pp. 107-112.

Salt Lake, El Paso, Los Angeles, San Francisco, Carson, Seattle, and Butte.

PRODUCTION OF LIME IN UNITED STATES

In 1924 lime was produced in 42 States and Territories, including Hawaii and Porto Rico. Although lime plants are thus widely scattered, some centers are much more productive than others. More than 98 per cent of the lime manufactured in the United States comes from 22 States. The accompanying chart (fig. 2) shows the location of the plants. As the chart is on a small scale, it gives only an approximate idea of relative output in the various producing centers.

Table 1, prepared by the division of mineral resources and statistics of the Bureau of Mines, shows production, by States and uses, during 1924.

TABLE 1.—*Lime sold by producers in the United States in 1924, by uses*

	Building		Agricultural		Chemical		Total	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
Ohio.....	671, 510	\$6, 891, 769	19, 686	\$134, 943	243, 211	\$2, 484, 558	934, 407	\$9, 511, 270
Pennsylvania.....	288, 899	2, 500, 901	116, 966	883, 225	294, 515	2, 250, 680	700, 380	5, 634, 875
Missouri.....	82, 051	797, 665	(1)	(1)	¹ 161, 414	¹ 1, 556, 510	243, 465	2, 354, 180
West Virginia.....	29, 365	259, 785	18, 289	122, 594	191, 060	1, 502, 303	238, 714	1, 884, 602
Wisconsin.....	227, 978	2, 028, 839	(1)	(1)	¹ 7, 052	¹ 100, 862	235, 030	2, 129, 786
Alabama.....	54, 422	517, 802	-----	-----	149, 637	1, 294, 480	204, 059	1, 812, 221
Massachusetts.....	151, 974	2, 333, 577	4, 928	17, 995	37, 500	341, 456	194, 402	2, 693, 042
Virginia.....	86, 161	759, 188	19, 906	130, 571	66, 709	519, 688	172, 776	1, 409, 488
Tennessee.....	73, 496	707, 774	791	5, 407	70, 005	398, 600	144, 292	1, 111, 727
Maine.....	77, 258	1, 374, 100	8, 166	40, 424	40, 264	395, 405	125, 688	1, 809, 901
Indiana.....	21, 656	188, 222	5, 157	35, 622	90, 114	767, 159	116, 927	991, 099
New York.....	24, 490	228, 478	3, 988	30, 215	70, 114	733, 106	98, 592	991, 793
Illinois.....	44, 587	524, 516	-----	-----	44, 545	409, 683	89, 132	934, 179
Michigan.....	12, 416	113, 067	(1)	(1)	¹ 60, 680	¹ 589, 005	73, 096	702, 039
Texas.....	44, 017	420, 518	(1)	(1)	¹ 16, 548	¹ 149, 816	60, 565	570, 332
California.....	40, 914	447, 535	3, 251	44, 992	15, 418	165, 611	59, 583	658, 144
Connecticut.....	56, 345	774, 452	(3)	(3)	(3)	(3)	58, 851	796, 538
Vermont.....	27, 923	397, 514	829	4, 277	27, 732	308, 948	56, 484	710, 751
Maryland.....	9, 416	72, 568	40, 628	355, 776	6, 134	41, 761	56, 178	470, 109
Washington.....	20, 742	266, 174	(1)	(1)	¹ 7, 446	¹ 87, 276	28, 188	353, 450
Arizona.....	(3)	(3)	(3)	(3)	(3)	(3)	27, 972	331, 756
Minnesota.....	19, 412	242, 385	-----	-----	6, 352	76, 681	25, 764	319, 066
Undistributed.....	104, 668	1, 165, 106	4, 095	47, 824	49, 170	557, 035	127, 455	1, 416, 120
Total.....	2, 169, 700	23, 011, 935	248, 336	1, 864, 514	1, 653, 964	14, 719, 974	4, 072, 000	39, 596, 423

¹ Included under "Chemical." ² Includes "Agricultural." ³ Included under "Undistributed."

Table 2, compiled from reports of the United States Geological Survey, gives the sales of lime, in tonnage and value, from 1908 to 1924, inclusive.

TABLE 2.—*Quantity and value of lime sold in the United States, 1908-1924*

Year	Quantity, short tons	Value	Year	Quantity, short tons	Value
1908.....	2, 766, 873	\$11, 091, 186	1917.....	3, 786, 364	\$23, 807, 877
1909.....	3, 484, 974	13, 846, 072	1918.....	3, 206, 016	26, 808, 909
1910.....	3, 505, 954	14, 088, 039	1919.....	3, 330, 347	29, 448, 553
1911.....	3, 392, 915	13, 689, 054	1920.....	3, 570, 141	37, 543, 840
1912.....	3, 529, 462	13, 970, 114	1921.....	2, 532, 153	24, 895, 370
1913.....	3, 595, 390	14, 648, 362	1922.....	3, 639, 617	33, 255, 039
1914.....	3, 380, 928	13, 268, 938	1923.....	4, 076, 243	39, 993, 652
1915.....	3, 622, 810	14, 424, 036	1924.....	4, 072, 000	39, 596, 423
1916.....	4, 073, 433	18, 509, 305			

USES OF LIME

According to its uses, lime may be classified as agricultural, constructional, or chemical. Figures compiled for 1924 show that 6 per

FIGURE 2.—Map of the United States, showing distribution of active lime-producing districts in 1924. Districts producing less than 10,000 tons of lime a year are not shown

cent of the total lime manufactured in the United States was used for agricultural purposes, 53.5 per cent for construction, including

mortar, plaster, concrete, stucco, sand-lime brick, and cold-water paint, and 40.5 per cent for chemical purposes. Although lime was primarily used almost exclusively in construction and for agriculture, it has gradually found wider use until to-day its employment in the chemical and allied industries is of almost equal importance. Holmes says³ that lime is an essential raw material in 120 different industries. Some of the more important products in the chemical group for which lime is used include paper, glass, sugar, leather, refractories, acids, alkalies, calcium carbide, bleaching powder, and soap. Large quantities of lime are used in metallurgy and in water purification.

FACTORS GOVERNING SITUATION OF PLANT

The main factors that determine the proper situation for a lime plant are markets, transportation facilities, quality of raw materials, quarry conditions, and fuel supply. Although some exceptionally favorable conditions may offset features that are somewhat unfavorable, in general, continued successful operation of a lime plant demands that all the factors enumerated must be reasonably advantageous.

MARKETS

Easy access to an adequate market is of first importance to the success of any lime-manufacturing enterprise. The availability of the market depends largely on transportation facilities. Cost of production is an influential factor in marketing. A plant that operates at low cost has a wider field than one that operates at high cost. The distance to which lime may be shipped depends also on the nature of the product. Lime peculiarly adapted for special uses may command a price that will justify shipment over long distances, and a strong market may be developed through an established reputation for reliability.

TRANSPORTATION FACILITIES

Railroad or water facilities at the plant are essential. Two or more competing lines are preferable. A local line connecting with a trunk line is often unsatisfactory because of delay and confusion in shifting cars from one line to the other.

QUALITY OF RAW MATERIALS

Although limestone occurs in virtually every State of the Union, rock of a quality suitable for lime manufacture is not as common as

³ Holmes, M. E., "Lime in the chemical and allied industries": Rock Products, vol. 24, Sept. 10, 1921, p. 17.

is generally supposed. Most of the lime now sold in the United States is manufactured from limestone of exceptional purity. Emley⁴ gives analyses of 35 limestones used for lime manufacture in various parts of the Eastern, Southern, and Middle Western States. The average content of the combined calcium and magnesium carbonates in these rocks is 99.04 per cent; the lowest is 96.90 per cent and the highest 99.95 per cent. The prospective operator should, therefore, keep before him the fact that, in general, successful lime manufacture demands a limestone of exceptional purity.

High-calcium limestones are most commonly employed in lime manufacture, although high-magnesium limestones or dolomites are widely used. The high-magnesium stones calcine at somewhat lower temperature than the high-calcium stones; thus, the fuel cost is relatively low. For some purposes, notably for finishing plaster, some of the high-magnesium limes give very satisfactory service.

The most common impurities in limestone are silica, alumina, iron, and sulphur. Silica may occur in the form of silicates, such as clay and tremolite; it may be present in the free state, as sand in grains, beds, lenses, stringers, or nodules, or as flint or chert. Alumina is usually present as a constituent of clay. Iron may occur as an oxide, as the sulphide (pyrite), or less commonly as carbonate or silicate. Sulphur may be present in the form of gypsum (calcium sulphate), celestite (strontium sulphate), or as pyrite (iron sulphide).

The kind of impurity that may be allowed, or the permissible percentage of impurities, depends largely on the purposes for which the lime is to be used. Certain impurities may actually improve the quality of a building lime. Thus, it is claimed that a small percentage of silica increases the plasticity and sand-carrying capacity of a mortar without detracting from its strength. A small amount of alumina may also improve the quality. Impurities in agricultural lime have no harmful effects; they merely dilute the product, reduce the percentage of active elements, and involve the consumer in the payment of purchase price and freight charges for inactive material. On the other hand, for specialized chemical uses, even small percentages of impurities may be decidedly harmful. Impurities also differ greatly in their effects, depending on the application of the lime. For one use a certain impurity may be very objectionable, but for a different use this impurity may cause no difficulty if present in reasonably small amounts. An impurity quite different in character may render the lime worthless. Thus, the prospective operator must give careful heed to the impurities in

⁴ Emley, W. E., *Manufacture of Lime*: U. S. Bureau of Standards Technol. Paper 16, 1913, pp. 8, 9.

his deposit of stone and their relation to the use for which the lime is to be employed.

Another point to be noted is that the percentage of impurities in the stone is greatly increased, virtually doubled, in the finished lime. There is little or no loss of the main impurities during calcination, although the weight of the limestone is reduced nearly one-half through loss of carbon dioxide. All the impurities in each hundred pounds of limestone remain in the approximately 56 pounds of lime that results from calcination. Therefore, if 4 per cent is the maximum permissible percentage of an impurity in a finished lime, the proportion of this impurity in the limestone should not exceed 2 per cent.

If impurities are scattered uniformly throughout the deposit, conditions are favorable for the production of a single uniform product. If the chemical composition of some parts of the deposit differs from that of other parts, the manufacture of a series of limes suitable for different purposes may be advisable. In some deposits certain beds are unsuited for lime manufacture, and if the proper conduct of quarry operations demands the removal of these beds, some market for the low-grade stone should be sought.

Physical as well as chemical properties may affect the treatment, cost of calcination, and use of a limestone. Porous, coarsely crystallized limestones tend to break up in burning. Porous limestones may contain water in quantities that require an appreciable amount of heat for removal. Heat readily penetrates dense, nonporous limestones; hence they may be calcined in less time than the loose-textured or porous stones. The physical properties of the stone undoubtedly affect the quality of the lime produced, but little study has yet been given to this subject.

QUARRY CONDITIONS

If the stone is suitable for the manufacture of lime, the next step is to determine the extent of the deposit and the conditions that favorably or unfavorably affect quarrying. By a study of outcrops or by trenching or drilling a general idea may be gained of the tonnage available. In general, in order to insure profitable operation an available tonnage for at least 20 years' work should be proved. The depth of overburden, dip of the beds, and drainage conditions must all be carefully considered in their relation to the most economical working plan, as outlined on later pages.

FUEL SUPPLY

Coal, wood, mixed coal and wood, producer gas, powdered coal, and fuel oil are used for burning lime. Coal is most commonly

employed. In average American practice a fuel ratio of about 1 to $3\frac{1}{2}$ is attained; that is, about 570 pounds of coal are required for each ton of lime. Fuel is the second largest item of expense in lime manufacture, being exceeded only by the cost of quarrying the limestone. It is therefore important that an adequate supply of fuel be available at reasonable cost.

GENERAL PLAN OF QUARRY OR MINE

Inefficient operation and high costs of production are frequently the outcome of an improperly planned quarry. Although the proper development of a limestone deposit is a matter of first importance to the prospective operator, it should also receive the serious attention of operators long in the industry. Operators who may have to extend their present workings should make new developments or extensions only after careful consideration of all the governing factors. Even at workings that have long been in operation, although the original layout largely controls future working, existing unfavorable ways of development can often be modified, and gradually placed on a better working basis.

The chief factors involved in the plan of quarry development are the thickness of the limestone beds, topography of the region, depth of overburden, availability of area for disposal of waste, the position of the beds, whether flat or tilted, and the strength and soundness of the rock.

Data on the composition, extent, and structure of the rock—the information regarded as necessary for a proper plan of working—are commonly gained only from surface observation or from trenching, and frequently the data thus gained are too meager for intelligent use. Prospect drilling to determine conditions at depth is employed to a small extent, and a much wider use would be advantageous. Some companies employ the prospect drill not only to obtain data preliminary to new enterprises but to plan properly and intelligently a future expansion of workings. The Rockland & Rockport Lime Co., of Rockland, Me., is doing much prospecting with core drills. The limestone beds worked lie nearly vertical, and in order to penetrate them the drill holes are projected at angles of about 20° from the horizontal. Although the core drill is used partly as a necessity, for no other type of drill could be operated successfully at such an angle and depth, an additional reason for its employment is the information it gives on the pitch of the beds and the physical structure of the rock, as well as the data on chemical composition.

The position of the limestone beds is a matter of great economic significance at any proposed quarry. If the beds are flat-lying and relatively thin, enlargement of the pit must take place laterally, and

the extent of the area available and the depth of overburden are matters of first importance. Thus at Marblehead, Ohio, a 22-foot horizontal bed of rock with very light overburden has been removed from an area of more than 1 square mile. If the beds are tilted at steep angles and are many feet thick, deep quarrying may be pursued.

If tilted beds are thin, any lateral extension must be in the direction of the strike or outcrop. If the beds dip at a steep angle, the quarry may be worked to considerable depth, but the removal of waste rock to avoid a dangerous overhang involves ever-increasing expense as the quarry floor is deepened. The narrowness of the working face is a great disadvantage in quarrying steeply inclined beds that are of limited thickness. Operations are cramped, and a large daily tonnage is difficult to obtain. This condition is partly overcome by quarrying at several levels, each bench providing an additional working face. If work beyond moderate depths is necessary, resort to underground methods may be advisable.

STRIPPING

STRIPPING OPERATIONS

Stripping is the process of removing from the limestone the overburden of clay, gravel, or sand. At some deposits beds of inferior stone may overlie the good limestone, and in a sense such rock may be considered overburden. However, as the methods of removing solid rock, whether barren or useful, are quite distinct from those employed in handling soil, the removal of inferior rock will be considered as a quarrying rather than a stripping problem.

Stripping is a process in which every lime-plant operator is interested. A few fortunate quarrymen have no overburden to handle, but although they may view their neighbors' stripping problems with a certain degree of complacency they nevertheless must see the wisdom of keeping informed on the subject. Extension of present pits or the development of new properties may at any time transfer them into the larger and less fortunate group of operators who must conduct stripping.

CLEAN STRIPPING

Clean stripping is not required for some types of limestone quarrying. In the manufacture of Portland cement clay is added to the limestone to obtain a proper mixture; hence if some clay is quarried with the rock and proper care is exercised in the subsequent addition of clay, no detriment to the product will ensue. The lime manufacturer, is, however, permitted no such latitude in stripping. Silica and alumina, which are the chief constituents of sand and clay, are harmful impurities in lime, and only very small percentages are

allowable; therefore the lime manufacturer, at some stage in the process of procuring his raw materials, must eliminate as much as possible of the débris overlying or associated with his serviceable stone.

STRIPPING CONDITIONS

No problem in quarrying is more variable than that of stripping. The removal of overburden may range from the mere cleaning of an exposed rock surface to removing 40 or 50 feet, or even more, of soil. The material to be removed may be loose and incoherent and readily handled by hydraulic or other simple methods, or it may be firmly compacted or may contain large boulders, conditions that demand special modes of removal. The rock surface may be smooth, affording an even floor on which a steam shovel may work to advantage, or it may be dissected by solution and have tortuous pockets and clay-filled caverns from which the soil is removed with difficulty. Thus, the stripping cost may range from nothing to 6, 8, or even 10 cents per ton of rock quarried.

As overburden conditions are extremely variable, so are the types of stripping equipment employed. The chief variable factors that must be taken into account in the choice of equipment are the composition, consistence, and thickness of the overburden, the roughness of the rock surface, the nature and proximity of the area on which the waste is to be deposited, and the magnitude of the quarry operations.

STRIPPING AHEAD OF QUARRYING

In general, the rock surface should be stripped before the ledge is shot down. Most operators recognize the wisdom of keeping the soil and stone separate, particularly where nature has already deposited them as separate masses and has thus enabled the quarryman to strip back the soil and expose a clean rock surface for drilling and blasting. At several lime-plant quarries, however, no attempt is made to strip before blasting; rock and soil are shot down together and are separated on the quarry floor. Figure 3 illustrates this method. One reason given for its use is the availability of transportation equipment within the quarry. For removing soil at the surface a drag line, trackage and cars, dump carts, scrapers, or some other form of haulage must be added, but soil within the quarry may be removed in the cars and on the tracks that are used for rock, the only addition required being a track to a waste bank.

Although such a reason may sound plausible and the method may be justified under exceptional conditions, rarely will any real justification be found for shooting down the overburden with the rock. The chief objections to thus mixing soil and rock are (1) contamina-

tion of rock, particularly during rainy weather, (2) loss of stone fragments that are mixed with soil and discarded, (3) loss of time in separating stone from soil, and (4) slow and expensive hand loading of soil at the quarry floor. Removal of overburden from the surface before blasting is therefore highly desirable. An irregularly eroded rock surface may present exceptional difficulties for stripping

FIGURE 3.—Overburden shot down with rock and separated on quarry floor

in advance of quarrying, and this phase of the problem is considered in some detail on the following pages.

Instances have been observed of overburden shot down with the rock but moved back and left on the quarry floor. When at a later time a lower bench has to be worked, a second tedious handling of all this débris is necessary. In removing overburden, as in all other phases of quarrying, the operator should plan for the future rather than sacrifice future economy for any seeming immediate need.

EROSION CAVITIES

As limestone is slowly soluble in water containing carbon dioxide, the upper zone of many limestone deposits has been partly dissolved and carried away by circulating water. The watercourses naturally are along open joints or cracks in the rock, and thus pockets or channels of varying sizes may be formed which become filled in with clay or sand. Commonly, therefore, the tops of limestone deposits are extremely irregular, and to remove clay from the tortuous erosion cavities is costly.

In the Shenandoah Valley of Virginia and West Virginia are extensive caverns in which part of the dissolved calcium carbonate has been redeposited as stalactites and various other forms. Some of the caverns have been commercialized by illuminating them and opening them to the sight-seeing public. Although large caverns may thus in a limited way constitute a commercial asset, the solution cavities the quarryman meets present decided disadvantages. Most of them are not open but are filled with a sticky red clay, which may have followed joints or other planes of weakness to a depth of many feet. Masses of clay 30 to 60 feet wide have been seen 80 feet below the rock surface. In general, however, the clay pockets are numerous at the surface and are absent or much smaller at depths of 10 to 20 feet. The bulk of the clay usually occurs in the upper 6 to 12 feet of the rock mass; at many quarries this upper zone contains as much clay as rock, and at some the proportion of clay is higher.

Conditions like the foregoing are not by any means confined to the Shenandoah Valley; they may be found in almost any deposit of limestone that has been exposed to the action of ground water. Thus, the problem of removing overburden from uneven surfaces is not local but is general. It commands the attention of many operators in widely separated regions. As the irregular surface is the most difficult phase of the problem, the equipment and methods used in removing overburden will be considered on this basis first, and the necessary modifications for less complex conditions will be discussed later.

METHODS OF REMOVING OVERBURDEN FROM ERODED SURFACES

Two general methods are followed in removing overburden. The greater part may be stripped back before the ledge is blasted down, or the clay and rock may be shot down together and separated later on the quarry floor. The first method is usually followed where 1 or more feet of solid clay lies above the highest points of rock. Where numerous knobs or ridges of rock are exposed at the surface, the difficulty of digging the clay from between the rock masses commonly results in the quarryman's following the second method—

that of blasting down rock and clay together and separating them while loading.

Merits of methods.—When a large volume of clay is free enough from rock masses to permit the use of such mechanical equipment as the steam shovel or drag-line scraper, the wiser method undoubtedly is to remove as much as possible of the clay before blasting down the rock. If the rock surface is so rugged that the use of hand tools only is advisable, the relative merits of the two methods are more difficult to judge. When rock and clay are shot down together, their separation is made slow and difficult. In rainy weather the clay adheres to the rock fragments, and the quarrying of clean rock becomes impossible. On the other hand, if the pockets are cleaned before blasting, the clay is fairly free of loose fragments of rock,

FIGURE 4.—Eroded rock surface stripped by hand labor

and the rock subsequently shot down is clean in wet or dry weather. In loading dirt at the quarry floor, however, the laborer is required to lift it only high enough to clear the edge of the quarry car, but in cleaning out pockets from the surface clay must sometimes be raised 10 to 20 feet. Clay on the quarry floor is loose and it usually is loaded much more rapidly, whereas the firm, undisturbed clay in the pockets may require excessive use of the pick, or may even require blasting; thus its removal is slow and expensive.

High cost of hand loading.—Hand loading of clay is laborious, slow, and costly. Most quarry operators recognize this fact, but, owing to the difficulty of removing clay from irregular cavities by mechanical means, the hand method is still widely used. (See fig. 4.) The cost of loading dirt by hand at the quarry floor in 1922 ranged from

15 to 25 cents a cubic yard; hand loading of clay at the surface cost 30 to 45 cents a cubic yard. The latter figures apply to direct loading of the clay from the bank to the car or dump cart. The cost may be very much higher where the clay is removed from deep cavities. At one quarry visited four men shoveled the same masses of clay to successively higher benches, and the fifth man loaded it into a dump cart. Under such conditions the cost might reach \$1 or \$1.50 per cubic yard. Cheaper methods now employed or proposed are discussed in the following paragraphs.

Hydraulic method.—Equipment for hydraulic stripping includes a stream of water under pressure, usually supplied by a pump; a pipe line; a mounted nozzle or monitor; and possibly an additional dredging pump with the necessary source of power. The possibility of natural pressure on the water is not to be forgotten, for in

FIGURE 5.—Eroded limestone surface stripped by hydraulic method

mountainous regions it may be important. Hydraulic stripping is the most economical method known if conditions are favorable (see fig. 5), but the governing factors are somewhat exacting. The chief requirements for successful hydraulic work are as follows:

1. There must be an ample supply of water. On an average, about 10 tons of water are required for each ton of material moved. The same water may, however, be used repeatedly if settling basins are provided for its clarification.
2. A favorably situated area for waste disposal is a prime necessity. The most favorable conditions exist where the overburden may be washed back from the quarry face or washed laterally into a ravine or basin where it can remain. Under such conditions one pump only is needed—that which supplies a stream of water under pressure to the nozzle or monitor. If the waste must be raised, a pump of some

kind or a hydraulic elevator is required, and this adds to the expense. The construction of dams or walls for an artificial settling basin may increase the cost further.

3. Power is usually the heaviest item of expense in hydraulic work. Electric power is preferable but is not essential.

4. Hydraulicking is most effective where the overburden is so friable that it can be readily washed down and carried away with a stream of water. The presence of hardpan or numerous heavy boulders may render the hydraulic method unprofitable. A hard soil may, however, be successfully handled if it is first shattered by light blasts in holes made with a soil auger.

Although the conditions mentioned above are usually regarded as essential, successful hydraulicking has been done under some adverse conditions. At a cement-plant quarry near St. Louis, Mo., that the writer visited a few years ago, the soil washed down by the hydraulic method was carried across the quarry to a river by aqueduct. At a cement plant in Virginia the clay overburden is washed to the quarry floor, where later it is loaded by steam shovel and removed in cars.

One outstanding advantage of the hydraulic method is its adaptability for removing overburden from irregularly eroded surfaces. The stream of water may be forced into cavities and pockets from which clay is removed with great difficulty by any other means. Figure 5 illustrates an eroded surface of limestone stripped by the hydraulic method. If conditions are at all favorable, hydraulicking is undoubtedly the cheapest means of stripping uneven surfaces.

The hydraulic method has been used with success in the Shenandoah Valley, removing soil at a cost of not more than 12½ cents per cubic yard. The Bureau of Mines has a record of hydraulic stripping at a marble quarry in Tennessee, in 1916, which cost only 2 cents per cubic yard. In the gold districts of California, where some years ago hydraulic mining flourished, the cost of handling gravel was about 2½ cents per cubic yard. As the actual gold content of much of the gravel did not exceed 3 to 5 cents per cubic yard, the cost of hydraulicking must have been kept considerably less. At one of the large iron mines in Minnesota extensive hydraulic stripping was done about 1914 at an average cost of 6.7 cents per cubic yard, including upkeep and office expense. In the Florida phosphate fields the hydraulic stripping of fine overburden cost 5 to 8 cents per cubic yard in 1912. In the brown phosphate fields of Tennessee hydraulic stripping some years ago cost about 7 cents per cubic yard. At a Missouri cement-plant quarry that the writer visited in 1916 the cost of hydraulic stripping, including the blasting of hard soil, was about 7 cents per cubic yard. Under 1925 operating costs these figures should be increased approximately 50 per cent. In 1923 the hydraulic stripping of a granite quarry in California required only three men—

a nozzleman and two helpers with pick and shovel to break clods and perform other incidental duties. It is estimated that they removed on an average 100 cubic yards of soil per eight-hour day.

Drag-line excavator.—A drag-line excavator worked from a derrick arm has been used successfully in cleaning out clay pockets in Pennsylvania, as Figure 6 shows. The entire equipment is on a portable mounting, and the excavated material is loaded on cars in the same way as when a steam shovel is employed; it cleans out shallow depressions fairly well, but the deeper cavities require some handwork. The lateral motion of the derrick arm gives the excavator a wide range and great flexibility of movement.

FIGURE 6.—Drag-line excavator used in stripping

Drag-line scraper.—The simple drag-line scraper may be used where a convenient dumping ground is available. Although some handy devices for shifting the sheave attachment have been devised, in general this scraper lacks flexibility of lateral motion. In 1921 one Ohio operator used a drag-line scraper for removing about 6½ feet of stripping from a fairly smooth surface with only 10 to 15 per cent of the clay in pockets. Between 7,000 and 8,000 cubic yards of material was removed at a cost of 50 to 60 cents per cubic yard.

Clamshell bucket.—A clamshell bucket worked from a derrick arm or crane has been used to move soil overburden. Its usefulness in removing clay from erosion cavities remains to be established. Best service would be obtained in cavities 6 feet or more across.

Tractor excavator.—In Pennsylvania a small tractor excavator widely used in road grading has been employed with success on eroded limestone surfaces. The dipper slides back and forth on an arm 12 or 14 feet in length, which may be raised and swung aside for dumping into cars or wagons. The excavator is so arranged that the dipper may be lowered into a pit and loaded as it is drawn toward the surface. This arrangement permits the dipper to be used in cleaning out clay pockets.

Steam shovel for soil only.—Several operators have used steam shovels with success on very uneven surfaces. Rock projections so interfere with continuous operation that great patience is required, and the operator must be prepared for much lost time both in loading and in moving. The shovel will not dig from deep pockets, hence much handwork must follow; but where several feet of clay is encountered the steam shovel is much more economical than hand loading. The smaller type of tractors, or caterpillar shovels with dippers not more than three-fourths yard in size, are best adapted for such work.

The actual cost of steam-shovel stripping shows a wide range. In the Florida phosphate fields the contract price for steam-shovel stripping in 1912 was 20 cents per cubic yard. At several cement-plant quarries visited by the writer in 1916 and 1917 the cost of steam-shovel stripping ranged from 11 to 16 cents per cubic yard, including transportation to the dump. The Dolomite Products Co., of Cleveland, Ohio, in substituting a steam shovel for hand loading of soil overburden, found that the daily cost of handling the same amount of material was reduced from \$137.50 to \$35 a day. At one quarry in the Middle West a steam shovel with a $3\frac{1}{2}$ -yard dipper strips 15 to 20 feet of soil and loads it into cars hauled by locomotives. The rock ledge quarried is only 25 feet thick, and it is claimed that the stripping charge against the quarry is only 5 cents per ton of rock removed. The costs given above relate mainly to stripping fairly smooth surfaces. Where the surface is rough and as much as possible of the soil is to be removed mechanically, the cost will be much higher; also, some of the figures relate to pre-war conditions. Steam-shovel costs of 40 to 50 cents per cubic yard were noted in 1922, although much lower figures have been attained under favorable conditions.

An interesting modification in the use of the steam shovel has been proposed but has not yet been tried. It is suggested that rock and soil be blasted down together, the serviceable stone sorted out and removed, and a steam shovel employed to clean up the soil and waste on the quarry floor. All good stone in the waste material could be thrown aside in loading. As previously mentioned, the

adherence of mud to the rock during rainy weather is a disadvantage, but as waste is much more slowly loaded than good rock by hand methods the proposed scheme has some merit.

Steam shovel for both rock and clay.—A method recently tried with success in Virginia involves the use of the steam shovel for both rock and clay in the upper part of the deposit. The great bulk of the clay in pockets and seams is confined to the upper 6 to 12 feet of the limestone deposit. A cut 6 to 12 feet deep is made with a small shovel, the clay loaded into cars, and the rock masses drilled and blasted as they are encountered. The cut is parallel to the quarry face and close to the edge of the excavation. All rock masses encountered are thrown over the edge with the shovel dipper and are later blasted and loaded by hand on the quarry floor. This makes possible clean separation of rock and soil. Figure 7 shows the load-

FIGURE 7.—Steam shovel handling mixed rock and soil; soil being loaded into horse-drawn cars

ing of soil into horse-drawn cars, and Figure 8 the process of throwing rock masses over the edge of the quarry pit.

As thus briefly outlined, the method is one of the most promising now in use, for it permits removal of almost the entire mass of clay with the steam shovel and leaves the underlying limestone ledge relatively clean and well prepared for ordinary methods of quarrying.

Steam shovel with washing and screening plant.—A proposed method which has much in its favor for large projects uses a washing and screening plant. Heavy overburden may be stripped back with a steam shovel, but it is proposed that all clay not readily handled by this means be blasted down with the rock, and the mass of mixed rock and soil loaded with a steam shovel on the quarry floor and conveyed directly to the washing and screening plant. Most opera-

tors will admit that with present high wages the steam shovel is far more efficient than hand methods for loading rock or soil. The great weakness of the mechanical shovel is its inability to sort the materials that it loads, and hand methods are employed because the stone must be sized and separated from the clay. The washing and screening equipment accomplishes the necessary sizing and purification of the rock and thus permits steam-shovel loading. Small operators probably could not employ such equipment profitably, but at the larger plants there is no evident reason why washing and screening equipment could not be employed successfully.

Removal of clay from deep erosion cavities.—Occasionally clay-filled cavities of large size are found. In one quarry in Virginia a mass of clay 60 feet across reached to the bottom of an 80-foot excavation.

FIGURE 8.—Steam shovel handling mixed rock and soil; rock masses thrown over edge into quarry pit

The slow hand methods employed for its removal seriously curtailed the output of the plant for two years. A mechanical shovel working on the quarry floor could have removed such a mass in a few weeks.

There are often deep erosion cavities in places where it is difficult or impossible to employ ordinary mechanical methods of removal. Several instances have been observed where a succession of laborers shovel the clay from bench to bench until it is finally thrown to a point from which it can be loaded into cars or dump carts. Such methods date back to antiquity and are prohibitive under modern wage conditions. If a clamshell bucket, drag-line excavator, or similar device can not be employed, it is suggested that the soil be elevated mechanically by means of some type of wagon-loading equipment now so generally used. A portable belt or bucket elevator is easily placed in position and may be operated at low cost by electric

motor or gasoline engine. With such simple equipment two men could easily do the work of six or seven.

AVOIDANCE OF STRIPPING BY UNDERGROUND MINING

Some operators have solved the stripping problem simply and effectively by adopting underground methods, a type of rock removal that has much in its favor. The problem of mining limestone is discussed in some detail later and is also covered by a special report, *Underground Limestone Mining*, Bulletin 262, Bureau of Mines, by J. R. Thoenen.

STRIPPING FROM SMOOTH ROCK SURFACES

Moderately uniform rock surfaces favor mechanical stripping, which should be employed wherever possible. The power shovel is the most popular type of equipment. Drag-line scrapers, excavators, or the hydraulic method may be employed if conditions are favorable. The advantages, methods of operation, costs, and other information on the various types of equipment are given in some detail in previous paragraphs. In general, when the rock surface is smooth, stripping costs will be lower for any type of equipment than when surface irregularities impede operations.

DRILLING AND BLASTING

TYPE OF BLASTING REQUIRED

Limestone for lime burning is obtained chiefly from open-pit quarries in ledges of high-grade rock. In blasting down these rock ledges the disruptive force exerted should be somewhat less severe than in blasts at cement-rock quarries yet more intense than at dimension-stone quarries. In blasting rock for Portland cement the purpose is to shatter the strata as much as possible, for the raw materials are all ground to a fine consistence before calcination. On the other hand, blasting for dimension stone must be conducted with the greatest care, as the massive blocks must not be shattered in any way. Blasting for lime manufacture falls in an intermediate position between these two extremes, for while the charges must be heavy enough to throw down great masses of shattered rock the purpose is to obtain a large proportion of fragments larger than 4 inches and a minimum of fines, for in burning lime with the shaft kiln most of the materials under 4 inches must be excluded. In working out the spacing of drill holes and the nature and quantity of explosive this principle must be kept constantly in view.

DRILLS USED

Piston drills are used in many localities for drilling horizontal, inclined, or vertical holes for primary blasting. Hand-manipulated compressed-air hammer drills are used to some extent in primary drilling, but chiefly in secondary drilling in preparing pop shots to break up the larger fragments. Of late years the churn drill, commonly called the well drill, has been used very widely for primary drilling in place of piston drills.

PISTON AND HAMMER DRILLS

Some years ago steam supplied the power to nearly all piston drills. Steam is uneconomical, as losses of heat by radiation and condensation are very high, although they may be overcome somewhat by insulating the pipes or by using superheaters. Compressed air has proved much more economical than steam, and it is now in general use at lime plants.

Although the hammer drill works rapidly, is mobile, and may be held with the hands without a tripod or bar support, even for down holes 12 to 20 feet deep, it is not in general use for heavy blasting because the drill bit is small. The ordinary hammer drill uses a 1½-inch bit to start a hole, while the piston drill is 2¼ inches in diameter. As the depth occupied by 4 pounds of dynamite in the hammer-drill hole would accommodate 9 pounds in the piston-drill hole, the latter is generally preferred. Some quarrymen, however, believe that the speed of operation of the hammer drill more than compensates for the restricted size of the holes, therefore the hammer drill is used for primary shots. Operators who keep drilling and blasting records that show the relative efficiencies of the piston and hammer drill would render a useful service to the lime industry by submitting the figures to the Bureau of Mines for analysis and general circulation.

A piston drill supported by a tripod or bar may be used for holes drilled from the top or from the face. Horizontal or inclined holes drilled from the face are often used where an irregular or seamy rock surface makes vertical drilling slow and costly. In some places drilling from the face is preferred even where there is no impediment to vertical drilling. Moreover, horizontal holes at the base of the bench, known as "snake" holes, may supplement the vertical holes where the mass to be removed is heavy, or where it is otherwise difficult to break the rock effectively along the quarry floor.

Where snake holes are used in conjunction with vertical holes the former are usually started 1 to 2 feet above the floor to give

working space for the drill and are slanted downward at an angle that will bring the end of the hole 1 or more feet below the quarry-floor level. Holes that are to be sprung are commonly terminated at or slightly above the floor level.

FACE DRILLING AND BLASTING IN PENNSYLVANIA

In the Bellefonte and Tyrone districts, Pennsylvania, much of the drilling is from the face. A typical method is to drill holes in pairs, beginning about 5 feet above the quarry floor, one hole slanting downward, so that at a depth of about 10 feet it is 1 or 2 feet below the level of the quarry floor, the other starting from about the same point and slanting upward. Four or five pairs of such holes are drilled at intervals along the face. They are sprung several times to obtain a chamber large enough to hold an effective charge. In springing, 1 to 3 or 4 sticks of dynamite

FIGURE 9.—Method of working quarry face of limestone with inclined open bedding planes: *a*, First bench; *b*, second bench; *c*, drill holes; *d*, walls of quarry excavation; *e*, quarry floor

may be used in each hole for a first charge, 5 to 8 for a second, 10 to 20 for a third, and 20 to 30 for a fourth. The holes may be sprung more than four times, but it is not advisable to make the springing charges very heavy, for cracks may be opened that will decrease the effectiveness of the final charge. The effect of the succession of springing charges is to make a chamber at the bottom of each hole

large enough to hold at least two boxes of dynamite. For the final charge the chambers and part of the drill holes are completely filled with explosive and the remainder of the holes tamped with clay or rock dust. The charges are fired simultaneously by electricity.

BENCHING ON INCLINED BEDS

In many lime districts the limestone strata dip at steep angles, and where the rock lies in beds separated by open seams special methods of benching may be pursued. The position of the beds and the method of quarrying at one Virginia quarry are shown in Figure 9. The beds dip about 45° , are 3 to 6 feet thick, and are separated by thin seams of clay. To drill vertical holes in such rock is difficult, for the drill is diverted from its true course when it meets the open seams. Also, much of the explosive force of the charge is dissipated in the spaces between the beds. It is found better, therefore, to work out the benches on inclined floors, utilizing

the bedding planes for floor seams. The mass *a* above the first open seam is worked out by blasting in holes drilled from the surface, or the charges may be placed in "dirt holes" made with a bar in the clay-filled seam. The latter blast may be of low efficiency, but the cost of drilling is saved. Working from the floor of the first bench, holes are drilled in the second bench *b* perpendicular to the bedding, as shown at *c*. Successive beds are worked out in the same manner.

Although some difficulty is encountered in moving and operating tools and machines on the inclined floors, the advantages of drilling and blasting in sound rock justify the method. Mounted piston drills are now used, but it would probably be more efficient to use hammer drills on such low benches.

BLASTING IN "DIRT HOLES"

In many limestone deposits, particularly in the Shenandoah Valley of Virginia and West Virginia, clay seams 1 or more feet across may continue many feet beneath the rock surface. Such seams are sometimes utilized to save the expense of drilling. A hole 12 to 18 feet deep is made in the clay seam with a soil auger and is sprung once with one stick of dynamite, forming a chamber about the size of a nail keg. The chamber and part of the hole are filled with dynamite, tamped, and fired. The charge, being deep in the rock mass, is fairly effective.

CHURN-DRILL BLASTING

The churn drill, or well drill, as it is commonly called, has been used very widely in quarry work in recent years. The mode of operation is so familiar to all quarrymen that a description is unnecessary. Recent modifications and improvements are described in manufacturers' catalogues. Churn drills may be driven by steam, gasoline, compressed air, or electricity. The latter is probably the most convenient and requires the least labor.

Heavy blasting in deep churn-drill holes is very commonly employed in limestone quarries, particularly where the product is used as crushed stone or for cement manufacture. The method is used less widely at lime-plant quarries, partly on account of unfavorable quarry conditions and partly because quarrymen are unfamiliar with the advantages or the method of operation of this type of equipment. Faulty blasting in churn-drill holes has also aroused the prejudice of some observers. A few years ago a churn drill was tried in a limestone where clay pockets were numerous and continued many feet below the surface. Unfortunately the drills either

penetrated or came close to the clay pockets or cavities, thus most of the force of an expensive charge was dissipated and the rock ledge was scarcely shattered. Churn-drill blasting is now done very successfully in this same quarry by carefully avoiding clay seams and pockets, but the one glaring example of failure and heavy loss has discouraged surrounding quarries from using such drills. In many large lime-plant quarries, particularly in the Middle West, churn-drill blasting is widely employed and with marked success. Figure 10 illustrates a four-hole blast on a 115-foot face at the moment of discharge.

In view of the wide use of other methods and the difference of opinion on the subject, consideration of the advantages and disad-

FIGURE 10.—Quarry face 115 feet high blasted with explosive in churn-drill holes; view at moment of blast

vantages of the churn drill and the conditions that govern its successful use is desirable.

Advantages claimed for churn drill.—An outstanding feature of churn-drill work in deep quarries is the substitution of a single bench the full height of the face for a series of benches. Disadvantages of multiple-bench quarrying that may be obviated by using the churn drill are (1) the danger to workmen of rock fragments falling from one bench to another, (2) the loss in productive capacity where men are watching for rock from the bench above, (3) loss of time and danger of accident where workmen climb ladders and move explosives and equipment from bench to bench, and (4) unduly complicated transportation of rock from different levels.

Another undoubted advantage is the fact that churn-drill holes are as large or nearly as large at the bottom as at the top, whereas piston-drill or hammer-drill holes diminish with increasing depth; the small holes are, therefore, usually sprung with dynamite to give space for the explosive, a tedious and somewhat dangerous operation, but churn-drill holes seldom require springing.

According to some authorities, the drilling cost is lower for churn drills than for smaller drills, but opinions differ on this point. The purpose of drilling is to obtain space for the explosive, consequently the only fair method of comparing costs is to consider drilling, not in terms of cost per foot but rather on the basis of the volume of space obtained. Churn-drill holes are usually about 6 inches in diameter. It is claimed that some of the improved hammer drills will project holes to a depth of 30 to 36 feet and will maintain a diameter of 2 inches at the bottom. The volume of drill holes of various sizes varies as the square of the diameter, therefore a 6-inch churn-drill hole of a given depth has nine times the volume of a 2-inch hole of the same depth. Hence, if no springing is employed nine 2-inch holes are needed to provide space for explosives equal to that supplied by one 6-inch hole. For lower benches tripod or hammer-drill holes may maintain a diameter of $2\frac{1}{2}$ inches to the bottom, and about six such holes are equivalent to one churn-drill hole. It is then evident that the small drill competes more keenly with the churn drill in the shallower holes, where there is little loss in diameter from top to bottom. Therefore, where springing is not employed the problem of relative cost resolves itself into the question: Is the total cost per foot, including repairs, overhead, interest on investment, etc., six times as great for churn-drill operation as for small drills that bottom with $2\frac{1}{2}$ -inch diameter, or nine times as great as for small drills that bottom with 2-inch diameter? The advantage probably lies with the small drills for shallow benches, and with churn drills for high benches. It would be very interesting to obtain cost figures indicating the height of face for which the drilling costs were equal for each type of machine.

If the small drill holes are sprung, comparison of efficiencies of large and small drill holes is more difficult. To compare the methods properly, the cost of the time and explosive employed in chambering the holes must be added to the drilling cost, and the volume of the chamber obtained must be compared with the volume of the churn-drill hole.

There is considerable delay in all quarry operations when primary blasts are discharged. All quarry workers must remain a safe distance away, and it may be found necessary to move some equipment. Blasting in churn-drill holes is usually on a large scale, a

single blast at times supplying rock for several months' handling. There are then smaller losses from delays incident to big-hole blasting than where more frequent blasts are discharged in the smaller drill holes. Such delays are reduced where blasts are fired at the end of shifts.

Some quarrymen claim that heavy blasts in churn-drill holes break the rock very effectively and little secondary blasting is necessary, but advocates of small-hole blasting claim that the more general distribution of the explosive throughout the rock mass in small holes breaks the rock more completely, and less block-hole shooting is necessary than with churn-drill holes. These opposing views leave one somewhat in doubt. Undoubtedly different results are obtained with different types of rock. In any event the amount of secondary blasting depends largely on the quantity of explosive used and the arrangement of drill holes for the primary blast.

Unfavorable conditions for churn drill.—A churn drill is most advantageous where the quarry face is 30 to 100 feet high, although it has been used successfully on benches of not more than 20 feet. As low benches require closer spacing of drill holes and lighter charges, smaller drills are usually preferred.

In many limestone regions the rock is greatly dissected by erosion, leaving a very rugged surface, over which it is difficult to move a churn drill, and mounting the drill on a timber staging is necessary. Where this condition is pronounced it may be cheaper to drill from the face with piston or hammer drills.

Limestone beds, particularly in the Appalachian belt, may be tilted at steep angles and may be separated by open or clay-filled seams. When the churn-drill bit meets such a slanting surface it may be diverted, forming a crooked hole in which the tools may bind, causing great loss of time with possible loss of the drill bit and abandonment of the hole. To overcome this difficulty, pieces of rock, wood, or cast iron may be thrown into the hole, so that the drill will pound on them for some time. When the downward progress of the drill is thus retarded it enlarges the hole, particularly by cutting away the rock that tends to divert it from its vertical course; thus the hole is straightened. Another method of overcoming the difficulty is to enlarge the hole by exploding a stick of dynamite in it. The claim is made that with improved types of cutting tools inclined seams give little difficulty. If delays from this cause are excessive, drilling into the face may be preferable. An alternative method is to work out the rock in low inclined benches, utilizing the open seams for bench floors, as described on page 28.

In some deposits successive beds may so vary in composition that they must be applied to different uses. In one Pennsylvania quarry

the upper beds are used for fluxing and road stone and the lower beds for the manufacture of pure chemical lime. Obviously, such a quarry should not be worked as a single bench, hence is not adapted for churn drills unless one or more of the separate benches is at least 20 or 25 feet high. In this particular quarry the upper ledge is drilled from the surface with mounted piston drills, and the lower ledge is reduced by blasts in chambered snake holes.

Factors governing successful blasting in churn-drill holes.—*Arrangement of churn-drill holes.*—According to Russell,⁵ a single row of holes is probably best where the quarry face is 50 or more feet high. If the face is 20 to 30 feet high, two to five rows of holes may be shot at a time. When two or more rows are shot at once the alternate rows are usually staggered. The burden (distance of hole from face) and spacing (distance from hole to hole in the row) may vary considerably in different types of stone. It is probably better to begin with close spacing and increase it gradually until the maximum spacing that will effectively shatter the rock is attained. In average limestone worked from a quarry with a 35 to 40 foot face the spacing should be 10 to 12 feet and the burden 12 to 15 feet. Spacing and burden should increase with increasing depth of holes but should rarely exceed 20 to 25 feet for the deepest holes.

Clearing the toe.—In approximately flat-lying beds an open bed plane may sometimes be utilized to form the quarry floor; it is then comparatively easy to blast out the rock to the base of the ledge. Where no open bed seam exists or where the rock is steeply inclined and no joint is present that may be utilized for a floor seam, clearing the rock at the toe is more difficult. A common mistake in drilling is to project the hole too short a distance below the quarry-floor level. One blasting expert advises a depth of 5 feet below grade in solid limestone. A certain amount of rubbish usually accumulates in the drill hole before it is loaded, therefore drilling too deep is better than drilling too shallow. It is also claimed that drilling 5 feet or more below grade tends to reduce the percentage of fines in the lower part of the bench.

Avoidance of pockets and seams.—In drilling large or small holes it is of first importance to keep the drill in solid rock and as far as possible to avoid drilling close to seams and pockets. If open seams occur in any definite system or exhibit any degree of regularity, it may be wise to plot their direction and dip and thus determine the proper position for drill holes. Where irregular erosion cavities occur their positions may not be foreseen and drill holes may be lost by meeting cavities. If large open or clay-filled spaces are

⁵ Russell, S. R., "Pointers on use of explosives in quarry blasting": Cement, Mill and Quarry, Jan. 20, 1922, pp. 36-40.

encountered, it is generally advisable to abandon the hole. Where the drill hole cuts a seam of moderate size the hole may be utilized if no explosive is placed close to the seam, the drill hole, from a point 3 or 4 feet below the seam to a point 3 or 4 feet above it, being filled with stemming. Concreting the cavity and redrilling it when the cement has set has also been employed.

Choice of explosives.—Ammonia dynamite is the most common explosive in quarry work. Gelatin dynamite should be used in wet holes. In producing limestone for lime manufacture explosives with a high rate of detonation should not be generally used. High-grade explosive tends to shatter the rock into small pieces that are not used in lime burning, except in the rotary kiln. Dynamite of 30 to 40 per cent strength is most satisfactory. In seamy rock some operators advocate the use of black blasting powder, which will penetrate the seams and push out the rock masses with little shattering.

Estimation of charge.—At many quarries determination of the amount of explosive to be used for the entire charge or for each drill hole is mere guesswork. Neither high blasting efficiency nor consistent improvement in blasting methods is to be expected unless the charge is regulated according to the estimated tonnage of rock to be moved. The determination of tonnage is so simple that any blasting foreman with a common-school education can work it out without difficulty. The tonnage for any particular drill hole is found by multiplying the burden in feet by the spacing in feet by the depth in feet (thus obtaining the number of cubic feet of rock) by the weight of a cubic foot of limestone (usually about 160 pounds) and dividing by 2,000. Thus, if the burden is 15 feet, the spacing 12, and the depth 50, the number of short tons of rock to be moved by the explosive in each drill hole is $\frac{15 \times 12 \times 50 \times 160}{2,000} = 730$ tons.

In determining the charge careful consideration must be given the number of tons that should be broken by each pound of explosive. In average quarry practice this varies from 3 to 6 for each pound of 40 per cent ammonia dynamite, depending on the toughness of the rock. The first charge may be estimated on an average basis, say, 4 tons per pound. For the drill hole mentioned above, 180 pounds of dynamite would constitute a reasonable charge. When the blast is discharged, results will indicate how correctly the charge was estimated. If the rock is not broken enough, the next charge may be calculated on the basis of $3\frac{1}{2}$ tons per pound; if too greatly shattered the charge may be increased to 5 tons per pound.

Best results are obtained not only by varying the charge but by changing the spacing or burden of the drill holes. If the rock is very brittle and is pulverized close to the explosive charge,

though not broken enough at a distance, it may be advisable to use smaller drills and thus distribute small charges more generally throughout the rock mass.

Russell⁶ advises that where more than one row of holes is shot at once the back rows should contain at least 10 per cent more explosive than the front row. He also recommends a shorter burden for the back rows.

Modifications in charge for steam-shovel and hand loading.—For hand loading the rock should be thrown out in a thin sheet, but for loading with a steam shovel the fragments should be piled in a steep ridge near the quarry face. The charge should be adjusted to give the desired result. In quarries with low faces, where several rows of holes are shot at one time to provide stone for steam-shovel loading, a method known as “buffer” or “blanket” shooting is sometimes employed. Part of the broken rock from the previous blast is left against the face to offer resistance or confinement to the charge, thus assuring better fragmentation, and to prevent rock from hurtling over the quarry floor and damaging or burying tracks. The buffer method is not applicable to faces more than 50 feet high.

Methods of firing the charge.—During the early period of quarry blasting all charges were fired by fuse. A multiple shot is, of course, much more effective where every hole is fired at once; it was made possible by the invention of the electric detonator. The methods of connecting wires for a multiple shot are explained in an earlier publication⁷ of this bureau, which is quoted as follows:

FIGURE 11.—A, Wiring in series;
B, wiring in parallel

Methods of connecting shots—series and multiple.—There are two general methods of connection that may be used when several shots are to be fired at one time. These methods are known as series connection and parallel or multiple connection; their distinguishing characteristics are shown in Figure 11. As a general rule, shots should be connected in series when they are to be discharged by hand or by spring-operated magneto generators, because these generators have not sufficient current capacity to fire shots in multiple. Where the shots are discharged by current taken from a power circuit, either series or multiple connection may be used. If shots are connected in series, a minimum potential of about $1\frac{1}{2}$ volts per shot will be required if the source of

⁶ Russell, S. R., Work cited, p. 39.

⁷ Bowles, Oliver, Safety in Stone Quarrying: Tech. Paper 111, Bureau of Mines, 1915, pp. 21–22.

potential is constant, and if it is variable, as is the case when hand or spring operated magneto generators are used, a somewhat larger voltage will be desirable. The source of power used to fire shots connected in series should be capable of supplying at least $1\frac{1}{4}$ amperes.

When the shots are connected in parallel, the source of power should have sufficient capacity to supply about an ampere for every shot to be fired and should be capable of supplying sufficient potential to force the total current through the conductors that connect the shots to the source of power.

Relative safety of the two methods.—When the shots are connected in series, it is easy to make a preliminary test to determine whether or not the circuit is open and, barring the presence of defective detonators, all shots will be discharged if the proper voltage is applied to the firing circuit. If the shots are connected in multiple, there is no easy way of testing for poor connections or for faulty detonators, and consequently the presence of either is more likely to pass unnoticed. On the other hand, if the shots are in wet ground and the wires are not properly protected from moisture and from leakage to ground, it is quite possible for some shots to fail when connected in series that would surely be discharged if they had been connected in multiple. It is practically impossible to state which of the two methods of connection is inherently safer if a sufficient supply of voltage and current is available.

Multiple or parallel series.—A third method, which is sometimes employed where many holes are fired at once, is a combination of the above methods and may be termed a "multiple-series" or "parallel-series" connection. Holes are connected in series in small groups, and the groups are connected in parallel. Each subseries must have the same resistance.

Each electric detonator should be tested with a reliable galvanometer. If any detonator shows abnormally high resistance, it should not be used when firing with a battery or where connected in series. The entire circuit should be tested in the same way when all connections are made, except those to the blasting machine or power circuit. For such tests the galvanometer should have long lead wires and should always be placed at a safe distance.

For parallel connection there should be 1 ampere of current for each detonator, and for series or parallel series at least 2 amperes for each series. When a blasting machine is used, the charges should always be connected in series. Whatever the method of firing, the current used should be much stronger than that actually required.

Strong detonators must be employed. No detonators weaker than No. 6 should be used with high explosives, and with less sensitive explosives, such as gelatin or ammonia dynamite or nitrostarch powder, No. 8 detonators should be used.

As a safety precaution at least two detonators should be placed in each charge. If a broken charge is employed, each separate part should have at least two detonators. Where heavy charges are fired in churn-drill holes, four or five detonators are commonly used in each hole, being distributed at regular intervals throughout its

length. Enough detonators should be used to insure sudden and complete discharge of the explosive.

Detonating fuse.—A method of firing that is gradually finding wider application in big-hole blasting involves the use of the detonating fuse known in the trade as cordeau. It consists of a lead tube carefully drawn to uniform size and filled with trinitrotoluene. The fuse extends to the bottom of each blast hole. After the holes are loaded and tamped a main line of fuse is placed on the surface and attached to the branches from each hole. No detonators are placed in the holes; one detonator is attached to the main line and when fired the explosive wave flashes along the main line and into each drill hole. As the rate of detonation of the fuse is very high all charges are fired at virtually the same moment.

Cordeau is wound on wooden spools. When a hole is ready for loading, the end of the fuse should be laced through a dynamite cartridge, which acts as a weight in lowering it to the bottom of the hole. The fuse should be drawn taut so it will lie along the side of the hole and not interfere with further loading. When the loading process is completed, the main line of cordeau is unreeled across the tops of the holes and the fuse projecting from each hole connected with it by splitting each projecting fuse in the center and placing the main line in the crotch of the split. The two halves are then twisted firmly about the main line in opposite directions. Placing the detonator on the end of the main line is the last step, and discharging it sets off the entire blast.

The advantages of the detonating fuse are greater safety and increased efficiency. Trinitrotoluene can not be exploded by friction, fire, or ordinary shock, but requires the shock of a detonator; thus it is much safer to handle and store than detonators. When the fuse is used, no detonators are required in the holes; thus the danger from accident during loading is greatly reduced.

As the fuse passes to the bottom of every hole it is in intimate contact with every part of the charge. When every part of every charge is thus fired at the same moment, the disruptive force is at a maximum. As the rate of detonation is very high the effect is to increase the rate of detonation of any low-grade high explosive used, thus increasing its disruptive force.

The detonating fuse is of great advantage in firing broken charges. Some limestone deposits consist of alternating weak and strong beds, the former requiring little or no explosive to shatter them. It may thus prove advantageous to fill the drill hole with explosive in strong beds and with stemming in weak beds. When detonators are used, one or more must be placed in each part of the charge, but the cordeau fuse is in contact with every part of the charge, irrespective

of the number of parts into which it may be broken, thus reducing the danger from misfires in broken charges.

The actual cost of cordeau for a given blast is much higher than for the detonators and wiring that may be substituted for it; however, the increased efficiency of the discharge permits reduction in the amount of explosive used, and time is saved in loading. These economies, plus the increased safety, encourage wider use of the detonating fuse.

Blasting records.—The development of steadily increasing blasting efficiency in any quarry depends upon the maintenance of proper records. One blast or a long series of blasts may be notably successful, but the results are of little advantage to a blasting foreman if he has no records indicating the spacing, burden, and depth of drill holes or the grade and quantity of explosive in each hole, for if such records are not at hand he can not duplicate the conditions of the successful blast. If such records are kept, it is easy gradually to develop better spacing of drill holes, better distribution of the charge, and other factors.

That the actual cost of explosive per ton of rock produced is not necessarily a measure of blasting efficiency should be emphasized. Loading costs can be materially reduced by increasing the amount of explosive, thus increasing the explosive cost. On the other hand, a poor primary blast may necessitate excessive block-hole drilling and secondary blasting, with much lost time. A measure of blasting efficiency may be obtained only by considering all items of cost, including drilling and explosive for primary and secondary blasts, loading, transportation, crushing, and overhead expense. A decrease in one item may lead to a disproportionate increase in others, and only by striking a proper balance between the various elements can the total minimum cost be found.

LOADING ROCK

IMPORTANCE OF LOADING

Removing fragments of broken rock from the quarry floor and placing them in cars for transportation to the kilns is a very important feature of quarrying. As loading rock constitutes the largest single item of quarry expense, consideration of the relative merits of different methods and the conditions under which each method may be most advantageously employed merit special attention.

HAND LOADING

Rock fragments are loaded by hand at virtually all small lime plants and at many large ones. Hand loading at a large Ohio quarry

is shown in Figure 12. Although the wide application of the method may be due partly to reluctance of operators to abandon methods long in use, its employment by many progressive companies suggests inherent advantages that merit careful scrutiny.

ADVANTAGES OF HAND LOADING

The small outlay required for loading equipment is an undoubted advantage to small operators with limited capital. Such equipment includes trackage, cars, and ordinary hand tools, such as pick, shovel, sledge, and fork. A second advantage is the opportunity it affords to select suitable material. Personal observation of every fragment

FIGURE 12.—Hand loading of limestone at a large Ohio quarry

permits rejection of siliceous or otherwise impure masses. The hand loader can reject clay or sand that has been blasted down with the rock. Such undesirable materials are loaded on separate cars and removed to the waste heap or to a screening plant for recovery of the best stone.

A third advantage, which has exceptional importance in the lime industry, is that a hand loader can keep the amount of fine materials at a minimum. In modern lime burning in shaft kilns very little rock smaller than 4 inches is acceptable, as it retards the draft. Although all exceptionally large rock masses encountered in loading are blasted, masses of medium size are sledged so as not to exceed

10 or 12 inches across. A skillful sledger can break rock into desired sizes, producing very little fine material. A mechanical breaker, such as the jaw or gyratory crusher, handles the rock much more roughly and will thus produce more fines.

A fourth advantage in hand loading is the steady flow of rock from the quarry to the kilns for the manufacture of lime. Delay often results from failure of loading equipment where loading is done by one large machine, as breakage of some essential part will cut off production entirely. The uninterrupted stream of rock from a number of independent units insures more continuous operation.

DISADVANTAGES OF HAND LOADING

The tonnage of rock handled per man employed is much lower with hand loading than with mechanical equipment, such as the steam shovel; a large gang of hand loaders is therefore required to produce the output necessary for a large lime plant, which is a decided disadvantage at times when labor is scarce or wages high. The rate of loading depends somewhat on transportation equipment. Low cars and a track arrangement that permits easy and rapid exchange of loaded cars for empties promotes a maximum loading rate.

Hand loading is usually on a contract basis at so much per ton. The desire to attain a large tonnage naturally tends to encourage carelessness in sorting for quality or in making a clean separation from soil. Even with constant supervision, much of the advantage of hand selection may be sacrificed to attain high tonnage. To overcome this tendency, the ledge should be shot down when possible in such a manner as to avoid mixing inferior rock or waste material with the good stone.

In loading waste materials the mechanical shovel has decided advantages. Hand loading of dirt and rock chips is slower than the loading of kiln stone. Commonly the contract price for loading dirt is 2 or 3 cents per ton higher than the price paid for loading good stone. In other quarries there may be no price differential, although it is recognized that loading waste may be twice as slow as loading rock, but this fact is taken into account in fixing a contract price to cover all materials. Although some operators prefer hand methods for loading limestone, they admit that such methods of loading quarry rubbish are very costly. Several have suggested the advisability of introducing some type of mechanical equipment for loading quarry waste to supplement hand loading of good rock, for it is realized that a mechanical shovel will load dirt even more quickly than it loads rock.

OPINIONS OF OPERATORS

Of 18 operators reporting to the Bureau of Mines on loading methods, 15 preferred hand loading and 3 machine loading. The principal reasons given by those favoring hand loading were ease of selection by size and quality, elimination of dirt, and high cost of mechanical equipment. Of the three that preferred mechanical loading, one represented a very large crushed-stone company that makes lime only as a side issue, another preferred the steam shovel to hand loading on account of labor shortage, and the third operates a mine in a very uniform clean stone where no sorting for quality is required.

FIGURE 13.—Loading with steam shovel at a large quarry

MECHANICAL SHOVELS

Mechanical shovels are very widely used for rock loading, but in producing stone for lime burning this type of loading equipment is used less extensively than in most other branches of the stone industry, largely because of the necessity for sorting stone by size and quality. As a steam shovel can not select its materials, crushing and screening equipment must be added, involving so heavy a first cost that many operators prefer to retain hand methods. The necessity for careful selection of stone to maintain a superior quality product is, however, the main reason for keeping to hand loading. Mechanical loading is confined chiefly to large operations. Figure 13 is typical of steam-shovel loading at a large quarry.

SIZE OF SHOVEL

The extent of the project should govern the size of the shovel. For a daily output of 150 to 300 tons of rock small tractor shovels

with $\frac{3}{4}$ to $1\frac{1}{4}$ yard dippers are suitable. Caterpillar tractors offer special facilities for rapid moving or for working on a soft bottom. For larger quarries heavier shovels should be used. It is uneconomical to use either too small or too large a machine. If the shovel is small in proportion to the size of equipment that will handle the output next, many blocks too large for the shovel to handle must be blasted, even though they are small enough to be readily crushed. Unnecessary blasting expense and waste of time result. On the other hand, the operating cost for a large shovel when the output is limited is excessive.

At one lime plant observed a 110-ton shovel with a 5-yard dipper handles a maximum of 900 tons of stone per day. Such equipment is too large for the operation.

ADVANTAGES OF MECHANICAL SHOVELS

With hand loading all rock masses must be broken to "one-man" size at least. A mechanical shovel, however, can handle rocks weighing several hundred pounds, or even more than 1 ton. If the primary blast breaks the rock moderately well, very little secondary blasting may be required, whereas in hand loading much secondary blasting and a great deal of laborious hand sledging are necessary.

To produce an equal tonnage a much smaller gang of men is required with a steam shovel than for hand loading. Figures were compiled by the Bureau of Mines a few years ago for tonnage of rock loaded per man at cement-plant quarries. At 14 quarries where steam shovels were used an average daily output of 112 tons per man was obtained, pitmen and shovelmen only being included. At 11 quarries where hand loading was used the daily tonnage per man for loaders only was 16, showing that about seven times as much rock per man can be loaded with steam shovels as by hand. The possibility of greatly reducing the number of workers by substituting machines has an important bearing on many problems that confront the operator. In some instances maintaining a large output with a greatly reduced staff has, for various reasons quite distinct from the actual cost, constituted the deciding factor in the introduction of mechanical loading.

DISADVANTAGES OF MECHANICAL SHOVELS

The ability of a mechanical shovel to load all sizes of rock from chips to masses weighing over 1 ton is a great advantage in so far as the actual loading process is considered, but it necessitates additional work later. For lime burning the rock must be in sizes approximately between 4 and 12 inches; thus it is necessary to have

crushing and screening equipment to supplement steam-shovel loading. Any operator who plans to add a mechanical shovel to his quarry equipment and who has no crushing plant must face the additional expense for machinery to break and size the rock.

A further limitation of the mechanical loader is its inability to sort material by quality. If flint, iron stain, or other undesirable impurities are scattered irregularly throughout the rock mass, the steam shovel loads them with the good rock. Lime manufactured from stone from which such impurities are not separated is of lower quality than that manufactured from hand-picked stone. A mechanical shovel handling rock of fluctuating quality therefore tends to degrade the final product.

A mechanical shovel and the necessary crushing and screening equipment require a heavy investment which may not be justified for a small plant, though it may be profitable for a larger one. For small to moderate-size plants with limited capital it may be more economical to load by hand.

SUGGESTED USE OF PICKING BELT

The inability of the steam shovel to sort for quality may be partly overcome by passing screened kiln stone over a picking belt, which is simply a belt conveyer from which inferior stone may be picked as it passes along. One or more employees skilled in the selection of stone stand by the belt, pick out impure lumps, and toss them into a convenient chute. This combination affords the advantages of mechanical loading, crushing, and screening, plus hand selection, and is decidedly superior to the ordinary method of selection during loading, for a hand loader is paid on a tonnage basis, quantity rather than quality being his chief incentive. On the other hand, the sole duty of the operator at the picking belt is to select for quality, and ability to perform this duty efficiently is the only justification for his employment. The picking belt is widely used in many metallic mineral industries but finds limited use in the nonmetallic. It is of interest to note, however, that one lime-plant operator in Ohio employs a picking belt from which two men pick siliceous or iron-bearing rock fragments. It gives a better selection of stone than could be obtained by hand loading and at the same time permits the use of steam shovels and a crusher. The quality of the lime has been greatly improved since the picking belt was introduced.

DIFFICULTY OF COMPARING COSTS

In any attempt to compare the cost of mechanical shovel and hand loading consideration must not be confined to the mere loading processes. The secondary blasting cost is higher for hand loading

than for shovels. On the other hand, a steam shovel loads a mixed product from masses weighing tons to fine chips and dirt, while hand-loaded rock is broken to size and separated from the fines. A hand sledge is a poor substitute for a rock crusher, and sizing of rock by hand picking is less efficient than mechanical screening; nevertheless they serve the purpose in a degree, and part at least of a crushing and screening cost must be added to the steam-shovel loading cost to allow a fair comparison of the methods.

The cost of hand loading is easily found, for it is done almost entirely by contract. In 1922 the average cost of hand loading for 17 quarries in eastern and southern United States was 17.5 cents per ton. To this must be added the small expense for tools, such as picks, shovels, and forks. Steam-shovel costs are more variable, as some operators estimate a cost as high as 15 cents per ton, though most of them give a much lower figure. Two operators of large lime plants gave a cost in 1922 of 6.4 and 6.2 cents, respectively, per ton. The cost of steam-shovel loading involves varied and complex factors. To the wages of shovel operators and pitmen must be added the necessary expense for fuel, oil, repairs, interest on investment, and amortization (a proportion of the value set aside each year large enough to replace the shovel, when it is unserviceable, with a new one). As noted above, in comparing the cost with that for hand loading part of the cost of crushing and screening should be added to the cost of steam-shovel loading and a deduction made to compensate for the reduced cost of blasting where the shovel is used. When the direct cost is considered, loading by steam shovel may appear to be very much lower than the cost of hand loading, but when all factors are taken into account the difference is not so great. However, for work on a large scale mechanical loading is probably much cheaper than hand loading.

FACTORS GOVERNING EFFICIENCY OF MECHANICAL SHOVELS

Dependence on blasting methods.—Small blasts on shallow benches are unsatisfactory when loading is by steam shovel, for a succession of small supplies of rock involves losing much time in moving the shovel and placing tracks. Heavy blasts that throw down large volumes of stone are more suitable for economical work with steam shovels. Furthermore, the blast should not throw the rock down in a thin sheet, for not only does that necessitate frequent moves, but the shovel dipper is filled with difficulty when it works against a small resistance.

Adjustment of the charge to break the rock properly is, of course, a prime necessity. Insufficient shattering causes the loss of much time in shifting masses of rock to one side for secondary blasting.

Influence of clean stripping.—As the steam shovel can not sort materials, a clean product can not be made if only part of the overburden is removed. Loading mixed rock and soil is justified only where equipment is provided for subsequent separation. Screens may give a clean separation in dry weather, but a mixture of clay and rock is more difficult to handle in rainy weather. If, through the presence of seams or clay-filled pockets, the overburden can not be removed entirely, washing equipment may be of great aid in promoting successful use of the steam shovel.

Suitable transportation facilities.—The great advantage of the steam shovel is its ability to load many tons of rock an hour, but this advantage is largely nullified in many quarries by delays in waiting for cars. Tracks should be so arranged that empties may be placed and loaded cars removed with the smallest possible loss of time. The supply of cars should also be adequate, so that small delays at the crusher will not halt loading through shortage of empties.

Ability of shovel runner.—The efficiency of a mechanical shovel depends largely on the skill of the shovel runner. An experienced man can load rock rapidly and can use the dipper to move cars or to set aside large masses of rock for blasting later. Care and good judgment are necessary qualifications. The ability to estimate properly the size and dimensions of blocks is an invaluable qualification for a shovel runner, because the loading of oversize fragments may greatly hamper work by delays at the crusher. So prevalent are delays from this cause that some quarries have the fixed rule that all rock loaded should pass through the dipper.

Maintenance of clean quarry floor.—Quarry floors are constantly littered with rock fragments thrown out by blasts or dropped from loaded cars. If the fragments are allowed to accumulate the quarry will become very untidy, making movement about it actually unsafe. At some quarries visited, numerous rock fragments, abandoned tracks, spare rails, and ties scattered at random over the quarry floor gave a chaotic appearance; other operators take pride in keeping the floor clean and neat, both for the improved appearance of the quarry and for the advantage gained in operating. Figure 14 illustrates a quarry floor which is kept remarkably clean by specially designated men.

TRANSPORTATION

EQUIPMENT

Transportation involves the motive power and equipment required to convey the rock from the loading place at the quarry face to the kilns where it is burned into lime. When crushing and screening plants are operated in connection with the quarry, a separate trans-

portation system is required to convey the rock from screens to kilns and to dispose of the fine materials. Ordinary transportation equipment may be divided into three classes—trackage, cars, and haulage systems. Trackage may for convenience be subdivided into horizontal or slightly inclined tracks and steeply inclined tracks that require cable haulage. Some special types of equipment are also used, for example, aerial tramways.

TRACKAGE WITHIN QUARRY

The arrangement of tracks for quarry cars depends on the loading method and the size and shape of the quarry opening. For hand loading it is desirable, for maintenance of a maximum output, to have many working places, each with independent trackage from the main line. A track arrangement provided by one Alabama company, as shown in Figure 15, is convenient for hand loading. A

FIGURE 14.—Remarkably clean and neat quarry floor at an Ohio lime-plant quarry

main track parallels the face; from it a series of spurs runs to the face, each spur ending in a Y. Thus space is provided on one branch for an empty car that may be loaded while a gasoline locomotive conveys the loaded car from the other branch of the Y to the main track. This arrangement allows uninterrupted loading and is most suitable for quarries with long working faces. At one quarry in Pennsylvania two such main lines are provided, one for empties and one for loaded cars; the latter are hauled away by locomotives in trains of 15 or 20 cars. At some plants the tracks converge like the spokes of a wheel from the quarry face to the point where the rock leaves the quarry. Thus cars may be placed at many points along the face, and the cars loaded at each working place may be moved independently. Such an arrangement is shown in Figure 16.

For steam-shovel loading two different systems are followed, according to the width of the working face. Where the face is wide

enough to permit necessary movement of cars, the car track should preferably be placed parallel with the face, as shown in Figure 13, so that cars may be moved along and filled in succession until a train of cars is loaded. This system is followed in virtually all large quarries.

To provide a wide face, however, is not always possible. A thin bed of limestone may stand at a steep angle and may be worked from the end, or other conditions may be present that make operation of a steam shovel on a narrow face necessary or advisable. Under such conditions the tracks should run directly toward the face; preferably there should be two tracks, both within reach of the shovel dipper, as illustrated in Figure 17. One, two, or (if the shovel arm has a long reach) possibly three cars may be placed on one track and loaded. Meanwhile, empties may be placed on the parallel track. As the empties can be filled while loaded cars are being taken away, fairly continuous operation of the shovel is assured. If, on the other hand, a single track only is provided, the shovel must remain idle while the loaded cars are being removed and empties returned.

Utilization of gravity as fully as possible for moving cars within the quarry is important. The

FIGURE 15.—Track arrangement for hand loading at a long quarry: *a*, Quarry face

possibility of gravity transportation should be kept in mind in the general layout of tracks in order that proper gradients may be obtained. In general, it is advisable to maintain a grade that will permit gravity movement of loaded cars from the face to the point of egress from the quarry, then horses, mules, or some form of mechanical haulage can return the empties to the face. Such a gradient also provides for drainage away from the quarry face. Tracks can be arranged to utilize gravity for all car movement within the quarry. At one cement-plant quarry in New Jersey empty cars are switched off considerably above the foot of the incline and conducted by gravity to the steam shovel, where the wheels are blocked until the car is loaded; then a continued down grade permits the car to run to the foot of the incline, so that transportation within the quarry is almost automatic. Conditions do not always favor such track arrangement, but in general gravity can be utilized much more than present quarry practice seems to indicate. Many operators have so arranged their quarries that gravity supplies the major power requirement for moving rock, but some quarrymen, even under favorable conditions, have failed notably to make any use of this cheapest of all sources of power.

In large quarries, where loaded cars are hauled in trains by locomotives, a suitable gradient of the tracks to utilize gravity has less importance than where cars are handled by mules, horses, or in part at least by quarry laborers.

At some point in the quarry the method of haulage usually changes. In pit quarries this point is at the foot of the incline up which the cars are hauled to the quarry bank. At shelf quarries it is the place where the cars are assembled for removal in trains. When shelf quarries are at elevations above the lime kilns, the method of transportation may be changed at the top of an inclined railway. Whatever the change in method may be, maintenance of adequate quarry trackage is important. Here empty cars are exchanged for loaded cars, and a system of switches and sidings

FIGURE 16.—Radial arrangement of tracks to quarry face

should be provided that will promote the greatest facility in this exchange of cars. From the branch tracks within the quarry a double track may lead to the foot of the incline or other position where the method of haulage is changed. One track is used for loaded cars, and the empties are switched over to the second track. When the incline is some distance from loading places one track may be used, but a siding must then be provided to accommodate empty cars. If several classes of materials are handled, several sidings are convenient. At one Virginia quarry sidings are provided for rock cars, dirt cars, and empties. The trackage plan is simple where loading is by steam shovel in wide quarries and the cars are removed in trains. The train of empties is brought in on a track beside the shovel, the cars loaded in succession, and the train of

loaded cars removed. If the grade permits, the entire train may be taken directly to the kilns. If an incline is used, the train of loaded cars is left at the incline and a train of empties obtained from a near-by track or switch.

Where loaded cars are removed in trains from quarries that use hand-loading methods, the trackage may be more complex. Tracks may be so arranged that loaded cars from the various spurs leading to the face may be assembled in a train; provision must also be made for so disposing of a train of empties that they may be readily distributed to the spurs.

Under exceptional circumstances no quarry trackage is required. The rock may be removed with overhead cableways, derricks, revolving locomotive cranes, or motor trucks. These methods are discussed later.

INCLINED TRACKS

Tracks so steeply inclined as to require a cable-haulage system are common at most lime plants. On such tracks rock may be removed from pit quarries, elevated to the kilns, or less commonly let down from high elevations to lower levels. The incline may consist of one, two, or more tracks. Where it is desirable to keep the crusher supplied with rock almost continuously, double tracks are often provided and carloads dumped into the crusher from opposite sides in alternation. On short inclines each car is usually handled independently, but on long inclines a car may be attached to each end of a long cable, the empty being returned while the loaded car is elevated. The weight of the empty car thus assists in elevating the loaded one and time is also saved. Such a system may have double tracks the entire length of the incline or a single track below the center switch and a double or three-rail track above it.

QUALITY AND CONDITION OF TRACKS

The gauge of quarry tracks is generally 24 to 42 inches, although standard railroad gauge, 56½ inches, is occasionally used. Twenty-four-inch gauge is most common where cars are hand loaded. When there is any prospect of extended development it is advisable to employ a 36-inch gauge from the start. A 24-inch gauge is too

FIGURE 17.—Track arrangement for steam-shovel loading at narrow face: *a*, Quarry face; *b*, steam shovel

narrow for satisfactory operation of cars loaded by power shovel, and if a quarry has already established a narrow-gauge system changes are expensive. Thus, a quarry may be very greatly handicapped by starting its career with a narrow gauge. Some companies are now unfortunately suffering the penalty of heavy expense for specially built narrow-gauge cars and in other ways are reaping the accumulating disadvantages of a narrow track. Few quarry operators would err by starting out with at least a 36-inch gauge.

Tracks should be of fairly heavy rail steel. A light rail is inexpensive and convenient to handle, but it requires close tie supports and is easily bent. The unevenness resulting from such bends causes many car derailments. The weight of steel required for tracks depends on the method of haulage and size of cars. For 2 to 3 ton cars hauled by animals or moved by gravity a steel 16 pounds to the yard may serve, but a 20 or 25 pound rail is better. For cars or locomotives weighing 7 to 10 tons the minimum weight of steel should be 35 to 40 pounds per yard. These weights greatly exceed those usually recommended, but money is well spent for additional weight in steel, as it results in easy haulage with few derailments and low upkeep.

Quarry tracks are very often damaged or destroyed by masses of rock hurled down by heavy blasts. One operator who employs moderately heavy blasting uses only heavy railroad rails and does not move them back when blasting, as they are strong and rigid enough to resist the blows of falling rocks without damage. Some operators dump carloads of stone on the tracks for protection. Most of them, however, move the tracks away from the danger zone. Track constructed in standard portable sections with steel ties aids rapid removal or replacement. Such sections should be of 16 to 25 pound steel.

A good roadbed should be maintained. An uneven track not only strains cars and wastes power but results in frequent derailments, with consequent breakage of equipment and great loss of time. The time thus lost may not only affect those who are loading and transporting but may seriously delay later operations.

Home-made switches that frequently fail to operate at critical times cause frequent derailments. As so much depends on switches, operators are urged to provide those that are properly manufactured. Saving a few cents or even dollars on a switch is poor economy if the cheap switch wastes time, wrecks cars, and causes maiming of employees.

Centrifugal force tends to overturn or derail cars on curves if the outer rail is not elevated adequately. The following table ⁸ gives the

⁸ The Mining Catalog (Metal-quarry edition) : Consolidated Keystone Publishing Co., 1924, p. 347.

correct elevation of the outer rail for a velocity of 6 miles per hour on a 30-inch track.

TABLE 3.—*Proper elevation of outer rail on curves of different radii for a speed of 6 miles per hour on a 30-inch track*

Radius of curve, feet	Elevation, inches	Radius of curve, feet	Elevation, inches
40.....	1¾	100.....	¾
50.....	1½	150.....	½
60.....	1¼	200.....	⅓
80.....	1		

The elevation should vary directly with the width of gauge; thus for a 36-inch gauge it should be $36/30$ or $6/5$ of that given in the table. The elevation should also vary as the square of the velocity. Thus for a velocity of 12 miles per hour, which is twice that given in the table, the elevation should be four times the number of inches given. This statement at once suggests the great risk involved in greatly increasing the speed beyond the rate for which curves are designed.

Grades should be modified to suit the method of haulage. It is not wise to use locomotives on very steep grades, as too much time and power are consumed. When a grade becomes unduly steep, it should be extended in length if possible, so as to reduce the gradient to a point suitable for satisfactory locomotive haulage. If this is not feasible, cable-car haulage should be substituted.

There is room for great improvement of trackage on inclines. Through unevenness of rail joints, improper spacing of ties, lack of uniformity in roadbed, or poor switches, cars may jump the tracks, losing time and damaging equipment. At one quarry the writer visited, cars jumped the track near the top of the incline four times in one-half hour. Part of the trouble may have been due to improper control by the hoist engineer, but poor trackage accounts for many similar mishaps. At one Pennsylvania lime plant the rails on the upper part of the incline consist of 5 by 5 inch angle steel, the 5-inch vertical web effectively preventing derailment.

The curvature of roadbeds is also an important feature of inclines, particularly with regard to safety. Lateral curvature is undesirable owing to the difficulty of controlling cables and the danger that results from the lateral movement of the cable as the car passes around the curve. Another undesirable condition is an upward or convex curvature of the roadbed, which renders the top of the incline invisible from points near the bottom. Such a condition is dangerous, for a workman at the foot of the incline can not observe the approach of a descending empty car until it has traveled possibly nearly half the total descent.

QUARRY CARS

Quarry cars are of many different types and sizes. For hand loading 2 to 2½ ton cars seem to be the most popular. Cars for hand loading should be low to save loaders the laborious task of lifting rock unnecessarily high above the ground. One company uses a car with one side 42 inches above the rail but with the loading side only 24 inches high. An open-side car, as shown in Figure 18,⁹ is adapted for hand loading, as the open side is only 15 inches and the opposite side 31 inches above the rail. The open-side car has an advantage also in dumping because there is no need of discharging the entire load at once; it may be tilted gradually and the load discharged as desired.

There is a strong tendency among hand loaders in some quarries to pile rock high above the sides to get a high tonnage with small

FIGURE 18.—Open-side quarry car well adapted for hand loading

cars. Rock masses are built up along the sides like piles of wood, a process known as “cording,” and smaller stones are thrown in the center. Cars thus loaded are dangerous to handle, as straining on a curve or an uneven track or the bumping of one car against another may dislodge the stone, causing injury to employees or derailment of cars. It is better to use larger cars moderately filled.

For steam-shovel loading larger and stronger cars are required. Side-dump cars are the most common, though end-dump cars are sometimes used. Although hand-loaded cars should be low, cars for steam-shovel work should be high, as a high position gives a better angle of discharge from the shovel dipper.

Both wooden and metal top cars are used, and each type has its advocates. The metal top is in general more durable than wood but

⁹ Photograph supplied by Easton Car & Construction Co., Easton, Pa.

is more difficult to repair. Where steam shovels are used metal tops are bent with the heavy rock masses, and it is difficult to straighten them. Some operators, therefore, prefer wooden tops that may be easily and quickly repaired in the quarry shops. Metal-protected wooden tops are most popular. Some quarry cars for heavy steam-shovel work are made of steel plate, an oak cushion over the plate and a light steel cover plate protecting the wood. The top plate allows a smooth sliding surface for discharging the load while the wooden cushion protects the main body plate. The light plate and wood are bolted to the body plate, thus may easily be replaced when worn out. One car manufacturer recommends a heavy protective plate over the wood, as a thin plate is too easily destroyed. It is also claimed that the lower steel plate should be omitted, as oak plank confined with steel plates on both sides is inclined to deteriorate from dry rot. Probably the most desirable and satisfactory car top for use with steam shovels consists of 4-inch white oak with no metal plate beneath it, but protected with a one-half-inch steel plate.

Quarry cars of many varieties are now in use. Opinion differs widely among operators as to the advisability of standardizing cars and reducing the number of sizes and styles now employed. Many approve such standardization, particularly where loading is by contract, as cars of uniform size and height remove a possible cause of complaint by loaders and simplifies the fixing of contract prices. On the other hand, many operators see little prospect of standardization, not only because of the great variation in quarry conditions but also other factors, such as size of crusher and type of haulage. As there are probably at least 250 different types of cars now in use, some reduction in variety would seem advisable. The demands are so variable that car manufacturers find it impossible to meet many requirements from stock. As special orders involve delay and increased cost, some simplification would undoubtedly be advantageous to manufacturers and users of quarry cars. One car-manufacturing company encourages the sale of two main types of cars for hand loading and two for use with steam shovels, but many specials are constantly required.

An adequate supply of cars must be provided. If few cars are available, any unusual delay in disposing of loaded cars may keep quarry loaders or loading equipment in idleness; on the other hand, delay in loading may soon retard later operations if there is no reserve supply of loaded cars. The number of cars required depends on the method of loading, the haulage distance, and the tonnage required. For a given tonnage hand loading requires more cars than machine loading, as many cars are being loaded simultaneously.

Obviously, more cars are necessary to insure continuous operation where a long haul is involved than where the haul is short.

HAULAGE WITHIN QUARRY

Gravity is the most economical means of propulsion if conditions are favorable. The utilization of gravity depends chiefly on track arrangement and has already been discussed in that connection. An economical method is to maintain a gentle down grade from the face to the incline, permitting loaded cars to proceed by gravity. The empties may be returned by horses or mules. Many operators prefer animal power for short hauls within a quarry or mine, especially where the rock is hand loaded, but there is a growing tendency to replace it with smaller types of electric or gasoline locomotives. As a later paragraph on costs shows, animal haulage is not economical for long distances. For larger operations, particularly where loading is mechanical and the haul exceeds 500 feet, locomotive haulage is generally employed. Steam locomotives or "dinkeys" are widely used and are favorably regarded by many. They may haul trains of 5 to 15 or 20 cars. Others prefer the gasoline or electric locomotives, some of them small and able to handle one to three cars only, although some of the newer gasoline locomotives will haul 10 to 15 cars. Under exceptional conditions the cable drum, which is almost universal on inclines, is used for the entire haulage distance from the loading point at the quarry face.

Some large quarries use the Woodford central-control electric third-rail system. The track is divided into sections, with an independent current for each section; thus cars on different sections are subject to independent control. The movements of cars are controlled from a central tower.

HAULAGE ON INCLINES

Cable-and-drum haulage is commonly employed on inclines. Usually at lime-plant quarries each car is handled as a single unit independent of other cars, but in many classes of rough-stone operation the empty descends on one end of the cable while the loaded car ascends on the other. Two or more tracks are ordinarily used, each with its own haulage system.

The so-called "ground hog" or "barney car" is used on some inclines in connection with a cable hoist. A heavy buffer, mounted on four wheels and attached to the cable, operates on a narrow-gauge track situated between the rails of the car track. Some distance from the foot of the incline the narrow-gauge track runs into a depression below the car-track level. When the cable is out, the buffer rests in this depression. The loaded cars pass along the track over

this excavation. As the cable winds on the drum, the buffer comes up behind the car and pushes it up the incline. Usually one car only is taken up at a time. One advantage of this method is that the inconvenience and danger of attaching the cable to loaded cars and unhooking it from empties are eliminated. Moreover, when the empty car is returned to the pit there is no need of stopping it or even of slackening speed at the foot of the incline, and the uninterrupted momentum may thus suffice to carry it to any part of the quarry.

The crushing plant and sometimes both the crushing and screening plants may be located on the quarry floor, and the sized rock elevated by cable car or otherwise. Figure 19 illustrates such a plant in Pennsylvania. Rock cars are taken by locomotive up an elevation to

FIGURE 19.—Crushing and screening on quarry floor prior to hoisting stone with cable car

the crusher house shown near the center of the illustration. A 40 by 42 inch jaw crusher reduces the stone to minus 8-inch size, and a pan conveyer takes the product to the screening house shown in the foreground, where it is screened to two sizes. All over $5\frac{1}{2}$ inches is taken up one cable incline and used for lime burning and for flux. Sizes under $5\frac{1}{2}$ inches are elevated by a second incline to a crusher house for recrushing and screening to various sizes for metallurgical uses, concrete aggregate, road work, agriculture, and glass manufacture. The inclines are shown in the lower right corner of the illustration.

In some localities the quarry is on higher ground than the lime plant, thus the rock descends by gravity, and a safe and efficient brake becomes an essential of the system. Figure 20 illustrates

such a plant where the quarry floor is 360 feet higher than the tops of the kilns. The incline is shown by the white line near the center of the illustration just left of the hydrating plant.

Skill and care are important requisites of an efficient hoisting engineer. Cars are often wrecked, operations delayed, and accidents caused by running cars at dangerous rates on inclines, by stopping or starting them too suddenly, or by failing to check the speed or bring cars to a stop at the proper points. Carelessness is the most usual cause of derailment.

Haulage equipment on inclines should frequently be inspected with care, and any weaknesses corrected without delay, as failure of equipment on an incline may have more disastrous results than similar failure on level tracks.

FIGURE 20.—Lime plant at foot of incline from quarry

HAULAGE BY AUTO TRUCKS

At one quarry in Ohio no trackage is maintained, all rock being hauled by auto trucks with specially provided extra-low gear. With smooth roadways and moderate grades the system is satisfactory.

ELEVATION BY BELT CONVEYERS

As shown in Figure 21, an inclosed belt conveyer is sometimes used instead of cable haulage. It can be used to greatest advantage where crushing equipment is provided at the quarry floor. The crushed rock may be elevated to bins which discharge to the belt as desired. At one Ohio plant the crushed rock is screened to plus and minus 4 inches. The plus 4-inch size is drawn from a bin to cable cars and hauled up an incline to the kilns, while the minus

4-inch stone is discharged from another bin to a 26-inch belt conveyor with 480-foot centers and 18° inclination leading to the screening, secondary crushing, and storage plant. Other plants are adopting this same type of equipment.

Operators should prevent unnecessary wear and damage to belt conveyers. Sharp-cornered rock fragments should not fall upon the belt directly from a high elevation; some sort of baffle plate should absorb the impact. Where coarse and fine materials are mixed it is customary to feed the stone over a slotted slide which lets the fines reach the belt first and thus form a protective cushion on which the larger fragments fall.

With proper care a belt conveyor will last several years, it requires little supervision, and the maintenance cost is low.

FIGURE 21.—Belt conveyor for raising stone from quarry to screening house

OVERHEAD CABLEWAYS

Where the plant and quarry are some distance apart, and the intervening topography is unsuitable for rail transportation, aerial cableways are sometimes used. Cableways are in common use at slate quarries where the pits are wide and deep but are not commonly employed for elevation of rock from limestone quarries. Figure 22 illustrates the use of a cableway in southern Virginia to carry rock from a mine on one side of the James River to a lime plant on the other side. Figure 23 shows the return of an empty skip from the cableway to the mine entrance. The main cables in general use range in diameter from 1½ to 2½ inches and draw cables from ¼ to ¾ inch. Most cableways are designed to carry loads not heavier than 3 to 5 tons. Great care should be exercised to see that cables and supports are in good condition. The overhead cableway is ordinarily more easily kept in repair than trackage, and is not subject to damage from floods.

DERRICKS

Derricks are used at lime-plant quarries only under exceptional conditions. Figure 24 illustrates a type of derrick used at Rockland,

FIGURE 22.—Cableway for carrying stone from mine to lime plant on opposite side of river

Me., where the limestone beds stand vertically and thus require excavation at depths of 300 to 400 feet, too deep for any form of inclined track haulage.

TRAVELING CRANES

As illustrated in Figure 25, one large company in Ohio employs a unique type of hoisting by traveling crane. Three cranes travel

FIGURE 23.—Return of empty skip from cableway

back and forth on double railroad tracks, raise from the quarry floor buckets containing $1\frac{7}{10}$ tons of rock, and dump them directly into the kilns. Thus, no superstructure around the kiln tops is required. One disadvantage of the system at an open quarry is

lack of provision for storage. Even one day of bad weather will affect production, for a supply of stone is available only when

FIGURE 24.—Type of derrick used for deep quarry in Maine

loaders are at work. This difficulty could be met by driving a tunnel and mining underground during bad weather.

FIGURE 25.—Rock hoisted from quarry to kilns by traveling cranes, shown in background

A rotating traveling railroad crane, as shown in Figure 26, is used by the Kelley Island Lime & Transport Co. for hoisting skips of

rock from the ledges and dumping them into railroad cars on the quarry bank. One advantage is the absence of trackage on the quarry floor, a great convenience, as it saves the expense of general upkeep and extension and the necessary removal and replacement when heavy blasts are discharged. The tracks on the bank must, of course, be moved as the quarry face is advanced.

FIGURE 26.—Traveling railroad crane hoisting stone from quarry

TRAVELING SKIPWAY HOISTS

Another unique system is employed by the Rockland & Rockport Lime Co. at Rockland, Me., for elevating rock from storage bins to a battery of six kilns. Figure 27 is a view of the storage bin, showing the gates from which the rock flows to the skip. Figure 28 is an end view of the kilns, showing the traveling skipway hoist. The skip loaded at the bin is elevated and may be discharged into any kiln desired.¹⁰

¹⁰A more complete description of this plant may be found in an article by Rockwood, N. C., "The new Rockland lime plant": Rock Products, vol. 25, June 17, 1922, pp. 35-44.

BUCKET ELEVATOR FOR KILN STONE

The use of a Stephens-Adamson bucket elevator to deliver stone into the kilns is a unique type of equipment that was seen at one plant only. The 24-inch square buckets travel beneath the lime drawing floor, upward at one end of the battery of six kilns, over the tops of the kilns, and down at the other end. Thus the same conveying system may be used both to elevate stone to the kilns and to convey finished lime to storage, although both operations can not be carried on simultaneously.

TRANSPORTATION COSTS

No item of quarry cost is probably more variable than rock transportation. Figures submitted to the bureau vary all the way from

FIGURE 27.—Storage of kiln stone and gates from which stone flows into skips

21½ to 65 cents per ton because conditions differ so widely at different quarries. The chief variable factors are distance, grades, and haulage equipment. Many quarrymen keep no separate record of transportation costs, but figures by a number of operators who keep separate records would no doubt interest all lime manufacturers. In 1922 costs at four quarries for which no details are given were 2.5, 5, 7.7, and 10 cents per ton, respectively. At a well-managed quarry in Tennessee the total cost of horse haulage of cars for the 500 feet from the face to the top of the incline, then down a 1,400-foot incline by gravity, plus the cost of labor for dumping cars at the kilns, was 5.5 cents per ton in 1921, excluding repairs and depreciation. At one efficiently operated plant in New York locomotive-transportation costs, including labor, coal, and repairs for two

different quarries in 1922, were 5.76 and 5.81 cents per ton, respectively. At a Missouri quarry the cost of an 800-foot haul is 11.5 cents per ton.

A transfer of stone from one type of haulage equipment to another usually increases the cost greatly. At one Massachusetts quarry reporting to the Bureau of Mines, rock is hauled in wagons to a point near the kilns, then transferred to cars which are hauled up the incline by electric power; the total transportation cost is 35 cents per ton.

Most lime-manufacturing plants are close to the quarries where they get their raw materials. If the kilns must be at a distance from the source of supply, transportation becomes an important

FIGURE 28.—End view of a battery of kilns showing traveling skipway hoist, as used at Rockland, Me.

item of expense. Distance haulage by horses and wagons or dump carts is estimated by one operator at 26 cents per ton-mile, by another at 30 cents. Motor-truck transportation costs one quarryman 26 cents per ton-mile. For economical operation the lime plant should evidently be close to the quarry.

One lime company in Washington State carries rock 1,400 feet down a mountainside to the kilns by an aerial tramway. The buckets hold 1,000 pounds. Gravity supplies all necessary power. The cost of labor and maintenance for this system in 1922 was 11¾ cents per ton of rock handled.

At some lime plants the cost of rock transportation alone costs more than the total cost of quarrying and placing the rock in the

kilns at other plants. The production cost of lime could be much reduced in many localities if transportation could be made cheaper.

ROCK CRUSHING

At quarries where kiln stone is hand loaded no primary crushing is required, as the hand-loaded rock is conveyed directly to the kilns. Where steam shovels are used for loading rock, crushers and screens are required. Various types of crushers are used and each has its advocates. Operators should not forget that the main object in crushing rock for a lime plant is quite different from that in crushing rock for a cement plant. At the latter establishment materials must be pulverized; therefore the greater the percentage of fines the primary crusher makes, the better. The lime producer, however, must keep the percentage of fines as low as possible, and this point should guide selection of equipment. It is a generally recognized principle that "choke feeding"—that is, keeping the crusher filled to capacity—tends to give more fines than when the rock is fed in gradually, not faster than the crusher can handle it. In general, it may therefore be regarded poor policy for a lime operator to dump large carloads of rock directly into the crusher. One of the most popular types of crushing equipment at lime plants is a jaw crusher with apron feed, which will supply the stone to the crusher at any speed desired. Many believe that this combination gives a minimum of fine materials. Gyratory crushers are in common use, but some operators think that the gyratory crusher produces a greater proportion of fines than a jaw crusher. At one plant visited a massive hammer mill is used as a primary crusher. Both single and double rolls are in use. McGrew¹¹ has claimed that the single-roll crusher will produce less fines than any other type.

Selection of the most economical size of crusher demands very careful study. The size should be governed not only by the daily tonnage expected, but also by the size of the loading shovel. If the shovel has a 2½ or 3½ yard dipper, the crusher must be large, or much time and energy will be wasted in the effort to force large masses through an undersize crusher. On the other hand, a very large crusher requires too much power. However, it is probably better to buy one that is too large rather than too small. An undersize crusher is a serious handicap, retarding all operations, requiring excessive secondary blasting, producing a high percentage of fines through choke feeding, and involving heavy repair charges. Although an oversize crusher may demand excessive power, the maintenance expense is usually low; furthermore, it is generally

¹¹ McGrew, Brownell, "Rolls as primary crushers": *Rock Products*, vol. 26, Mar. 10, 1923, p. 74.

conceded that it is cheaper to break rock by crushing than by drilling and blasting.

ROCK SCREENING

When mechanical crushers are used, some type of screening equipment must follow. Occasionally an inclined railroad rail or bar grizzly with 3½ to 5 inch spacing is used, but the rotary screen or trommel is usually employed. Some trommels have 6-inch, some 5-inch, and some 4-inch round holes, and all stone that fails to pass through such openings is sent to the kilns. To allow utilization of a greater proportion of the rock, manufacturers have recently tended to reduce screen openings from 6 or 5 to 4 inches or even smaller. The trommel is the best established and most popular type of screen for large sizes. Lately a type of screen built on an entirely different principle has been introduced at some lime plants; it is known as a cataract grizzly and consists of a series of rotating disks with spaces between them through which the finer stone drops. As the oversize rock descends it successively encounters disks that rotate at greater speeds, preventing binding and grinding. The advantages claimed are long wear, absence of vibration, and minimum grinding and breaking of rock, as there is no cascading action of rock on the screen.

ROCK CONVEYING

Pan conveyers or bucket elevators are widely used to raise rock from crushers to screens or to storage. If the angle of elevation is low, a belt conveyer may be used. As noted elsewhere, a belt conveyer for kiln stone may be used as a picking belt to improve the average quality of the stone.

Where kiln stone is delivered to storage bins some means must be employed to prevent breakage of rock through cascading into the bin from a high elevation. At some plants so much fine stone is produced in this way that it becomes necessary to pass the stone over a grizzly before it is elevated to the kilns. Until some advantageous means of utilizing fines is developed an effort should be made at every stage of manufacture to reduce to a minimum the percentage of stone under 4 inches.

ROCK STORAGE

OBJECTIONS TO STORAGE

Most lime plants keep little or no reserve supplies of rock in storage, largely to avoid repeated handling, as direct transfer from quarry to kiln is regarded as cheaper than transfer from quarry to storage and later from storage to kiln. Although this

assumption is true in general, there are certain advantages that are worthy of consideration in maintaining a storage pile.

ADVANTAGES OF STORAGE

To be efficient lime burning should be continuous. At many lime plants there is a notable shortage of stone on Monday, for the kilns run Sunday while the quarries are idle. A supply of loaded cars may be provided to fill in this gap, but if cars are not available, or if the quarry force is too small to build up a reserve supply the kilns may be very low on Monday forenoons. Such a condition in shaft kilns not only lowers production but reduces the quality of the lime. When a low kiln is filled with a mass of rock, the lower part is inclined to be underburned with excessive core, and the heat balance throughout the kiln is thrown out of adjustment. A reserve storage of stone to supply kilns during and immediately after Sundays and holidays is highly desirable.

In open-pit quarries, particularly during fall and winter, bad weather causes much lost time. It may be deemed advisable to discontinue operations for some time after a rain, as the clay adhering to the rock may carry too much impurity into the lime. Some companies now have sheds where a limited supply of stone is kept under cover for use in rainy seasons, a practice that might be followed with profit by many others. One company in Virginia keeps a stock pile near the kilns for rainy days. Rock from different parts of the quarry varies, and the stock pile is made up of stone taken at random from all parts to maintain a uniform product.

Another advantage of storage is to provide against labor shortage. If labor tends to be scarce at certain seasons and plentiful at others, the latter periods may be employed profitably in storing up a reserve to tide over the lean seasons.

RELOADING FROM STORAGE

As pointed out above, one objection to rock storage is the necessity for rehandling. Profitable operation therefore demands facilities for the most easy and convenient methods of reclaiming stone from storage. Hand loading from storage is so expensive that it largely nullifies any advantage of maintaining a reserve stock. A power shovel has been used to load a stock pile of small stone for which no immediate market could be found, but it has not been noted as a means of loading kiln stone from stock piles. Storing in bins into which the stone may be dumped from above and drawn off into cars beneath as needed at the kilns is the best method, for very little labor or time in rehandling is required thereby.

A method of storage observed at one locality that seems to have doubtful advantages involves dumping surplus stone into an unused part of the quarry. The rock is both loaded and reloaded from storage by hand.

EFFICIENT STORAGE SYSTEM

One lime company has an admirable storage system that is worthy of comment. As shown diagrammatically in Figure 29, the stone is taken up the incline *a* to the top of the kilns. Back of the quarry face *b* a great trough-shaped hollow has been blasted out of the solid rock beneath the trestle, as indicated by the dotted lines *c*. Beneath this trough a concrete tunnel has been constructed with rock chutes *e* in the roof. When quarry production exceeds kiln requirements the rock cars are stopped midway on the trestle and dumped into the storage trough. When, owing to delays incident to bad weather, or on days following holidays, not enough stone from the quarry is at hand, cars are loaded through the chutes in the tunnel, hauled out to the foot of the incline, and taken to the kilns in the usual way. Thus, an emergency supply of stone is always at hand, little rehandling is required, and the system has the added advantage of providing steady employment for men who would otherwise remain on part-time duty when the kilns were oversupplied.

FIGURE 29.—Diagram of efficient rock-storage system: *a*, Trestle from quarry to kilns; *b*, quarry face; *c*, storage trough; *d*, tunnel; *e*, rock chutes in tunnel roof

QUARRYING TO OBTAIN LIME OF UNIFORM QUALITY

MODIFICATION OF QUARRY PROCESS

Limestone beds are formed by natural processes that have been in operation for thousands, and perhaps millions, of years; their composition and physical properties are, therefore, long established and unalterable factors over which man has no control.

The character of lime undoubtedly depends largely on the nature of the parent limestone. A high-calcium lime can not be manufactured from a dolomite, and a pure lime can not result from calcination of an impure raw material. However, when turning limestone into lime, man can exercise some control over the quality. Although a deposit is of variable character one lime product of uniform quality may be produced by judicious quarrying. Uniformity of the product is, of course, influenced greatly by such steps in manufacture as cal-

cining, hydrating, grinding, or storage, but the present discussion is limited to the influence of raw materials only.

NECESSITY FOR HIGH STANDARD

Every lime-plant operator knows that market conditions and prices are largely controlled by the quality of his product. If quarry methods can be changed to allow production of a more salable or higher-priced lime, it is most important for the operator to devote time and effort to effect such a change. Market conditions may dictate production of a single grade of lime. If so, the aim should be to establish a standard and to manufacture a uniform product that always meets standard requirements. Fluctuating quality is a constant worry to the producer and a constant source of annoyance to the consumer.

VARIATIONS IN LIMESTONE DEPOSITS

A series of limestone beds rarely has constant chemical composition and physical properties throughout its entire extent. When limestone beds were first formed materials of one kind were usually deposited over a considerable area at once; thus a single bed should be reasonably consistent. Succeeding beds may have been formed after long intervals and under quite different conditions, hence variations in composition, structure, and physical properties may be expected in passing from bed to bed. Certain beds may be unsuitable for lime manufacture and should be discarded or diverted to other uses. Many deposits, however, consist of a thick series of beds that vary somewhat in quality but may all fall within such reasonable limits of purity as permit utilization for marketable lime.

QUARRYING TO OBTAIN A SINGLE UNIFORM GRADE OF LIME

The reasons given in the previous paragraph justify the assumption that in most limestone deposits rock in the same bed or, to be more accurate, in the same zone of deposition has fairly constant composition, and that the maximum changes may be expected in passing from one bed to another. Operators who are fortunate enough to possess quarries where rock is uniform throughout have no difficulty, so far as quarrying is concerned, in keeping their product uniform. Where the quality of the stone at different levels or in different zones of the quarry face varies, a uniform grade of lime may obviously be obtained only by uniform selection of stone from the various beds. The following paragraphs outline the methods by which this may be done.

UNIFORM SELECTION IN FLAT-LYING BEDS

One method of obtaining a uniform mixture of rock that occurs in horizontal beds is to work the full face as a single bench, shooting down all the ledges together in a mixed mass. This method is now widely used at lime-plant quarries, is found to be very economical, and at the same time accomplishes the desired mixing of the rock fairly well. Such blasting may be done in churn-drill holes or in chambered snake holes. One Ohio operator uses a series of mixing methods. The stone is first mixed by shooting it down in large quantities by deep-hole blasting. The rock is then hand loaded, and to mix it further successive cars from each loader are distributed to different kilns. The finished lime is also mixed during loading; thus a general average is maintained.

Sometimes conditions do not favor single-bench operation, and the quarry is worked in a succession of comparatively low benches. If there are marked variations in the rock at different levels, maintenance of a uniform product will require simultaneous work on all the benches, the carloads of rock from the several levels being taken to the kilns in regular order.

An average quality of rock and also a regular distribution of impurities that are not easily removed may be maintained by either of these methods. If clay pockets or seams prevail in the upper beds, lime made from these beds exclusively tends to be high in silica and alumina, whereas lime made from strata below the clay seams will be much purer. The small amount of clay which can not be separated easily may suffice to condemn a lime if it is all concentrated in the small mass of stone from the upper levels, but if the clay is distributed uniformly throughout the entire mass of rock from top to bottom of the quarry, it constitutes a very small percentage, and probably will not lower the standard of the product materially.

UNIFORM SELECTION IN STEEPLY INCLINED BEDS

At many lime plants, particularly in the Appalachian district of eastern United States, limestone beds rarely lie flat but usually stand at steep angles. The conditions that govern uniform selection of rock depend on the position of the quarry face. The face may be parallel with the strike—that is, with the direction in which the beds run where they outcrop on a level surface—or the quarry face may cut across the beds at right angles to the direction of their outcrop. The first condition is illustrated in Figure 30, where a succession of steeply inclined beds *a*, *b*, *c*, *d*, and *e* is represented as dipping toward the quarry face. The lines that separate the various beds appear in horizontal position on the face, giving it the appearance of a quarry

opening in flat-lying beds. Working conditions are, however, quite different, for with each succeeding blast some beds disappear and new ones come into use. Thus, if the quarry face is blasted to the dotted line *x* a very small part of the bed *a* is available, and a new bed *e* will appear at the bottom of the bench. If bed *e* differs materially in composition from the other beds in the quarry, a change in the character of the lime must inevitably follow. The next blast would provide no stone from beds *a* and *b*, and another new bed would appear at the base.

Similar variations would evidently occur when the beds dip away from the face as when they dip toward the face. Thus, in variable rock, where the quarry face is parallel with the strike of the beds, it is almost impossible to keep the product uniform. A great difficulty with this type of quarrying is loss of the desirable beds, either by working them out to the surface or by their disappearance beneath the quarry floor.

FIGURE 30.—Advancing a quarry face that is parallel to strike of steeply inclined beds: *a-c*, Successive beds; *x*, face after blast

With inclined beds a uniform grade of rock is sometimes maintained by pursuing underground methods. It is thus possible to follow the desirable beds.

If conditions permit, it is advisable to maintain the quarry face in a position at right angles to the strike of the beds, as shown in Figure 31. In this figure it may be observed that beds *a*, *b*, *c*, *d*, *e*, *f*, and *g* cross the quarry face obliquely. To obtain a uniform selection of stone from the several beds a long working face should be maintained and rock loaded at the same time from many beds. In this instance it is noteworthy that when the rock is blasted to the dotted line *x* the same beds appear in exactly the same position as on the present face. Uniformity in the product may thus be maintained as the face is advanced.

The foregoing discussion shows that it is evidently desirable to maintain the quarry face perpendicular to the strike; in other words, it is advantageous with respect to maximum uniformity to work inclined beds from the end rather than from the side.

HAND PICKING

In many limestone deposits beds unsuited for lime manufacture alternate with beds of good rock. If the inferior beds are thick enough they may be worked as separate benches and the rock sold for other purposes or discarded. Defective rock commonly occurs in thin beds that can not be worked alone to advantage but must be shot down with the good stone. To maintain a high quality in the lime produced the impure fragments should be separated from the good stone during loading. Such hand selection is the chief factor in maintaining a uniform high grade of lime at many plants. At some plants the finished lime is also hand picked. Success in hand picking depends to a large extent on the ability and care of the worker.

Loading other than by hand is usually regarded as impractical where hand selection is required. Power-shovel loading, supplemented by a picking belt, has worked very successfully at many western mining camps, and lime-plant operators could no doubt use similar equipment to advantage. The advantages of the picking belt have been discussed.

FIGURE 31.—Advancing quarry face that is at right angles to strike in steeply inclined beds: *a-g*, Successive beds; *x*, new face after blast

CLEAN STRIPPING

An excessive amount of dirt in a quarry tends to impair the uniformity of the lime produced. During rainy seasons clean separation is difficult, and even in dry seasons, when rock and dirt may be separated easily, carelessness by the workmen or lack of adequate supervision may at times result in loading enough clay or sand to give an inferior product. A clean removal of overburden is desirable but is often difficult owing to the rugged nature of the rock surface and the presence of clay seams and pockets. Methods of stripping have been discussed in detail in another section of this bulletin.

UNIFORM SIZING

That the quality of the product is improved by maintaining fair uniformity in size of the kiln stone is generally recognized. Excessively large masses tend to produce too much core or lead to overburning of the smaller sizes if an attempt is made to calcine them completely.

SUMMARY OF QUARRYING PRINCIPLES

Whatever the quarry conditions the principles to be always remembered are (1) the separation, in so far as it may be practically accomplished, of all inferior rock or other impurities, (2) the uniform distribution of remaining impurities throughout the entire rock mass, and (3) the uniform selection of stone from different beds.

MIXING IN STORAGE BINS

In some branches of the stone industry, particularly the manufacture of Portland cement, raw materials may be mixed uniformly in the storage bin. Some plants keep thousands of tons of rock in storage, and by distributing rock uniformly throughout the full length of the bin and drawing off the rock from many points obtain a uniform quality of stone. With such methods great variations in the rock as quarried may be equalized in the bin. Few lime plants have a large storage for rock, and thus can not use the storage bin as a mixing device. More and more operators of lime plants are storing mainly to have clean, dry stone to use during rainy seasons and to insure continuous running of kilns. The added advantage of obtaining greater uniformity in the manufactured lime should encourage wider use of the storage bin.

QUARRYING TO OBTAIN DIFFERENT GRADES OF LIME

Production of a single uniform grade of lime has been the objective of most lime producers. Recently, however, the tendency toward specialization has been marked. Some manufacturers produce different types of lime suitable for different uses. For chemical uses, as a rule, greater purity is demanded than for agriculture or building. Limes from certain deposits that experience shows will yield products particularly adapted to specific chemical uses are sometimes shipped hundreds of miles. The unique qualities that these limes possess are obtained, in part, by special methods of calcination. However, the nature of the lime depends also on the quality of the parent limestone, not only on chemical composition but on physical properties. It is well known that limestones of identical composition may, under the same burning conditions, give limes that differ greatly in character. All lime burners are familiar with the fact that some limestones crumble more readily than others during the calcining process. Thus, if lump lime is desired, certain beds chemically suitable may decrepitate or crumble so badly that it may be advisable to reject them as raw materials or to quarry and calcine them separately. Moreover, some beds are commonly more refrac-

tory than others and either demand a higher temperature of calcination or give an excess of core if the temperature is kept lower.

A definite relationship undoubtedly exists between the character of the lime and the physical properties of the limestone from which it is obtained, but little serious effort has been made to correlate these relationships. Some profitable studies have recently been made and with an increasing demand for special types of lime a more earnest study will undoubtedly be undertaken. In many quarries it is also noteworthy that products other than lime are marketed from beds unsuitable for lime manufacture. The chief by-products are furnace flux, furnace lining, railroad ballast, road stone, concrete aggregate, limestone sand, and chicken grit.

If special grades of lime are desired, it is usually necessary to select the stone carefully in the quarry; such selection may demand different methods of quarrying than where a single uniform grade of lime is desired. The methods usually involve a higher cost per ton than when the entire quarry output is devoted to the manufacture of a single product, but the higher price usually obtained for specialized products repays the increased production cost of raw materials. The different grades may be obtained by hand selection. For example, at one quarry light and dark colored limestones are loaded into different cars and burned in separate kilns. When the beds must be quarried and calcined separately, each bed may be worked as an independent unit, which may involve quarrying a succession of low benches with tripod or hammer drills and loading by hand. No general rules can be given, for the method must be varied to suit the peculiarities of the rock formation and the relation of one bed to another.

In lime plants of this character the plant chemist and the quarry superintendent must cooperate closely. Control of quality in the product depends as much on raw materials as on methods of manufacture, and any changes or variations in the limestone beds should be detected immediately; such variations may demand modifications in quarry methods so that the quality of the product may not be impaired.

MINING LIMESTONE FOR LIME MANUFACTURE

UNDERGROUND OPERATION

In its broader sense the term "mining" is applied to all processes whereby raw materials are taken from the earth to be used as sources of mineral products. In a more restricted sense "mining" is applied to underground operations as contrasted with open-pit work, designated as quarrying. The term is here used in the restricted sense and covers the exploitation of limestone deposits by modern methods of underground operation rather than by open-pit methods.

CONDITIONS GOVERNING OPEN-PIT AND UNDERGROUND WORK

Limestone for lime manufacture is obtained chiefly from open-pit quarries. When the rock has little or no overburden the open-pit method is to be preferred. Modern methods of deep-hole blasting on a large scale have undoubtedly reduced the cost of production in general below that of underground work, even under the most favorable mining conditions. However, conditions do not always favor open-pit work, and more and more operators are finding it advantageous to resort to underground methods. The chief factors tending toward the mining method are (1) a heavy overburden of soil or inferior rock blanketing a flat-lying deposit of good limestone, (2) an inclination of the beds of serviceable stone that demands too great an extension of the pit along the strike or outcrop and results in an increasing overburden as the pit is enlarged in the direction

FIGURE 32.—Diagram illustrating quarry conditions that encourage underground mining: *a*, Direction of strike; *b*, direction of dip; *o*, overburden; *w-z*, desirable limestone beds

of the dip, and (3) the necessity for working at increasing depths as surface deposits are exhausted.

ADVANTAGES OF UNDERGROUND MINING

The conditions mentioned above that encourage mining, plus other favorable factors, are discussed in the following paragraphs.

The most important factor that encourages mining and in some places even forces

operators to work underground is the presence of a heavy overburden. Indeed, as the quarry is enlarged a heavier overburden may be continually encountered. Where strata dip at an angle the tendency is to quarry on the outcrop of the desirable beds, thus extending the pit in the direction of the strike. If, because of property lines or of any other reason, it is impossible or inadvisable to extend the quarry farther along the strike, or in other words, along the line of the rock outcrop, the pit must be extended laterally. In one lateral direction the beds run out at the surface, and in the other direction with each advance a greater depth of overburden must be encountered, as illustrated in Figure 32. If *w*, *x*, *y*, and *z* are the desirable beds, and if extension in the strike direction *a* is not permissible, it becomes necessary to extend the pit in the direction *b*, that is, in the direction of dip. With enlargement in this direction the overburden *o* clearly increases greatly with each ad-

vance and may soon become so heavy that profitable open-pit work is impossible. When this point is reached mining becomes imperative.

The upper ledges of some flat-lying deposits consist of alternating beds of good and inferior rock, with thick beds of good stone beneath. When the deposits are worked by open pits, the good rock of the upper ledges is picked out by hand during loading, and the great mass of useless rock is loaded separately and hauled to the dump. The necessity for handling an excessive amount of waste material may so increase the cost of quarrying that mining the good beds would be more profitable and would probably give a cleaner and more uniform supply.

Difficulty of stripping, because of the presence of clay pockets and seams in the upper ledges, may also encourage operators to mine the stone. When such conditions prevail, not only is stripping slow and costly, but separation of sand, gravel, or clay from the good stone is difficult. When the deposit is worked by mining methods, little or no foreign material is intermixed, for work is usually conducted exclusively in the solid ledges of good stone.

The fact that the rock obtained in mines is purer than that obtained from many open pits has an important bearing on use. Many lime-plant operators supply stone to users of flux who strongly object to the presence of fines. The objection of the open-hearth operator is chiefly on the basis of impurity, for any siliceous material, such as clay or sand, associated with the rock is segregated with the fines. For blast-furnace flux retardation of draft is one objection to fines, but the impurity of the fines is also important. Thus furnacemen object to the smaller sizes not so much because of their inability to use fines as to the fact that many years of experience have demonstrated that fine materials almost invariably contain an excess of silica. When the rock is excavated underground and no clay seams or pockets are encountered, the fines are as pure as the lump stone. When flux-stone users are convinced of this fact, a much wider market will probably be found for the smaller sizes of stone produced in mines. One lime producer, who also sells fluxing stone obtained from his mine, informed the writer recently that no objection is raised to large quantities of fine materials in his product, because the silica content of the fines is as low as that of "one-man" stone.

The absence of contamination from surface impurities is also reflected in the high quality of lime produced. When open pits are worked in rainy weather, the clay adhering to the stone tends to lower the grade of the lime made, whereas rock mined underground is not exposed to the rain or to surface débris.

At many quarries it is difficult to find a suitable area on which to dump stripped material. Property lines may be restricted or the land may be too valuable for such use. This is another factor that may influence the owner to avoid stripping and to use underground methods.

Although in general the cost of underground work per ton is somewhat higher than in open-pit quarrying, some operators have found by experience that mining costs are lower. One operator reduced his production costs 30 per cent by employing underground methods. The actual drilling and blasting costs may be higher, the saving being accomplished by the elimination of stripping, the reduction of the expense of hand sorting, and by more continuous operation.

With the quantity production demanded by consuming industries, limestone quarries are rapidly becoming larger. When the desirable stone is in flat-lying beds of limited thickness extension is lateral. Even in some thick deposits wide, comparatively shallow workings may be preferred if a large area is available and overburden is thin. When the surface area is restricted, as in tilted beds, the quarryman may have to work at great depths. The difficulties and dangers of working at depths of several hundred feet and the resulting increase in cost of production tend to encourage the adoption of mining methods.

Another advantage of mining is the protection from cold and rainy weather it gives workmen. In open quarries much time is lost during bad weather, particularly in the North. Snow and ice impede operations and render them more hazardous. If clay is mixed with the rock, rain prevents clean separation. Underground mining makes a workman quite independent of weather conditions, his activities are not impeded by ice, snow, or rain, and his product is not damaged thereby. Some lime producers think that continuous operation throughout the year with a comparatively small labor turnover is one of the chief advantages of mining.

DISADVANTAGES OF MINING

Mining methods require the use of small drills on comparatively low benches. The modern tendency in quarrying is to throw down great quantities of rock at one time with heavy blasts in deep churn-drill holes. Generally speaking, this is more economical than to use smaller drills on a series of low benches. The big-hole blasting method can not be used underground, thus the limestone miner loses any advantage it may afford. Moreover, the working face in a mine is usually much more restricted in area than the face of an open pit, operations are more crowded, and efficiency is reduced. The

actual cost of drilling and blasting is therefore usually higher in underground than in open-pit work, but the increase is offset to some extent by the production of cleaner rock and by elimination of stripping expense.

When rock is blasted in confined spaces the products of combustion constitute a hazard that the open-pit operator does not meet. Blasting should be done at the end of a shift, but can not always be done then. In some mines a drift is left unoccupied for an hour or two immediately after a blast, the workmen being employed elsewhere. Removal of noxious gases may be hastened by allowing air to escape from the compressed-air lines at the extremity of the drift. In extensive underground development the condition of the air will be improved, and the removal of gases will be facilitated by mechanical ventilation equipment such as fans and tubes or brattice curtains.

Another disadvantage is the vigilance required to avoid accidents from roof falls. When the limestone is sound it is comparatively easy to keep the roof safe, though with jointed stone, or stone inclined to spall easily, constant care is required. If enough support is given the pillars, the hazard will probably be no greater than in deep open-pit quarries, where like danger exists from falls of rock from the quarry face or over the edge of the pit.

A very important disadvantage of underground work to the lime producer is the increased proportion of small-size stone. If a ledge with a free upper surface is blasted in a drift or chamber, the proportion of fines may be no greater than in open-pit work, but in driving headings in solid rock with only one free face heavy blasting is required and the proportion of fines is usually high. As pointed out on page 80, better utilization of the smaller sizes of limestone is an outstanding problem at lime plants. The tendency of underground work to increase the proportion of fines further complicates this problem and makes satisfactory solution imperative. It is, however, important to emphasize the statement in a previous paragraph that the fine materials obtained in mines are usually much purer than those obtained from open pits, therefore they should be more easily marketed.

The impression prevails in some quarters that labor prefers to work in open pits rather than underground. Possibly this is a valid objection to mining, but when laborers become accustomed to underground work they will probably find that it has certain advantages over the open quarry, such as smaller loss of time through bad weather, protection from rain and snow, and a more uniform working temperature throughout the year. They will probably find also that a properly conducted mine is no more hazardous than a quarry.

Some operators unfamiliar with mining believe that all underground loading must be done by hand; however, power shovels or

loading machines are now in use in several limestone mines, and an increasing use of mechanical loaders has been noted.

One objection to mining is the loss of good stone in a ledge. In open-pit work, when a limestone bed is stripped for operation practically 100 per cent of it is available for use, whereas in mining a proportion varying from 20 to 25 per cent of the good rock must be left as pillars or walls for roof support. Thus, in mining one can not obtain as much rock from a given area as in quarrying.

A general lack of knowledge concerning mining is a serious drawback. Conditions at many limestone deposits indicate that a change from open-pit to underground work would be advantageous, but the operator naturally hesitates before undertaking a radically different method with which he is unfamiliar. A wider knowledge of mining among lime producers would undoubtedly encourage expansion of underground work in places where the change would prove advantageous.

INFLUENCE OF ROCK STRUCTURES ON MINING

A condition of first importance for successful mining is a sound rock that will provide a strong roof with little danger of spalling. Limestone is too cheap a product to justify the expense of timbering, except possibly in main entries or hoisting shafts, and no mine can be worked successfully if the rock is not strong enough to provide a safe roof for drifts or chambers at least 25 or 30 feet wide. Great care must be exercised in mining jointed rock, for the joints may permit masses of roof to fall. Where inclined joints meet a tunnel roof triangular fragments tend to loosen and fall. Closely spaced horizontal joints constitute a danger from roof falls, but where spaced several feet apart they sometimes facilitate mining greatly. An open seam that can be utilized as a plane of separation at the top of a drift provides a smooth and safe roof and makes blasting cheaper than in solid, unjointed rock. Similarly, a bottom seam provides an easy plane of separation at the floor, thus reducing drilling expense and conserving explosives. Thus, jointing of the rock plainly has an important bearing on the cost of mining and on safety.

Where limestone beds are inclined, mining is more difficult than where they are horizontal. The entries commonly follow the dip and the drifts parallel the strike, thus work in the drifts may be conducted on level floors with inclined haulage in the entry.

REPORT ON LIMESTONE MINING

Limestone mining is a comprehensive subject that applies not only to the lime industry but has equal interest to producers of Portland cement, fluxing stone, and crushed stone. Details are therefore omitted from this bulletin, as a comprehensive report on "Under-

ground limestone mining" has been published as Bulletin 262. Lime producers who are now mining or who propose to mine are directed to this report for a more thorough discussion of the subject.

SUMMARY OF LIMESTONE MINING

The outstanding features of limestone mining are as follows:

1. Quarry conditions are gradually forcing more general adoption of underground methods.

2. Limestone is too cheap to justify the expense of mine timbering, except possibly in shafts or entries, hence mining will be successful only where the rock is strong and massive enough to permit the maintenance of safe roofs in drifts and chambers, with supporting pillars spaced not less than 25 or 30 feet apart.

3. In general, the proportion of fines is higher in underground than in open-pit work; this condition further complicates the already serious problem of finding profitable use for small stone. However, the fine materials produced in mines are purer and thus more marketable than the fines from quarries.

4. The cost of drilling and blasting is usually higher with underground methods; on the other hand, cleaner rock is produced with no stripping cost, and the work is not delayed by inclement weather.

5. At various limestone deposits conditions exist whereby production costs could be reduced by changing from open-pit to underground methods, but the change is not made because the operators are unfamiliar with mining technique.

PART II.—UTILIZATION OF WASTE ROCK AT LIME PLANTS

By **W. M. MYERS**

IMPORTANCE OF THE PROBLEM OF SMALL STONE

Profitable disposal of limestone too small for making lime in shaft kilns is one of the most urgent problems in the lime industry. Reports received by the Bureau of Mines from 31 quarries show that the proportion of small stone ranges from 2 to 40 per cent, averaging 18 per cent of the gross production. Definite figures obtained during visits to many lime plants indicate that the percentage of fines is much higher than the above, the proportion running as high as 40 per cent in some important districts and as high as 60 per cent in several individual quarries. Figure 33 shows a pile of about 100,000 tons of virtually pure dolomite under 4 inches in size which has been discarded as waste, and even larger piles have been seen. Figure 34 shows another large accumulation thrown back into the quarry pit. If a market is found this stone may be reclaimed from the track shown at the foot of the pile, but most of it remains unutilized. Modern methods of heavy blasting and the use of crushers in large quarries tend to increase the proportion of small stone above that produced in early days when light blasting and hand sledging were used almost universally. There is also a growing movement toward underground working of some deposits, a method that in general produces a greater proportion of fines than does open-pit work. Some plants utilize virtually all of the waste in various ways, others use a part of it, and at many plants nearly all of the small or otherwise unserviceable rock is discarded; thus, small stone is probably the most serious problem now confronting the lime industry. Utilization of waste is the key to success in many enterprises, and when knowledge of this branch of the lime industry is broadened a tremendous advance in economical operation will be possible.

CONVERSION OF SMALL STONE INTO LIME

DESIRABILITY OF CONVERTING SMALL STONE INTO LIME

There are several markets in which small stone may be sold, but the competition there is generally keen and the prices are low. The

lime maker's chief product is lime; he understands its manufacture and marketing, and it brings him a greater return than can be obtained from most limestone by-products. It is therefore evident that the conversion of small stone into lime is the most desirable means of disposal.

SHAFT KILN

Many difficulties hinder the production of lime from small stone, and until the rotary kiln was adapted for this purpose little success was achieved. Any method for calcining small stone in the present shaft kilns, which could be installed at slight expense without involving extensive alteration or complete scrapping of the present equipment, would be a great boon to the lime industry. Many attempts have been made to calcine small stone in the shaft kiln, but none have yet shown any great promise.

An inconsiderable percentage of small stone 2 to 3 inches in

diameter can be calcined in the shaft kiln when mixed with the larger one-man stone. If appreciable quantities of small stone are introduced into the kiln, the draft is immediately retarded and the retardation may become serious enough to make successful operation of the kiln impossible. The proportion of the total charge that may be small stone and still permit the kiln to run successfully is usually low, although some operators can use a large percentage of fines by applying them uniformly. One company adds a uniform

FIGURE 33.—Waste pile, approximately 100,000 tons, of virtually pure dolomite under 4 inches in size

quantity of fines to each load of rock and claims that by such equal distribution a large proportion of the fines is used without materially affecting the draft or reducing the kiln capacity. Although this method may at times be successful, as a rule the shaft kiln can seldom accommodate more than a fraction of the total output of small stone from the average quarry. Retarding of draft is here due mainly to the small stone filling the voids between the larger fragments.

In a shaft kiln the actual combustion chamber in which the gases burn, whether they are from a wood or coal fire or a gas producer, is the void space between the fragments of stone. Theoretically this void space is the same whether the charge in the kiln is large or small stone, if the stone is sized so that all the fragments have the same dimensions. Actual experiment has shown that this theory

FIGURE 34.—Small sizes of pure dolomite thrown back into quarry

holds true for limestone which has been carefully screened; a charge of 2-inch stone has virtually the same void space as the "one-man" stone. When different sizes of stone are charged, the void space is greatly lessened, as the small stone fills the openings between the larger sizes and diminishes them just as an aggregate of sand and large and small gravel diminishes the void space in a concrete mixture.

The opinion has been expressed that small stone might be calcined in the shaft kiln if it were accurately sized so that the actual combustion chamber or void space would be the same as in the larger stone.

Interesting information was supplied on this possibility through an experiment by the Rockland & Rockport Lime Co., at Rockland, Me. Several tons of stone that had passed a 5-inch screen were

available. It was rescreened over a $3\frac{1}{2}$ -inch rotary screen, and the oversize, which had dimensions between $3\frac{1}{2}$ and 5 inches, was burned successfully in a shaft kiln. The minus $3\frac{1}{2}$ -inch material was again screened with the same $3\frac{1}{2}$ -inch screen, and some of the coarser pieces passed over, yielding a product that could be termed plus and minus $3\frac{1}{2}$ -inch. This result might be expected with any type of screen, as the dimensions of the fragments of stone differ greatly with direction and the chances of a stone being passed through a screen depend on the different attitudes the stone assumes during its passage. Stone could not be sized more closely than this by any commercial method. Attempts to calcine this plus and minus $3\frac{1}{2}$ -inch material in a gas-fired kiln of the shaft type were unsuccessful. The draft was retarded so much that gas was not drawn into the void space between the stone but backed up until it burned outside of the kiln.

The retardation of draft is due mainly to the frictional resistance to air flow offered by the stone and to the repeated change in direction of the air in passing through the charge. When either a cube or sphere is divided into smaller cubes or spheres whose diameters are one-half that of the original the surface is doubled. This holds true approximately for irregular fragments, so that the surface area of a charge of $3\frac{1}{2}$ -inch stone is many times that of the one-man material and the frictional resistance to gas flow through the charge is increased correspondingly. The channels for the passage of gas between the stones become small, intricate, and exceedingly tortuous, and their constant change in direction greatly increases the retardation. This experiment demonstrated that the possibilities of burning closely sized small stone in the shaft kiln are slight unless the design and operation of the kiln are radically changed.

Both forced blast and fans have been used to force or draw the air and gases from the fuel through the charge of stone in the kiln and thus make calcination possible. To date these attempts have not been successful. Use of forced draft, produced by the introduction of a blast of air at the fire boxes, has resulted in a concentration of intense heat which overburned the lime directly before the blast but did not penetrate to the uncalcined stone in the higher levels of the kiln.

The calcination of small stone is complicated further by the fact that the lime produced from the stone in some localities has little tensile strength and crumbles readily, producing much fine material in the kiln. The tendency of some limes to crumble is so excessive as to make trouble occasionally even when large stone only is used. In addition, the stone itself may shatter when it is undergoing its first gradual heating in the kiln, particularly if any

incipient fractures are present. These factors increase the retardation of the draft and add to the difficulties of calcining small stone.

IMPEDING CALCINATION OF SMALL STONE BY CARBON DIOXIDE GAS

During calcination the magnesium and calcium carbonates that compose the bulk of all limestones disassociate into carbon dioxide and lime, the latter being a mixture of calcium and magnesium oxides. Pure calcium carbonate contains 56 per cent calcium oxide and 44 per cent carbon dioxide; pure magnesium carbonate contains 47.6 per cent magnesium oxide and 52.4 per cent carbon dioxide. The percentage of carbon dioxide present in limestone depends on the purity of the stone, but will generally exceed 40 per cent in the stone now quarried for lime manufacture. A shaft kiln producing 15 tons of lime a day will yield nearly an equivalent weight of carbon dioxide, to which must be added the carbon dioxide formed by the combustion of the fuel used in the kiln.

As a cubic foot of carbon dioxide weighs 0.12341 pound under normal conditions, an enormous volume of gas is being evolved continuously during calcination of the stone in the kiln. If this carbon dioxide is not removed from the kiln as fast as it is formed, the limestone that is dissociating during calcination becomes surrounded by an atmosphere of carbon dioxide, and a state of equilibrium will be reached that makes it impossible for the limestone to dissociate further, and the production of lime will stop. Similarly any lime already formed and in contact with carbon dioxide tends to recarbonate and convert to limestone. Any increase in gas pressure increases the amount of recarbonation. Any retardation of the draft increases the gas pressure within the kiln, so that a kiln charged with any considerable amount of small stone tends to build up enough partial pressures of carbon dioxide to impede seriously or to stop the production of lime.

POSSIBLE CHANGES IN THE SHAFT KILN

The points already discussed indicate that there is little possibility of calcining small limestone successfully in present-day kilns of the shaft type. Whether shaft kilns could be so altered as to make calcination possible can be determined only by trial. A good draft is evidently essential for satisfactory operation of the shaft kiln. This draft must suffice to overcome all retarding agencies, draw the gases from the fuel into the void space between the fragments of stone, and remove the carbon dioxide as fast as it is evolved. Even if these conditions were fulfilled, some doubt still exists as to the possibility of successful combustion. Although the total void space in a charge of small stone would be the same as in a charge of the

larger material, the individual voids between the fragments of stone would be much smaller, and whether these small combustion spaces would permit the fuel gases to burn satisfactorily can be determined only by experiment.

The draft could be augmented by a combination of interior inlets for gas and mechanical exhausts for removing the products of combustion. If gas were supplied through interior inlets at different levels in the kiln, part of the resistance to the draft could be avoided and enough fuel for combustion brought into the interior of the charge. The introduction into the upper part of the kiln of flues at different levels, arranged to project directly into the charge of small stone, should increase the draft considerably, particularly if the flues were connected with a powerful exhaust fan. Certain lime-plant operators have suggested this modification.

Spalls have been burned successfully in a low, broad kiln. By reducing the depth of stone a fair draft is maintained, and the wide diameter increases kiln capacity. Such a design may possess merit, but its use is so limited that data are still very meager.

The possibilities of altering the shaft kiln so that the small stone may be calcined seem remote at best. Whether any of the preceding suggestions have value can be determined accurately only by experiments that would involve thorough investigation of the various factors, such as design of kiln, sizing of stone, choice of fuel, and forced or induced draft.

ROTARY KILN

The ever-increasing amounts of small stone available, as the output of quarries is increased to supply the demands of industry, has resulted in attempts to produce lime by other than the shaft kiln. The only successful equipment for calcining small stone yet developed is the rotary kiln, which is constantly becoming more important in the lime industry. It was used first for burning lime in 1885, when a patent was granted for the production of lime by calcining limestone in a revolving cylinder. This type of kiln did not win immediate favor, and the first attempts at commercial operation were discouraging and expensive. Some of the results were promising enough to warrant further investigation, and later experiments by operators in the cement district of Pennsylvania and elsewhere demonstrated that lime could be produced profitably by calcining small stone in the rotary kiln. In 1906 a rotary kiln using producer gas as fuel was installed at Carthage, N. Y., one of the first kilns of this type for the production of lime only. Since that date the use of the rotary kiln has expanded until it now operates successfully in many parts of the country, producing thousands of tons of lime annually, and constitutes an essential part of the lime industry.

The type of rotary kiln now in use is almost identical in construction and operation with the kilns used in the manufacture of Portland cement and in fact was largely adapted from the accumulated experience of the cement industry. As yet the operation of the rotary kiln is far from being a definitely established procedure; many factors that govern operation vary with the locality and the experience of the operator. The total experience of a number of operators with the rotary kiln and the solution of problems they have encountered in using it have made available a mass of information on the subject.

SIZE AND CAPACITY

The rotary kilns used in the manufacture of lime are 50 to 175 feet long and 5 to 10 feet in diameter. Small kilns have not been particularly satisfactory, as they have involved a larger investment than the output of lime warranted; moreover, their short length tended to lower the fuel ratio (pounds of lime per pound of fuel) and thus made the cost of production high. A kiln 50 feet long should produce about 18 tons of lime a day from about 36 tons of limestone. A kiln as small as this might sometimes be warranted, but in general its satisfactory operation is doubtful.

Most of the rotary kilns in successful operation to-day are 135 to 150 feet long and have an inside diameter of 6 or 6½ feet. These kilns will produce 80 to 125 tons of lime a day and take nearly twice as much limestone. Evidently such a tonnage of small stone could not be supplied by any minor quarry, and the kiln is only suitable for a lime plant making a large output and having much small stone constantly available.

FUEL AND FUEL RATIO

Rotary kilns have been fired with oil, powdered coal, and producer gas. The use of oil tends to be restricted to localities where oil may be procured cheaply, but is becoming more extensive. Although powdered coal is a desirable fuel in many ways, it has one objectionable feature for lime burning—part of the ash is deposited and intimately mixed with the lime in the kiln. This drawback has been overcome by passing the lime after hydration through an air separator of the Raymond type which separates the ash, core, and other coarse particles from the finer lime, leaving a good commercial product.

Producer gas is the fuel now used most commonly in rotary kilns because of its economy, ease of operation and control, and the long flame which favors effective calcination. The extensive use of producer gas in other industries has supplied much information on

manufacture and utilization, thus facilitating use in the lime industry.

The temperature of the rotary kiln at the hot end is commonly between 2,200° and 2,400° F. This temperature is much higher than that required to dissociate limestone but is necessary to overcome the heat losses through radiation and convection.

The fuel ratio of the rotary kiln varies at different plants, as it depends upon the composition of the stone and other local conditions. In general, in rotary kilns fired with producer gas the fuel ratio is now between 2.75 and 3.33 pounds of lime per pound of coal. Fuel ratios much higher than this have been occasionally attained for short periods of time in experimental runs. The fuel ratio of shaft kilns shows even a greater variation—from 3.0 to 5.0 pounds of lime per pound of coal. Although definite averages can not be easily obtained, the general opinion of lime manufacturers who operate both shaft and rotary kilns is that the fuel ratio of the rotary kiln now tends to be somewhat lower than that of a shaft kiln calcining the same stone. As the use of the rotary kiln becomes more extensive its fuel ratio will probably be increased.

SIZE OF STONE

Stone in sizes ranging from dust to over 2 inches in diameter has been burned in the rotary kiln. There is some difference of opinion as to what size is best. Stone that has a diameter range between one-half and 1½ inches is now most widely used and seems to be most satisfactory. The stone must be sized to fairly close limits; preferably the ratio of the largest stone to the smallest should not exceed 2 to 1. In actual practice necessity compels this ratio to be often exceeded, but the belief is general that the more uniform the charge of stone entering the kiln the better will be the product. When there is much diversity in the size of the stone, the quality of the lime produced tends to be more irregular, as fine stone and coarse stone naturally do not calcine at the same rate. Stone sized within narrow limits permits uniform operation of the kiln and the consequent making of a uniform product. When the size of small stone varies widely, it is advisable to rescreen the material and size it into two lots of more uniform dimension, which can be calcined in the kiln in batches.

The size and shape of stone that tends to produce the most core depend upon local conditions. In a charge of limestone not closely sized much core may appear in the larger pieces that have not had time to calcine completely in their passage through the kiln. Core, however, appears very often in the smaller fragments of stone, particularly if they are flat. It is probably due to the smaller stone

being carried in the center of the charge, where it is insulated from the heat by the larger stone surrounding it. The flat pieces tend to lie against the lining of the kiln where they slide as the kiln rotates and are blanketed by other material that effectively prevents their complete calcination.

PROPERTIES OF LIME PRODUCED

The physical properties of lime produced in the rotary kiln differ greatly from those of lime made from the same stone in the shaft kiln. The most pronounced difference is the extreme rapidity with which lime from the rotary kiln will slake, probably due to its porous nature. The passage of stone through the shaft kiln is slow, taking 24 to 72 hours. During this period the stone is gradually and uniformly heated to the calcination point. In the rotary kiln the total time between the charging of the stone into the kiln and the discharge of the lime seldom exceeds three hours. The stone is rapidly brought to a high temperature, which swiftly expels the carbon dioxide. This sudden removal of the carbon dioxide seems to make the lime more porous than the slowly calcined lime of the shaft kiln. Some differences in sand-carrying capacity and plasticity in lime from rotary and from shaft kilns have been noted.

Most lime produced in rotary kilns is immediately hydrated and marketed in that form. Some is sold as quicklime where markets are available. The established preference for lump lime and the prejudice which still exists against finely divided lime have hampered the sale of quicklime from rotary kilns. When lime was made in pot kilns and other earlier types, the prejudice against small material was established on good grounds; the finer material undoubtedly was of much poorer grade than the lump lime because the impurities tended to concentrate in the fines. This prejudice unfortunately still persists in the minds of many people. Lime produced in rotary kilns from small clean stone is just as pure as the lump material, and as this fact becomes evident prejudice against fine lime is rapidly disappearing.

ADVANTAGES AND DISADVANTAGES

The outstanding advantage of the rotary kiln is that small stone is burned to lime, a more valuable product than raw limestone. Although the kiln has been used mainly to calcine the small stone left after the larger stone has been removed for calcination in the shaft kiln, its performance has been so satisfactory in certain instances that it is being considered more and more as a primary rather than a secondary producer of lime. As a primary producer of lime—that is, one that takes all the quarry output directly and

not merely utilizes the by-products of small stone—it has one great advantage in that all the limestone may be crushed, sized, and calcined as soon as it is taken from the quarry, avoiding the expensive hand sledging and picking out of the one-man stone and subsequent rehandling of the material. Thus, considerable economy in operation is possible. The rotary kiln alone would work well using stone from a quarry free from clay seams, pockets, or a deep overburden, where the whole quarry output could be removed, crushed, and screened by mechanical equipment with no recourse to hand methods. Such quarries unfortunately are uncommon. The rotary kiln is especially suitable for calcining limestone from underground mining. Such stone is generally very clean and free from impurities and contains a higher percentage of fines than that from an open quarry.

In the rotary kiln calcination is under better control than in shaft kilns. Alterations of temperature may be brought about by regulating the producer gas, and such changes may be controlled by pyrometers on the hot and the cold ends of the kilns. The speed and slope of a kiln are likewise adjustable; thus a uniformly burned product may be obtained.

The chief disadvantage of the rotary kiln is that it is not adapted to small plants. A kiln that can be run economically has too large a capacity for the plant whose tonnage of small stone does not keep such a kiln in constant use. At such plants the best solution might be to abandon the shaft kilns and use rotary kilns alone to calcine the entire output. The initial cost of a rotary kiln and its necessarily associated equipment is high, which makes it further unsuitable for small plants. The fuel ratio of a rotary kiln, which tends to be somewhat lower than that of a shaft kiln, increases the cost of producing lime and has been one objection to use of the rotary kiln.

FUTURE OF ROTARY KILN

Rotary kilns will probably be much more used in the future than they are now and will be used more and more as primary producers of lime, calcining the whole quarry output rather than the small stone unsuited for calcination in shaft kilns. As more information becomes available on the operation of rotary kilns, the fuel ratio and the economies should be increased. Little attempt is now being made to save heat by insulation, which retains heat in the kiln, or by the use of waste-heat boilers. Both factors offer many interesting possibilities in effecting further economies. Although a waste-heat boiler is expensive, such an installation at one plant is recovering nearly enough heat from a rotary kiln to run a 200-horsepower boiler. In general, more extensive use of rotary kilns and greater economy in their operation may be expected.

NEW EQUIPMENT FOR CALCINING SPALLS

The Nonmetallic Minerals experiment station of the Bureau of Mines has made exhaustive lime-burning tests with a sintering machine, a type of equipment well known to metallurgists but new to the lime industry. The results of the tests indicate that the machine will calcine fine materials successfully and cheaply. No doubt some mechanical difficulties may arise before the process is perfected, but it bears enough promise to justify a trial. Details have been published¹ and may be obtained from the bureau on request.

OTHER USES FOR WASTE LIMESTONE

ACCUMULATIONS OF STONE UNSUITED FOR LIME BURNING

Through the presence of clay pockets and seams or by contamination from overburden the fines in many quarries are unsuited for lime burning unless they are washed and screened. The stone may also be so variable as to require hand sorting during loading. As the fines can not be sorted the use of spalls derived from such nonuniform rock would yield very poor lime.

Some limestone deposits consist of beds suitable for lime interstratified with beds better suited for crushing or flux. It is noteworthy, therefore, that even with well-established methods of burning spalls into lime there is still likely to be a varying surplus of stone that must be wasted or diverted to other uses. As much expense is involved in moving such waste products, operators should seek outside markets that will bring a small return, even though it may not cover the entire cost of production. Some lime plants that have a market for small stone do not utilize quarry waste. At one plant hand-loaded limestone of the regular kiln sizes was crushed to three-fourths-inch size and sold to furnaces, while the quarry spalls remained unused. All the outlets for waste limestone of which the bureau has any information are discussed below.

WASTE USED FOR METALLURGICAL PURPOSES

Fluxing limestone is usually prepared in 2 to 7 inch sizes. Most open-hearth steel furnaces demand stone not less than 4 or 5 inches in size, but for blast furnaces smaller stone may be used. Smelting companies that have their own quarries of fluxing stone may use stone down to three-fourths inch or smaller, mixed with the larger sizes, but where purchases are made from independent producers it is unlikely that sizes smaller than 1 inch would be acceptable.

¹ Myers, W. M., The Calcination of Small-Sized Limestone with a Sintering Machine: Repts. of Investigations, Bureau of Mines, Serial 2756, July, 1926.

The furnaceman may be prejudiced against limestone fines because they are commonly impure, but if a high quality of stone is prepared, as from underground operation, this prejudice may be overcome and the fluxing market for fines increased. Most high-calcium limestone used for lime manufacture is well adapted chemically for use as flux, and a number of lime companies sell fluxing stone.

High-magnesium stone may be used for furnace lining. In the northern Ohio lime district large quantities are sold in sizes ranging from three-eighths to three-fourths inch. This is an important outlet for small sizes, but the average price is low.

ROAD STONE

Small limestone—fragments unsuited for lime making—is used extensively for road building. In districts where road stone is widely distributed and plentiful it commands so low a price that lime plants can sell it only in small quantities in local territory. Some road-building projects, however, are undertaken in regions where rock is not easily obtainable, and instances have been noted of supplies of small stone being purchased at lime plants many miles away, thus involving a combined rail and water haul. It is therefore possible through enterprising salesmanship to develop a wider market for waste as road stone than that which now exists.

BALLAST, RIPRAP, ETC.

To maintain a good roadbed on railroad lines, a continuous supply of crushed stone is required. Some railroads operate quarries, but most of them purchase the necessary stone from quarries along their lines. By care in preparing a clean stone closely graded according to specifications operators may develop a steady market for railroad ballast.

Large fragments of rock unsuitable for making lime may be used for riprap for river or harbor work, such as spillways at dams, shore protection, or dock construction. Waste fragments are also used to fill in roadways and yards or for rough wall stone. Such uses have local significance only.

CONCRETE AGGREGATE

Tremendous quantities of crushed stone are now used for concrete aggregate, both in highway construction and in the building industries. Limestone makes a good aggregate and is widely used. Only those quarries that are within a reasonable distance of building operations may take advantage of this outlet but, as with road stone, aggressive salesmanship may often broaden the market greatly.

The production of crushed stone on a large scale is commonly conducted in conjunction with lime manufacture.

SPECIAL USES FOR SMALL FRAGMENTS

Dense, compact limestone of attractive color may be crushed into fragments for terrazzo floors. Marbles and certain silicate rocks are used widely in this type of flooring, but there is also a demand for good-quality limestone.

Limestone chips may be used for facing concrete blocks to give a rock surface effect. Small limestone fragments of good color and reasonably impervious to moisture find some use in stucco and pebble-dash work.

FINE AGGREGATE

Limestone crushed to the consistence of sand grains may be used as a substitute for sand in mortar and wall plaster. Although it is inferior to clean, sharp silica sand, in regions where natural sand is scarce the substitution of a limestone product may be justified.

Limestone screenings are used with success as fine aggregate in concrete for various purposes. Concrete brick, both common and face brick, are manufactured with limestone screenings as aggregate and are said to give satisfactory service in house construction.

Limestone screenings without a binder are used for station platforms; the screenings afford good drainage, while the footsteps of travelers and the wheels of baggage trucks pack them down into a firm, compact surface.

CHICKEN GRIT

Limestone crushed to granular form and screened to uniform sizes may be sold as chicken grit. The term is a general one, for the products included may be graded by size as turkey grit, chicken grit, pigeon grit, etc.

AGRICULTURAL LIMESTONE

Pulverized limestone is widely used for liming land. Although opinions differ somewhat regarding its use, the results² of carefully conducted tests extending over many years indicate that in their effect on productivity of the soil there is little choice between pulverized limestone and lime. Many lime-plant operators may utilize the "agstone" market as an important outlet for fines.

The demand for agricultural limestone is seasonal, being confined largely to the spring and fall. To overcome the disadvantages of this fluctuating demand, it is desirable to have a large

² Olson, G. A., "High-magnesium and high-calcium hydrates and limestone compared": Cement, Mill and Quarry, vol. 25, Nov. 5, 1924, p. 62.

storage space in order that the pulverized stone may be continuously prepared from waste and be held in stock for the rush seasons.

FILLER AND WHITING SUBSTITUTE

Limestone pulverized much finer than for agricultural use is being used in a number of products. Small quantities may be added to stock food as a bone builder. A dust, approximately 80 per cent of which will pass a 200-mesh screen, is the most widely used filler in road-asphalt surface mixtures, although slate flour, Portland cement, and hydrated lime are used to some extent. Some ground limestone is used as a fertilizer filler. It has the advantage over inert fillers in that it has valuable properties as a soil conditioner. Very finely pulverized limestone may be used successfully as a whiting substitute in certain classes of rubber, paint, and other products. For such uses it must be very fine and uniformly sized to exclude all comparatively large grains. In general, a limestone flour that will successfully meet the requirements of fillers of a type like whiting or china clay should approximate 300-mesh size. Few lime-plant quarries have the equipment for grinding or sizing to this degree of fineness and therefore have not been able to utilize this promising field of application.

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