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Mono Craters Tunnel Construction Problems

By H. L. Jacques

THE Mono Basin Project is being constructed in order to increase the water supply of the city of Los Angeles by approximately 145 second feet by extending the Los Angeles Owens River Aqueduct into Mono Basin, thereby bringing the aqueduct to its full carrying capacity of 480 sec.-ft. It is financed by a bond issue, which was voted by the citizens of Los Angeles in 1930, for the purpose of making general improvements and extensions of the City's water supply system. It is situated in Mono County approximately 350 miles due north of Los Angeles. The source of water is a group streams which drain the east slope of the Sierra into Mono Lake. Named from the north, the streams intercepted are Mill, Leevining, Walker, Parker, South and Rush Creeks.

The project comprises the construction of two large impounding and regulating reservoirs, one on Rush creek in Mono Basin with a capacity of 48,000 acre feet, the other at the head of the Owens River Gorge in Long Valley with a capacity of 163,000 acre-ft.; 15.42 miles of conduit; and approximately 67,000 ft. of tunnel.

The main feature of the project is the construction of the Mono Craters Tunnel, 59,812 ft. in length, through the mesa separating the Mono Basin and the Owens River watershed. Mono Basin is 662 sq. mi. in extent with Mono Lake (at an elevation of 6,419 ft. and covering an area of 54,720 acres) occupying its lowest part. The lake is fed mainly from the streams on the east slope of the Sierra and partly by springs and underground sources from the lava covered mesa to the south and east. At an earlier period the lake was several hundred feet higher in elevation than at present.

The eastern slope of the Sierra in this region is characterized by

A paper presented on October 26, 1939, at the California Section Meeting at San Francisco, by H. L. Jacques, Engineer of Major Construction, Bureau of Water Works and Supply, Department of Water and Power, Los Angeles.

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the presence of great glacial moraines extending from the base of the mountains far into the valley below.

To the south the boundary of the basin is partially formed by a series of eruptive volcanic cones, known as the Mono Craters, from which the tunnel derives its name. Some twenty in number, these volcanic peaks, attaining an elevation of 9,000 ft. or more, extend in a north and south direction for about 10 miles. Most of them are of very recent origin, being formed subsequently to the glacial flows that cover the ancient floor of the valley. For the most part, they are composed of acidic lava, ranging from fairly compact obsidian, a black volcanic glass, to light grey pumice. For a distance of approximately 10,000 ft., the tunnel penetrates these volcanic cones.

The mesa separating the basin and the Owens River along the line of the tunnel for about 8 miles has an elevation of approximately 8,000 ft.

The mesa occupies part of what was once a deep valley lying between the Sierra on the west and the White and Inyo Mountains to the east, each range rising to an elevation of 13,000 ft. or more. Portions of the floor of this ancient valley were covered with lakes which, at a later period, were filled with products of erosion from the steep slopes of the surrounding mountains.

During the quaternary period great glaciers, of which remnants are still to be found, existed in the High Sierra forming the west and southwest boundary of the Basin. In time, these ice and snow fields with their included debris built great moraines at the base of the mountains and far out onto the valley floor. At a later period, the region was visited by great volcanic activity resulting in the formation of high volcanic peaks, of which the Mono Craters are a part and the covering of the surrounding terrain for miles with lava and volcanic ash.

The Mono Craters Tunnel from portal to portal is driven through such formations.

Beginning of the Project

Preliminary surveys for the project were started in 1930. Several possible routes were studied. Borings by diamond and calyx drills were made on two other routes besides on the one adopted.

For the most part, the surface of the plateau separating the two watersheds is covered with volcanic ash of variable depth so that very few outcrops of the underlying rock formations are visible, making geologic determinations from surface indications practically impossible. Eight drill holes varying in depth from 386 to 1,003.5 ft. and from 5,360 ft. to 10,130 ft. apart were bored along what appeared to be the most favorable line for the tunnel.

The percentage of cores obtained from several of the holes at their lower depths was so small that it was difficult for even competent geologists to classify properly the true character of the formations at or near tunnel grade. One of the consulting geologists in his report recommending the location adopted, stated that, while great difficulties were to be anticipated in driving the tunnel, he believed none would be found to be insurmountable. He was right.

Preliminary construction, comprising roads, telephone and power lines, the building of water supply and the establishment of camps, was started in July, 1934. Excavation was started at West Portal in September and at East Portal in November, 1934.

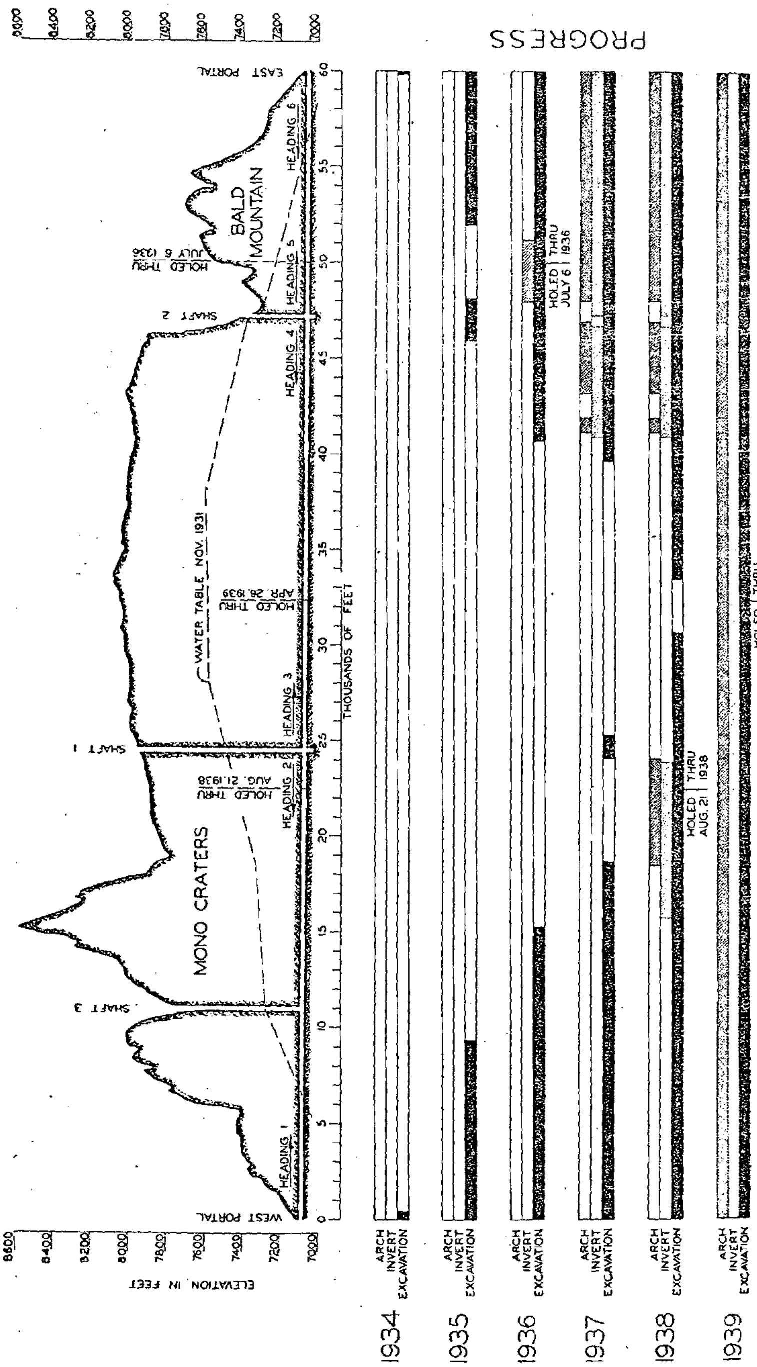
West Portal, at an elevation of 7,058 ft., is situated 7.8 miles southeast from the town of Leevining. From this point, the tunnel runs south $55\frac{2}{3}$ degrees east for 42,825 ft. to an angle point; thence south $43\frac{1}{3}$ degrees east for 16,987 ft. to East Portal on the Owens River—a total length of 59,812 ft.

The tunnel has a gradient of .0005, is almost circular in cross-section with a diameter of 9 ft. $7\frac{1}{2}$ in. inside the concrete lining. Based on a coefficient of $n = 0.012$, it will have a carrying capacity of 365 sec.-ft. Excavation was completed April 26 this year when Headings 3 and 4, driven from Shafts 1 and 2, respectively, met on that date. The concrete lining is 96 per cent completed, 2,708 ft. remaining to be lined October 24, 1939.

1939

With the completion of the three miles of conduit, now under construction, connecting the East Portal of the 3,450-foot Grant Lake Reservoir outlet tunnel with West Portal, Mono Craters Tunnel, it is expected that the waters of Rush Creek amounting to a mean annual flow of 51 sec.-ft., plus some 30 sec.-ft. made in the tunnel itself, will be delivered into Owens River early next year.

As shown in the accompanying profile, excavation was carried on from six headings; first from Headings 1 and 6, West Portal and East Portal, respectively; then from Headings 4 and 5 from Shaft 2 and from Headings 2 and 3 from Shaft 1. Each shaft has three compartments, two for hoisting, 5 ft. by 5 ft. 2 in., and a manway and utility compartment $5\text{x}6\frac{1}{2}$ ft.



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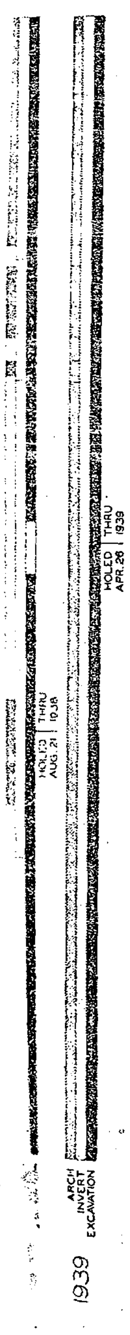

FIG. 1. Mono Craters Tunnel Profile

Shaft Sinking Problems

300'

Shaft 2, 12,735 ft. from East Portal, is 299 ft. deep from collar to tunnel invert and 361 ft. to bottom to allow for skip loading below muck pocket. This shaft presented no difficulties in sinking, which was started on February 9, 1935 and completed to tunnel grade four months later. 4 mos no problem

Formations encountered from the surface were: benching for the collar was in hard rhyolite tuff; from the collar 7 ft. of loosely cemented volcanic ash, 207 ft. of streambed clayey gravel, 113 ft. of basalt; and from 28 ft. below tunnel invert to bottom of shaft, a fairly well cemented glacial gravel.

The shaft being located on the rib of a small spur jutting out from high cliffs surrounding a small green meadow fed by springs, indicated considerable water might be encountered. Consequently, a 16-inch well was drilled about 10 ft. from one side of the shaft at the time sinking was started. After penetrating about 20 ft. into the hard basalt, with no increase of water, the hole was bottomed at 234 ft. from the collar. A deep well pump kept the shaft thoroughly dewatered as sinking progressed. The well made approximately 150 gal. per min. which undoubtedly materially facilitated sinking.

water pump

150 gpm

The hard basalt was excellent formation in which to excavate a spacious muck pocket and a large pump sump on each side of the shaft, also for the enlargement of the tunnel section for a battery charging station and the construction of a repair drift opposite the shaft. The shaft is lined with concrete for 40 ft. from the collar down. The shafts are constructed 20 ft. from the center line of the tunnel.

Driving was begun in Heading 4 August 28, and in Heading 5 September 7, 1935.

The construction of Shaft 1, 24,460 ft. from West Portal and 22,614 ft. from Shaft 2, presented a different problem. Sinking was started December 3, 1934, and tunnel grade, 896 ft. from collar, was reached May 12, 1937. The bottom is 48 ft. deeper to take care of the muck. From the collar, the formations are as follows: 18 ft. loose volcanic ash; 507 ft. fairly hard rhyolite tuff; 38 ft. volcanic ash; 308 ft. of glacial gravels; 73 ft. sandstone (old rock floor).

900

Sinking through the upper 525 ft. was made in good time. Water was encountered at a depth of 492 ft., or 33 ft. above the bottom of the hard rhyolite. When the softer formation, the ash, was encountered, trouble began and continued on down to tunnel grade. water 500 water pumps boils

A few feet of sinking below the water table brought water in large quantities, 200 gal. per min. or more at the start. A chamber was cut in the hard rock 480 ft. from the collar for the installation of pumps for boosting the water to the surface. The volcanic ash, in all degrees of fineness, was hard to hold as it would seep through the lagging or spiling or boil up from the floor, causing much cavitating back of the timbers. Below the ash the glacial gravels and other fragmental materials were even more troublesome.

Glacial gravels, as found at the base of the Sierra in the form of moraines, are a heterogeneous mass of debris ranging from boulders many cubic yards in volume down to exceedingly fine rock meal. In its initial state the whole mass is fairly well cemented and generally impervious to water. This is exemplified in the numerous lakes found on the eastern slope of the Sierra formed by terminal moraines across canyons and water courses. Grant Lake on Rush Creek is an example, and the new Grant Lake Dam-site has its abutments in a terminal moraine through which the stream had ultimately cut through.

In the periodic advance and recession of the ice field, the moraines were subjected to periods of erosion and sedimentation in which the materials were segregated and classified, resulting in beds of open coarse gravel, coarse sands, fine sands and silts.

While large boulders, of such size as to require blasting, were often encountered in the shaft, the greatest trouble was found in the fine sands and silts which, due to the water pressures behind or under them, as they were approached, would cause them to boil up and fill the shaft for many feet. At several places, as aquifers, or water bearing strata were encountered, small drifts were constructed leading from or around the shaft to intercept and control the water.

When construction of this shaft was started, some consideration was given to the desirability of sinking a well or drill hole as had been done at Shaft 2 and of installing a deep well pump to facilitate drainage. Calyx drill hole No. 4, 6,155 ft. to the west, and drill hole No. 5, 3,388 ft. to the east on the tunnel line, indicated the water table to be at an approximate elevation of 7,449 ft. at the shaft, or 492 ft. below the collar. That assumption proved to be correct. It was considered an unnecessary expense to drill such a well when sinking for half the depth or more would be in dry ground. Later experience draws the conclusion that the well would have been most desirable and economical.

Ultimately a 12-inch well, drilled to tunnel grade from the then

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bottom of the shaft 131 ft. above tunnel grade, helped tremendously in sinking operations. While no pumping was done from the well, it intercepted water bearing strata alternating with less pervious fine sands and clayey deposits, relieving the latter from uplift from water pressure as they were approached. The shaft is concrete lined No 1 from the collar down for 40 ft. From 40 to 520 ft., or to a level 5 ft. above bottom of the section in hard rock, it is gunited. Below that point, the shaft is lined with reinforced concrete, and octagonal in shape, better to withstand the heavy ground and water pressures. After concreting, the walls were backed with cement grout under considerable pressure. Holes were drilled later through the walls for drainage.

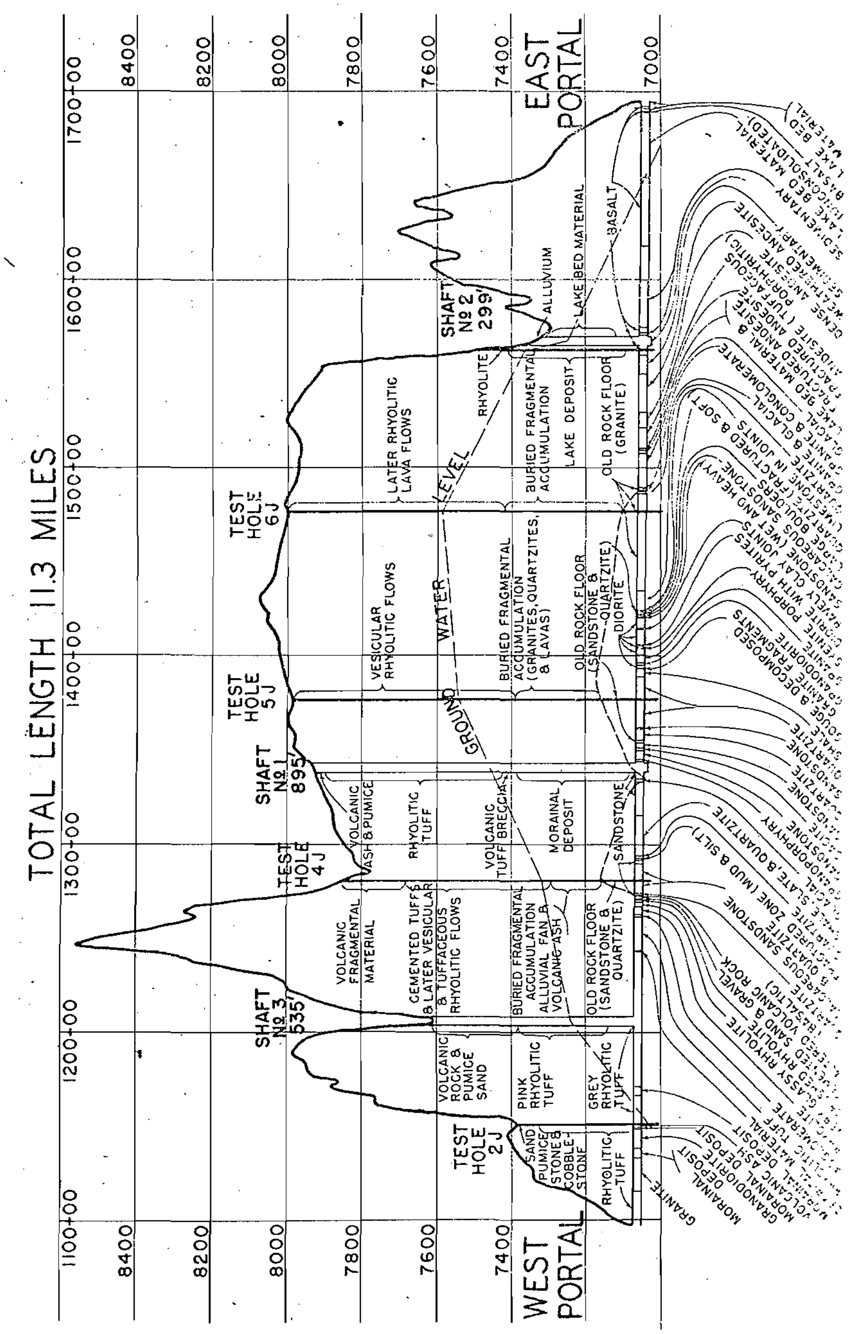
At a place 709 ft. from the collar, 250 gal. per min. of water was intercepted which, for a year or more, was used for camp domestic supply with no material decrease in volume. During period of sinking, the average flow in the shaft was approximately 550 gal. per min. and at times considerably higher.

Driving the Headings

The formation encountered in advancing Heading 1 for 17,300 ft. was mostly rhyolite which, as a whole, was fairly hard and required occasionally only light support. For the first mile from West Portal, small spurs of granite were penetrated with intervening valleys refilled with glacial gravels, volcanic ash and detrital materials. (See Geological profile.)

Water was encountered at 6,100 ft. At 7,800 ft. carbon dioxide gas was detected in small quantities. As progress advanced, both water and gas increased materially. In May, 1936, at 13,000 ft. from the portal the gas had increased to such a volume that the ventilating facilities were no longer adequate, and it became necessary to suspend driving at the face. At 11,000 ft. from the portal a ventilation shaft, CO_2 vent known as Shaft 3, was constructed by sinking and raising. A two-compartment shaft, 535 ft. deep, it was completed in 38 days.

At the shaft collar were installed several blowers with a total capacity of over 50,000 cu.ft. per min. Electrically operated, each unit had an auxiliary gas engine attached to operate the blower in case of a power outage, assuring adequate ventilation at all times. Advance at the face was resumed in July. At approximately 14,400 ft., the neck of one of the main craters was crossed which caused Neck of crater considerable trouble. For several hundred feet, the formation was badly broken indicating a major fissure or fault, probably one through



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which the craters erupted. Large quantities of water and some warm springs (up to 97°F.) highly charged with carbon dioxide, were intercepted. At one place, high water pressure back of the face caused a run-in, filling the tunnel for a hundred feet.

On reaching 15,230 ft., some large crevices were intercepted which increased the water flow by several thousand gallons per minute, temporarily flooding the tunnel. Work in the face was suspended to construct additional pumping installations, one at Shaft 3 and one at Station 15,000, each of 9,000 gal. per min. capacity.

On resuming work in the face, grouting off the water and gas was resorted to. The procedure consisted of drilling deep holes in the face, from four to eight in number up to 40 ft. in depth, then to pump cement grout in them to refusal at 1,000 to 1,100 lb. per sq.in. pressure. By using quick setting cement to finish the grouting of each hole, drilling and blasting at the face followed immediately after finishing grouting.

After grouting, the face was advanced 20 ft. and again followed by the drilling of the 40-foot holes. If water and gas in troublesome quantities were not encountered, the face was advanced another 20 ft., otherwise the face was again grouted. This procedure assured at least a 20-foot grouted wall ahead of the face at all times, decreasing the risk of run-ins on approaching soft or broken ground.

To reduce further the dangers of cave-ins on approaching soft zones, the water pressures were relieved by drilling holes in the walls and roof back of the face. Pipes placed in the drains would convey the water and gas back to pumps, thereby reducing the amount of water on the tunnel floor and keeping the air more free of carbon dioxide gas.

At 17,300 ft., Heading 1 passed through a transition zone of agglomerates consisting of debris from volcanic rocks and underlying alluvial deposits, and entered into the ancient rock floor, old metamorphics consisting of quartzites, sandstones, shales and slates. For the most part, these old sedimentaries are thinly bedded, have been subjected to great disturbances resulting in much distortion, fracturing and weathering. The bedding planes are usually found dipping at a steep angle between the vertical and 60 or 70 degrees, commonly toward the north. The strike is generally in an east and west direction. Their vertical attitude permits free percolation of water from the overlying alluvial and glacial gravels and other pervious materials. For about 3,000 ft. after entering the sedimentaries, the sandstone is calcareous and carbonates were generally

✓ Hot water CO_2
Filled tunnel 100'
3000± gpm

Pressure Grouting
1000-1100psi
20' walls

found in the joints of the quartzites and shales, a condition which probably accounts for the presence of carbon dioxide gas.

Fragments of granite and limestone were found in driving through the main vent of the crater, indicating also that the eruption must have penetrated upward through old granites and limestones.

CO_2

The source of carbon dioxide is most likely in these calcareous formations which have been broken down by volcanism and the action of sulfurous and other acids commonly found in active volcanoes. The gaseous zone extends approximately to 19,500 ft. from the portal or for a total distance of 11,700 ft. No carbon dioxide was found beyond that point anywhere in the tunnel. Since reaching the center of the craters the volume of gas up to the beginning of this year has averaged about 1,000 cu.ft. per min., the maximum approaching 1,400 cu.ft. per min. About 40 per cent of the carbon dioxide is generally retained in the water, the remainder being freed in the air. The volume of gas liberated depends considerably on the condition of the atmosphere, a great increase occurring during a rapidly falling barometer with a corresponding decrease of carbon dioxide with a rising barometer.

AVG 1000 CFM
MAX 1400 CFM

During periods of heavy gas, daily records were kept of the condition of the air flowing through the tunnel, the volume checked and the air analyzed for carbon dioxide and oxygen contents. It was endeavored to keep the percentage of carbon dioxide below 2.5 and the oxygen above 20.5. While carbon dioxide is neither toxic nor inflammable, an excess of it reduces the oxygen content of the air, making respiration laborious and exhausting.

On some occasions, while advancing the face, when large flows of water were encountered, gas was liberated so quickly and in such volume that the air would become saturated to 15 or 20 per cent, although the air line might be delivering some 8,000 cu.ft. per min. of fresh air within a few feet of the face. At such times the miners had to leave the face and seek a safer place, regardless of whether or not a run-in from heavy ground, water or gas pressure was impending.

The ground within the metamorphic zone was very heavy, requiring heavy support throughout to the holing-through point with Heading 2 at 22,426 ft. from the portal, and beyond throughout Headings 2 and 3 and into Heading 4 where the metamorphics come in contact with granite. It is most variable in character, changing from hard to soft or vice versa within a few feet. The tunnel is driven for 3½ miles through this formation. The area has been broken up by numerous faults running more or less in a northerly direction. Fissures filled with loose sand, silts, and clays were frequently encountered, which, generally accompanied with water, were very difficult to penetrate. The bulk of this area was heavily spiled and much of the distance was advanced behind breast boards.

Control of Water

Shortly before holing through Headings 1 and 2, Heading 1 was making 9,300 gal. per min. of water, about half being pumped to West Portal, the remainder up Shaft 3.

Due to the flat gradient and small width of tunnel, the water had to be picked up at close intervals. Pick-up pumps were quite uniformly spaced 1,000 ft. apart as were transformer stations. At places where carbon dioxide entered in a large volume it was necessary to place the pumps at much closer intervals to prevent the escape of gas from the water into the air. Carbon dioxide is especially corrosive to steel. Pick-up pumps pumping carbonated water were made of bronze and had bronze rotating elements. Any other material did not last long.

CO_2 pumps bronze

Main pumping stations, each of 9,000 to 10,000 gal. per min. capacity were installed at 7,800 ft., 11,000 ft., 13,500 ft. and 15,000 ft. from the portal, each generally made up of two units. Dewatering lines were two or three 14-inch #12 gage steel pipe flanged in 24-foot sections well anchored to the wall or floor.

Method of Support

At start of construction, timber sets made up of 8 by 8-inch timber were used for a few hundred feet at each portal heading; later steel sets of 5-inch 12¼-pound I-beam and 6-inch 12½-pound I-beams were used in lighter ground. For the last 25,000 ft. of tunnel driven, for the most part in heavy ground, 6-inch H-beams of 20- and 30-pound weight per foot were used throughout. In the heaviest ground, where 30-pound beams were used, a steel spreader was also employed made up of 6-inch 20-pound H-beams curved to a radius of 19 ft. 4 in. The sets are normally placed on 5-foot centers, though in many places they are much closer and in numerous cases only a few inches apart. While in ground requiring but normal timbering,

8 x 8 timber
5 I 12.25
6 I 12.50

the sets are generally lagged with 2x6 in. or 3x6 in. lumber, or crown bars of 4x6 in. or 6x6 in. timber, in heavy ground, spiling made up of 4x6 in. or 6x6 in. timbers had to be driven well beyond the position of the following set to prevent runs in soft material. In wet ground containing boulders and inclined to run, steel spiling made up of 6x2 in. 10.5-pound steel channels was used advantageously. Spiling was generally driven by the mucking machine acting as a battering ram, a long timber with reinforced ends being placed between the mucker and the spiling driven.

In driving Heading 2, westerly from Shaft 1, the contact between the old rock floor and the overlying gravels was followed for a considerable distance, going in and out of the sandstone and into the gravels. At every change considerable additional water was encountered, which with the highly weathered condition of the sandstone made for a tendency to run unless extreme care was taken in advancing the face.

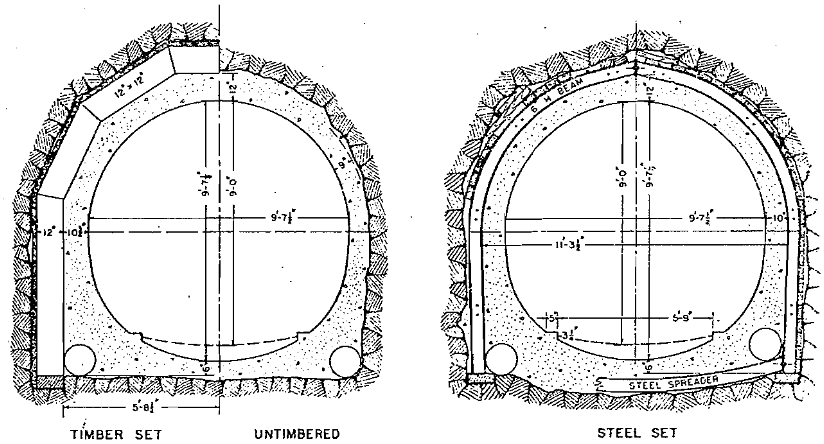

FIG. 3. Cross Sections, Mono Craters Tunnel

Heading 3 was driven about 7,800 ft. easterly from Shaft 1 wholly through the metamorphics—quartzites alternating with thinly bedded sandy shales predominating. Through this section numerous intrusions of granitic rocks (diorites, porphyries and related rocks) were encountered.

Each contact was accompanied by much faulting and weathering with the feldspathic minerals in the rocks in many instances highly

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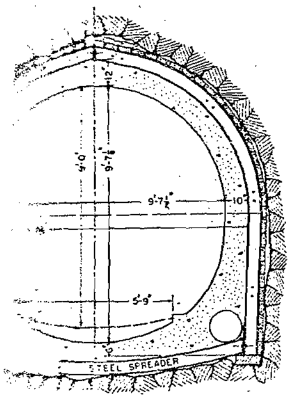

STEEL SET

Tunnel

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kaolinized, causing the ground to squeeze from the sides and arch and raising of the floor. The core of some of the intrusives, especially the diorites, was often very hard, sometimes requiring 60 per cent powder to break the rock. It also broke very blocky making mucking slow, often requiring secondary shooting.

In driving Heading 4, westerly from Shaft 2, various kinds of formations were penetrated. Starting at the shaft, excavation was in good hard basalt for a few hundred feet, then through volcanic agglomerates for a short distance when unconsolidated sediments, mostly sands and silts were encountered, some of these were very wet and heavy. Andesitic agglomerates followed the sediments, then good sound andesite for about 2,000 ft. While the latter stood well without support, large flows of water were encountered necessitating grouting.

Beyond the andesite driving was through several thousand feet of glacial gravels, followed by about 6,000 ft. of granite and then the metamorphics. Both the gravels and granite were crossed by numerous faults and made large quantities of water. The ground was heavy and required heavy support. In spite of utmost care taken, several runs occurred in advancing through the gravels; one such, occurring about 300 ft. back from the face, caused the suspension of driving operations for several months. During this period, all the tunnel in heavy ground from the run to the shaft for about a mile was lined with concrete for greater safety.

Heading 5, driven easterly from Shaft 2, like Heading 4, alternated in basalts and unconsolidated sands and gravels. In crossing an ancient stream bed about 1,500 ft. from the shaft, the roof caved in, partially filling the tunnel with debris and flooding the tunnel and shaft, the latter to within 80 ft. of the collar. Work was suspended for about a month.

Formations in Heading 6 also alternated between volcanics, mostly basalts, and unconsolidated ancient lacustrine deposits, the latter consisting of beds of volcanic ash, near the portal, then beds of silts, sands and gravels. Some of the silts, partially consolidated, would have a tendency to squeeze and heaving of the floor would occur. Very heavy timbering was required here.

The tunnel is supported for 40,322 ft. or for 67.4 per cent of its total length. Of the distance timbered, 23.2 per cent was spiled, and 18.5 per cent or 7,480 ft. was advanced behind breast boards.

The maximum water flow for all headings was a little over 20,000 gal. per min. ~~or 44 sec.-ft.~~

At the present time, the tunnel is making about 14,000 gal. water per min. and Heading 1 is making between 450 and 500 cu. of carbon dioxide gas.

Where heavy ground was encountered, the excavation was enlarg materially increasing the thickness of the concrete lining. Larg amounts of water still coming in the tunnel at the time the lin was being poured gave considerable trouble. Drains were pla in the floor, and, where possible, seepage from the sides and a was lead to them by sheathing with light sheet iron, or handled pipe drains through the arch forms. The sides and arch were pou after the invert. Both were placed with a pneumatic gun charg directly from the mixer in the tunnel.

The details of equipment and methods of operation have n been covered in this paper. Those interested may find a w written article descriptive of the tunnel in all its phases in the December, 1938, issue of the *Western Construction News*, written by Way W. Wyckoff, member of the A. W. W. A., and engineer of the proje

Safety Measures

Safety Reco

In spite of large quantities of water and gas, and in the face of heavy, treacherous ground, the safety record on the project has been very good. During the last two and a half years, during whi time over 25,000 ft. of tunnel has been driven and 40,000 ft. line not a fatality has occurred.

Mine Rescue Team

When carbon dioxide gas was first detected, a mine rescue cr was trained, organized and equipped and has been functioning eve since when emergencies arise.

Special safety equipment and appliances have been installed at strategic points in Heading 1 to take care of any emergency arisin due to exposure to gas.

At Shaft 1 heavy reinforced concrete bulkheads with steel doo were constructed on each side of the shaft to protect it from floodi in case a heavy run of water or a power outage should occur. Adequate standby pumping and ventilating equipment was installe at all headings and shafts.

The project is being constructed by force account under the direction of H. A. Van Norman, Chief Engineer and General Manage Bureau of Water Works and Supply, Department of Water an Power, with W. W. Hurlbut as Assistant Chief.